



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

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Abstract

The CASSARINA Project is a co-ordinated joint study of recent environmental change in North African wetland lakes. Nine primary sites were selected for detailed study comprising three sites in each of Morocco, Tunisia and Egypt. Multi-disciplinary studies were undertaken by scientists from each of these countries working in co-operation with colleagues in the UK and Norway. The detailed results are presented in a consecutive suite of papers that describe both modern ecosystem attributes and the recent environmental histories of each site. This paper presents an overview of the aims, structure and initial results of the project.

Modern site attributes measured were water quality and phytoplankton (Fathi et al., 2001), zooplankton (Ramdani et al., 2001b), fish (Kraïem et al., 2001) and littoral vegetation (Ramdani et al., 2001a). Baseline water quality data showed that one site (Megene Chitane) was acid with low salinity but the others had high alkalinities with varying degrees of brackishness. All the sites tended to be eutrophic and the phytoplankton was mainly dominated by green or blue-green algae. Where fish were present, growth rates were high with marginally highest rates in the Egyptian Delta lakes (Kraïem et al., 2001). Marginal vegetation surveys showed that emergent macrophytes were still extensive only in the Delta lakes (Ramdani et al., 2001a) where they form important refuges and restrict water pollution. In 1998, one Moroccan wetland lake (Merja Bokka) was drained completely for cultivation.

Site specific environmental change records for the 20th century period were obtained using palaeolimnological techniques. Sediment core chronologies (Appleby et al., 2001) were based mainly on radio-isotopes (^{210}Pb and ^{137}Cs). Sedimentary remains of aquatic biota, diatoms, zooplankton, higher plants and benthic animals (Flower et al., 2001; Ramdani et al., 2001c; Birks et al., 2001a) and pollen (Peglar et al., 2001) were investigated (Birks et al., 2001b). Major differences in past species abundances were found and were interpreted in terms relevant to biodiversity and water quality/availability change. Metals and pesticide residues in sediment cores indicated that lake contamination was generally lower than in some European sites but some DDE profiles showed a close correspondence with known usage histories (Peters et al., 2001).

Hydrological changes affecting water quality and availability mainly arose from land-use intensification during the 20th century and are shown to be the main driver of biodiversity disturbance at all nine CASSARINA sites. Summarizing floristic and faunistic changes using species richness values indicated that freshening of the Delta lakes during this century generally increased aquatic diversity. Species richness also increased during the final drainage of Bokka but tended to decline in acid Chitane. Modern sampling showed that phytoplankton and ephytic diatom diversity was higher in the Delta lakes but this was not so for zooplankton. Each biological group reacted differently to environmental disturbance and this lack of concordance makes overall diversity changes difficult to predict.

Implications of the combined study are that water quality and availability changes through landuse intensification remain the greatest *imminent* threat to the ecological integrity of remaining North African wetland lakes. For most sites, recent changes in freshwater supply have occurred causing sometimes catastrophic changes in lake biota (Bokka). The acid lake (Chitane) supports an acidophilous biota that is unique in Tunisia but habitat quality is currently diminishing due to both enrichment and inflow water abstraction. However, sediment records indicate that earlier in the 20th century many of the CASSARINA sites experienced temporarily *enhanced* freshwater supply from land irrigation and drainage improvements. This was especially marked for the Delta lakes and these remain the most biodiverse sites today. Intensified time-space multi-disciplinary environmental monitoring of aquatic ecosystems is identified as a key activity for effective wetland lake management and for validating future environmental change scenarios in North Africa.

Introduction

Sustaining biodiversity is a global problem that is exacerbated by high population growth and economic contingency. Yet biological diversity is part of every country's natural heritage and should be protected and conserved wherever possible. This principal is enshrined in the 1992 Rio Convention on Biological Diversity (Glowka et al., 1994) but as the 21st century begins, pollution, landuse intensification, and climate change all threaten sustainability of natural resources. This is particularly so in developing countries where pressing human needs can overwhelm many other environmental considerations. In these countries, wetlands and their associated lakes are amongst the most vulnerable ecosystems (Finlayson et al., 1992; Finlayson & Moser, 1992; Dugan, 1993). The problems of reconciling wetland diversity issues with resource usage are epitomized in North Africa. Growing human populations, accelerating demands for food, housing and water conspire with a dry climate to exacerbate degradation of continental aquatic ecosystems. Notwithstanding any longer term climate change problems, freshwater stress is rapidly increasing in North Africa as water usage increases (Hollis, 1992; Biswas, 1993; Matoussi, 1996; Sultan et al., 1999). Nowhere is the loss rate of wetlands and lowland lakes more alarming than in the North African coastal zone.

Many wetland lakes listed in recent inventories for the region (Kerambrun, 1986; Ramdani, 1988; Hughes et al., 1997) no longer exist or are severely degraded. Some remaining wetland lakes nonetheless support high value ecosystems that not only contribute essential regional biodiversity but also provide important resources for local human populations (e.g., Shaheen & Yousef, 1980; Hollis, 1986, 1992; Kerambrun, 1986; Benessaiah & Belhai, 1999). These environmental values are sometimes recognized in na-

tional legislation but planners need reliable relevant information about both current site status and environmental change trends so that effective measures can be taken to ensure ecosystem sustainability. Such information is not, however, generally available in North Africa where biological monitoring of aquatic ecosystems is typically absent or is uncoordinated and where records about past changes are generally inadequate (Flower et al., 1989; Turner et al., 1995). Furthermore, maintaining biodiversity whilst permitting exploitation of natural aquatic ecosystems is problematical and raises conflicts about defining resource sustainability in North Africa as elsewhere. These issues were recognised by the European Commission which in 1996, as part of a package of potentially mitigating measures, sponsored the CASSARINA (ChAnge, Stress and Sustainability: Aquatic ecosystem Resilience In North Africa) Project. CASSARINA aims to assess current and past biodiversity and rates of environmental change in nine wetland lakes selected from three North African countries (Morocco, Tunisia and Egypt). These sites are all in developing coastal regions where intensive agriculture is actively practised and yet the impact of this environmental stress is largely unknown, except that habitat quality is generally declining and migrant bird populations are threatened. There are four major objectives, to:

- Assess the impact of land-use practices and other changes on shallow coastal lake ecosystems in intensively farmed regions of North Africa during the 20th century.
- Establish ecological base-lines and pre-disturbance communities so that changes in biological diversity can be reconstructed for each lake investigated.
- Implement and integrate regional monitoring of aquatic organisms and water quality with centrally imposed analytical quality control.

- Establish internationally co-ordinated protocols for future monitoring and to set environmental objectives for future conservation management of selected lake ecosystems.

CASSARINA focuses on human impacts on the biodiversity and water quality of selected wetland lakes. Monitoring of these wetland ecosystems was generally absent and little was known about the resilience of their aquatic communities to recent environmental changes. Collection of survey data for setting modern base-lines was therefore an essential part of CASSARINA. Nevertheless, these alone are insufficient to detect ecosystem responses to human activities sustained over decades. Without long-term monitoring, the most reliable source of information about past ecosystem biodiversity is contained in lake sediments. Palaeolimnology can provide evidence of species no longer present in contemporary lake communities and also indicate rates of ecosystem change. The techniques are particularly appropriate for revealing species change trends in diatom algae, zooplankton, zoobenthos, and aquatic plants (see Berglund, 1986). Furthermore, the factors driving these changes (e.g. nutrient enrichment, salinization, metal and pesticide contamination, and soil erosion) can often also be identified.

Combining palaeolimnology with limnological observations offers a powerful way of tackling environmental change and aquatic diversity issues (Smol, 1990). Applying this approach to North African wetland lakes issues has not been undertaken previously and this paper introduces the CASSARINA Project and gives an overview of the methods of investigation, the initial results and their implications.

Background

Prior to the CASSARINA Project, there already existed a wealth of information about wetland lakes and aquatic diversity in North Africa. However, much of this work was on the taxonomy and distribution of aquatic animals and plants (e.g., Boulenger, 1907; Gauthier-Lievre, 1931; Gauthier, 1937; Feldmann, 1946; Gayral, 1954; Blanc, 1954 and standard botanical floras for North Africa) but contained little environmental context. More recently, Morgan and Boy (1982), Kraïem (1987), Ramdani (1988) and Chergui et al. (1999) presented broader views of freshwater biology in North West Africa. A series of papers about

pollution, water quality and the biota of Egyptian lakes appeared mainly from the 1970s (e.g., Saad, 1973; Shaheen & Yousef, 1980; El-Sherif, 1993; Drainage Research Institute, 1997; Gharhib, 1999). Fishery issues have attracted considerable research in Tunisia (Kraïem et al., 1986) but much conservational interest in North African wetland lakes has focused on their value as bird habitats in Egypt (Goodman & Meininger, 1989), in Morocco (e.g., Dakki et al., 1991) and in Tunisia (Hughes et al., 1997). In the Med-Wet Programme, conservation and economic aspects of wetlands around the Mediterranean region were assessed in an international manner (Farinha et al., 1996; Beessaiah & Belhaj, 1999). None of these studies measured rates of recent environmental change in wetland lakes.

Sedimentary records of recent environmental change have been investigated in a number of North African lakes and lagoons (Stevenson & Battarbee, 1985; Flower et al., 1984, 1989; Siegal et al., 1994). Usually, however, palaeo-studies were focused on Holocene time scales and used pollen analysis to indicate terrestrial vegetation changes during this period in Morocco (e.g., Reille, 1979), in Tunisia (Ben Tiba, 1980) and in Egypt (Mehringner et al., 1979). Diatom remains were also used to reconstruct wetland lake systems and climate change in regions of North Africa that are now arid (e.g., Gasse et al., 1987). In the Egyptian Nile Delta lakes both faunal and petrographic analyses of sediment cores were used to trace Holocene changes (Howa & Stanley, 1991; Arbouille & Stanley, 1991; Stanley & Warne, 1993).

CASSARINA builds upon on these earlier studies but attempts to integrate aquatic diversity with both contemporary and past site characteristics so that the current status of each lake can be placed in a recent historical context that is appropriate to conservation issues.

Methodology and rationale

Site selection

Twelve potential sites were initially identified (Figure 1) and all lie in coastal zones on an approximate geographical transect from west to east. This latitudinal gradient is reflected in declining annual rainfall, from >500 mm on the Atlantic coast of Morocco to ca. 100 mm for the eastern Nile Delta region. Being less

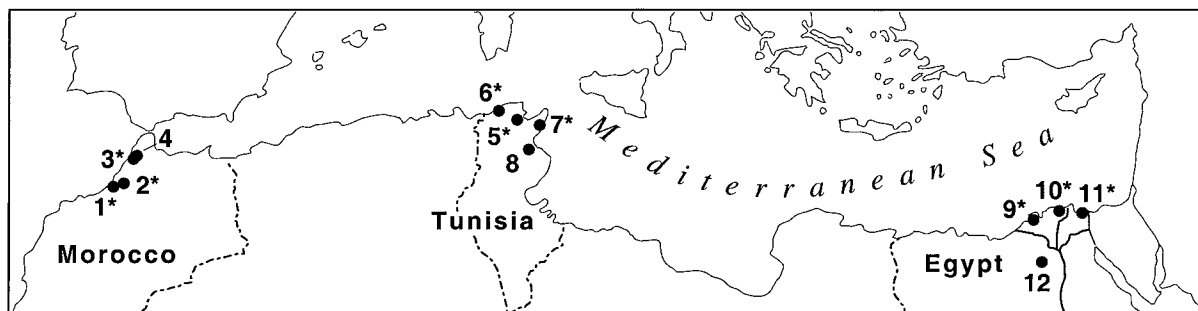


Figure 1. The distribution of the wetland lake sites across North Africa selected for the CASSARINA Project. Nine (*) of these twelve initial sites were used for monitoring and palaeolimnological investigations: 1, Merja Sidi Bou Rhaba*; 2, Merja Bokka*; 3, Merja Zerga*; 4, Merja Khala; 5, Garaet El Ichkeul*; 6, Megene Chitane*; 7, Lac de Korba*; 8, Sebkha Kelbia; 9, Edku Lake*; 10, Burullus Lake*; 11, Manzala Lake*; 12, Qarun Lake.

than 6 m in maximum depth, they are all classified as wetland lakes (see Davis, 1994). Following trial sediment coring (see below), nine of the twelve lakes were selected as primary CASSARINA sites. They were Merjas Sidi Bou Rhaba, Zerga, and Bokka (Morocco), Megene Chitane, Garaet El Ichkeul, and Lac de Korba (Tunisia) and Lakes Edku, Burullus and Manzala (Egypt). These primary sites are described in detail by Ramdani et al. (2001a). Several have considerable value for conservation and/or fisheries and Merjas Sidi Bou Rhaba and Zerga (Morocco), Garaet El Ichkeul (Tunisia) and Lake Burullus (Egypt) are recognised as being of international importance for water birds. All are affected by agriculture but environmental change impacts were poorly known.

Environmental monitoring

Sampling over a seasonal cycle (1997/8) was carried out and attributes investigated were:

- (i) Water quality (conductivity, pH, alkalinity and common ion concentrations).
- (ii) Phytoplankton and zooplankton composition and abundances.
- (iii) Fish species diversity and fish growth rates.
- (iv) Marginal vegetation along fixed littoral transects.

Sampling protocols and techniques used are described in the CASSARINA methods manual (Flower & Patrick, 1997).

Palaeolimnology

Sediment cores were collected from each site using a modified piston corer (see Berglund, 1986). Replicate cores (74 mm diameter) were collected within an

area of about 1 m². One core (the master core) was selected for radiometric dating and correlated with the other core using lithostratigraphy. Cores were generally from central lake locations (see Ramdani et al., 2001a, 2001c). Only in Burullus were locations of the two cores different, one was from the open central area (BULR1) and one from a sheltered bay (BULR2). With the exception of Sidi Bou Rhaba and Bokka, all cores were <1 m long. The typically cohesive and compacted deeper sediments were not amenable to coring without power assisted equipment.

Specific techniques used on sediment cores collected from the nine sites were:

- (i) Radioisotope assay and lithostratigraphic measurements: to provide sediment chronologies and sediment accumulation rates for the 20th century. These measurements can identify past erosion and disturbance episodes.
- (ii) Macro- and microfossil analysis: diatoms (siliceous micro-algae that indicate water quality and are often preserved in sediment), pollen (to indicate the vegetation change in and around each lake), plant and animal macro- and microfossils (to evidence water quality, benthic habitat and biotic changes).
- (iii) Sedimentary heavy metals and persistent organic residues: stratigraphic changes were used to indicate pollution impacts.

Project structure

Because CASSARINA is an international environmental evaluation programme, the co-ordination of specific investigations, designation of tasks appropriate to the skill-base available, and information and material exchanges were all central to its success. Follow-

ing mutual agreements, tasks were assigned to various CASSARINA participant groups. Each North African group undertook specialist tasks and was responsible for local site monitoring (water quality, plankton, fish and marginal vegetation) and documentary site information. Special tasks were zooplankton analysis (Institut Scientifique, Rabat, Morocco); fish diversity and growth rates (University of Tunis, Tunisia); water chemistry and phytoplankton (University of El Minia, Egypt). The two well established European research groups (ECRC, University College London and the Botanical Institute, University of Bergen) were responsible for some analytical quality control, sediment coring and diatom, pollen and macrofossil analyses. Pesticide analysis of sediments and sediment chronologies were done elsewhere (see Peters et al., 2001; Appleby et al., 2001).

Results

Results of the specific research themes within CASSARINA are reported in a suite of ten papers (see below). These themes are divided broadly into two groups, the first is concerned with describing the contemporary status of each wetland lake and the second with palaeolimnological assessment of recent environmental change. The final paper provides a numerical analysis and synthesis of some of these data.

Modern survey

Lake characterization

The nine primary CASSARINA lakes vary considerably in morphology and Ramdani et al. (2001a) shows that though all are shallow they vary greatly in area ($\sim 0.03 \text{ km}^2$ for Chitane to $\sim 1000 \text{ km}^2$ for Lake Manzala). Partial mixing with seawater occurs at several sites, (Zerga, Ichkeul, Korba and all three Delta lakes). However, only the first site is affected perceptibly by (Atlantic) tidal cycles. Intensive agriculture typically encroaches on to the margins of each site, except for Moroccan Sidi Bou Rhaba (a national nature reserve) and Chitane, where some semi-natural woodlands persist. Again excepting Chitane, ground water and irrigation water sources combined with the marine connections make delimitation of catchments difficult. The poignancy of threats to North Africa wetlands is, however, illustrated by Bokka which pos-

sessed 0.5 km^2 of open water in 1997 but by late 1998 the entire basin was drained and under cultivation.

Vegetation

Vegetation transects were monitored but showed relatively few changes during 1997–1999 (Ramdani et al., 2001a), except for Merja Bokka where aquatic vegetation was destroyed by agriculture and Megene Chitane where marked water level lowering affected plant distributions. Documentary evidence indicated that emergent vegetation (important for many bird species) was formerly extensive at Zerga, Bokka and Ichkeul. This is now severely diminished by grazing and cutting at Zerga, by salinization at Ichkeul, or is lost entirely (Bokka). At the strongly saltwater influenced sites, Zerga, Korba, Ichkeul, *Salicornia* marsh typically now (1997–1999) occupies the margins. Extensive emergent macrophyte vegetation (*Phragmites*, *Typha*, *Juncus*) only persists at the Delta lakes. Interestingly and despite active land reclamation, emergent macrophyte beds have tended to increase in these lakes, especially Manzala. Submerged vegetation is mainly *Potamogeton* spp. and *Ceratophyllum demersum* and all three Delta sites are affected by recent introductions of exotic aquatic plants (*Eichhornia crassipes* and *Azolla filiculoides*) (Birks et al., 2001a). Although small the acidic habitat provided by Chitane is unique in the study region and the lake still supported (in 1999) a soft-water community of *Isoetes velata*.

Documentary records

For the 20th century period, documentary landuse information varies from fragmentary to fairly detailed, according to the site (Ramdani et al., 2001a). Organization of large farming enterprises under French direction was typical of the early to mid 20th century period in the Gharb region of Morocco and this also occurred around Ichkeul and Korba in Tunisia. Agriculturally inspired drainage and irrigation schemes had major effects on surface hydrology in these regions. In these intensively agricultural regions management throughout the 20th century has tended to lower ground water levels and curtail winter floods. From the 1980s barrages have intercepted freshwater inflows to Ichkeul and coincided with major documented changes in the marginal vegetation and salinity. However, at Zerga and the Delta sites construction of affluent drainage canals have promoted freshwater water supply. The Egyptian sites are sustained by the Nile River rather than by local rainfall and the Aswan High Dam (built

in the mid 1960s) had an important effect on water supply but water regulation has long been practised in the region. In recent decades reclamation of the Delta lakes has been very active. For all the lakes with sea connections, water supply *per se* is not such a problem as water quality and site disturbance. Throughout North Africa, pollen from introduced plants provided a useful stratigraphic time marker (see below).

Water quality and phytoplankton

All the lakes were brackish to some extent (conductivities $>1000 \mu\text{S cm}^{-1}$), with Ichkeul and particularly Korba being hypersaline in summer months (Fathi et al., 2001). An exception is dilute Chitane, the only site where water pH is <7 . In several of these shallow and unstratified lakes, phytoplankton was poorly developed due to high suspended solids (Zerga, Ichkeul and Bokka) from wind induced resuspension of shallow sediment and/or inwashed soil (Bokka). Average total phosphorus concentrations (TP) were high or very high at all the sites indicating eutrophy, only Chitane and Manzala having values $<100 \mu\text{g l}^{-1}$. Fathi et al. (2001) also describes baseline species data as well as seasonality and spatial differences for phytoplankton communities of each site during 1998. Generally, abundances and species diversity were highest in the spring period and the most eutrophic sites, according to blue-green algal counts, were Sidi Bou Rhaba and Lake Manzala. These sites are at opposite ends of the CASSARINA west-east North African transect and both support high populations of *Microcystis aeruginosa*.

Zooplankton

The zooplankton and microinvertebrates collected from the CASSARINA sites were diverse and often had high abundances of Cladocera, ostracods and copepods (Ramdani et al., 2001b). Species of particular note and importance are *Eucyclops ceratulus*, the most widespread copepod species being only absent from seasonally hypersaline Korba and the partly desiccated Bokka. However, typical marine species, e.g., *Acartia clausi* were only recorded in Zerga. Cladocerans are rather less tolerant of water quality variation but *Chydorus sphericus* was present in six of the nine sites. The group was most diverse in the acid site Chitane (6 species). Here the 'cold water' copepod *Diaptomus cyaneus* occurred, a species only once previously recorded in Tunisia. Ostracods were even

less well distributed across the sites but *Cyprideis torosa* occurred in abundance at five sites. Chitane was again unusual in only supporting one species of ostracod, *Cypria ophthalmica* with poorly calcified shells. No east-west trend in species diversity was found.

Fish

All three Delta lakes support important fisheries based on *Tilapia (sensu lato)* and this contrasts sharply with the western Mediterranean sites in Morocco and Tunisia where mullet or cyprinids predominate. In Ichkeul and Zerga mullet provide the largest catches and are of commercial interest. At the other four sites, fish populations were either small (Sidi Bou Rhaba and Korba), or absent (Chitane, Bokka in 1998). Fish growth rates and condition were compared (Kraïem et al., 2001) using weight/length data of mullet (*Liza ramada*) populations in three sites with significant fisheries (Zerga, Ichkeul and Edku). Growth rates were highest in Edku but seasonal growth patterns were different. Overall production was slightly higher in Ichkeul. Total fish production, as captured biomass, was very variable with ca. 250 tons y^{-1} in Ichkeul to >1000 tons y^{-1} in the Delta lakes. Ichthyofauna diversity was highest in the Delta lakes and Ichkeul and was relatively low in the western lakes where five species or less occurred. The least diverse sites were Sidi Bou Rhaba and Bokka (only two species present) but fish in all the lakes were in good physical condition when sampled. Exploited fish are essentially: Ichkeul, mullet (*Mugil cephalus* and *Liza ramada*), eel (*Anguilla anguilla*), sea bass (*Dicentrarchus labrax*); Edku, Burullus and Manzala, tilapids (*Oreochromis niloticus* mainly, *Tilapia zillii* and *O. aureus*), mullet (*Mugil cephalus*, *Liza ramada*), vundu (*Heterobranchius longifilis*), Nile perch (*Lates niloticus*), grass carp (*Ctenopharyngodon idella*); Zerga, mullet (*Mugil cephalus*, *Liza ramada* and *L. saliens*), eel (*Anguilla anguilla*), sea bass (*Dicentrarchus labrax* and *D. punctatus*).

Palaeolimnology

CASSARINA sediment cores provided a unique archive for assessing environmental change at all nine sites during the 20th century. Providing adequate sediment chronologies is however a pre-requisite for reconstructing environmental site histories.

Sediment chronologies and accumulation rates

Lakes in dry climates with disturbed catchments often yield sediment profiles that are difficult to interpret, mainly because of high and/or episodic sediment supply and deposition. Also, deposition of radionuclides used in dating profiles can vary regionally. Appleby et al. (2001) used ^{137}Cs and ^{210}Pb isotope profiles to help construct core chronologies but these data showed that ^{210}Pb inventories were unusually low in the eastern CASSARINA lakes. This is partly a consequence of low rainfall and the value of this isotope as a dating tool in the Delta region is reduced. Mobility of ^{137}Cs was suspected in several cores and sediment mixing is undoubtedly also a problem. Core chronologies were established using a combination of dating tools, including exotic pollen (e.g., *Eucalyptus*, *Casuarina*) and site contamination dates. For one core (BULR1, central Burullus) only a single sub-surface date was possible (the mid 1950s), inferred by cross-correlating from the radiometrically dated particulate pollution record in Manzala.

At Zerga only the upper soft sediment, above compacted marine clays, was amenable to radiometric dating. Recent sediment accumulation probably began at the coring site only in the mid 20th century. Because of high accumulation rates and dilution of earlier ^{210}Pb records in Bokka and Chitane cores, the isotope chronologies are restricted to the last ca. 50 y. However, where sediment lithostratigraphy permitted, dates were extrapolated to the early 20th century. In Chitane, high and variable local erosion caused the sediment accumulation rate to exceed 1.5 cm y⁻¹ in the 1940s. Similar rates in Sidi Bou Rhaba were due mainly to autochthonous carbonate deposition and if current rates are maintained the site will be infilled by around 2050. Where rates are <1 cm y⁻¹ (the Delta lakes, Korba, Ichkeul and Zerga), despite being surrounded by disturbed landscapes, sea connections probably permit some particulates to escape from depositional zones. Interestingly, the estimated sediment accumulation rate in the Delta lakes (~3 mm y⁻¹) is similar to the Delta subsidence rate (Stanely & Warne, 1993).

Diatom stratigraphies

Diatom microalgae contribute to both the plankton and benthos of most lakes and many species are good indicators of salinity. However, in the CASSARINA cores, the diatoms are of variable value for environmental reconstructions (Flower et al., 2001). In the

Tunisian lakes, Korba and Ichkeul, sedimentary diatoms are very poorly preserved. Similarly, diatoms were absent in the lower core sections in the Delta lakes and in Bokka but here assemblages in the upper sections were sufficiently well preserved to infer recent water quality changes. Preservation was excellent in acid Chitane where acidophilous species predominated but some recent species changes indicate lake enrichment (*Cyclotella pseudostelligera*) and higher salinities (*Achnanthes delicatula*) since the 1960s. There is also a good diatom record in Sidi Bou Rhaba where small changes in palaeosalinity are indicated. Diatom stratigraphies in Zerga, Bokka, Burullus and Manzala all indicate water freshening during the early or middle 20th century. Burullus (BULR1) is the only core where planktonic diatoms (*Cyclotella* and *Stephanodiscus* spp.) are common and are generally indicative of eutrophication.

Zooplankton stratigraphies

Zooplankton (*sensu lato*) remains are generally well preserved in all the CASSARINA sediment cores (Ramdani et al., 2001c). Relatively stable diversity is displayed in the Sidi Bou Rhaba and Zerga cores (excluding basal marine sediments in the latter core). Except for some small changes (an early decline in *Cyprinotus salinus*) the biostratigraphy was also fairly stable in strongly hypersaline Korba. In Bokka, a major species change occurred early in the 20th century and again in ca. 1960 as more species indicative of very low lake level appeared. In Chitane, several new species of Cladocera appeared in the 1940's (e.g., *Alonella exsica*) with several taxa indicating oligotrophy. In Ichkeul the zooplankton community changed markedly in ca. 1960 (as Cladocera and foraminiferan abundances indicated a decline in salt water influence). Sediment mixing problems (Appleby et al., 2001) make interpretation of this core problematic, however. In lakes with sea connections (Korba, Zerga, Ichkeul, and the Delta sites), Foraminifera were usually abundant. Marked salinity variations were indicated by the faunal assemblages in all the Delta lake cores, with freshwater taxa increasing from the 1940s in Edku and from ca. 1930 in Manzala. In Burullus, the tentatively dated open water core (BULR1) had less freshwater taxa after the 1960s.

Pollen and macrofossil stratigraphies

In general, the pollen diagrams for each core typically show disturbed local terrestrial vegetation (Peglar

et al., 2001). Planting of *Eucalyptus* and/or *Casuarina* near many of the CASSARINA sites enabled sediment post dating ca. 1920 to be identified. At the two sites where perceived local agricultural disturbance was least (Sidi Bou Rhaba and Chitane), ruderal plant pollen declined compared with shrub/arboreal pollen indicating woodland regeneration during the 20th century. At the Delta lakes reed-marsh was replaced by salt-marsh around 1900 whereas in Ichkeul reed-beds then began to expand. During the 20th century freshening of the Delta lakes increased and reed-beds expanded again. Here and in Ichkeul and Bokka, aquatic macrophyte remains, particularly of *Potamogeton* and/or *Ceratophyllum* generally increased during the 20th century as salinity changed. Salt-marsh vegetation remained fairly stable at Korba but reed-beds around Zerga and Bokka were diminished or eliminated in during recent decades. Macrofossils, particularly of molluscs, are also good indicators of salinity and/or disturbance (Birks et al., 2001a). They are particularly useful indicators in Bokka and those sites with marine connections. The typical lagoon molluscs *Cerastoderma glauca* and *Hydrobia ventrosa* indicate higher past salinity phases in Zerga, Ichkeul, Korba and the Delta lakes. In the now drained Bokka, a diverse freshwater mollusc fauna existed until the early 20th century and was probably associated with the abundant aquatic plants that then occupied the site. The pre-1920 sediments in all three Delta lakes contained marine/lagoon faunas but before ca. 1900 the marine influence was generally less. In the most recent sediments of Edku and Manzala the abundance of freshwater molluscs is unprecedented compared with the previous hundred years.

Sediment contamination

Pesticide residues were detected in all nine CASSARINA lakes (Peters et al., 2001). The two most commonly found in the sediment cores were hexachlorocyclohexane (HCH) and dichloro-diphenylethane (DDE, a DDT residue). Relatively high levels were found in recent (post-1970) sediments from Sidi Bou Rhaba and Bokka but in Chitane pesticide residue peaks dated to ca. 1980. There were also indications that contamination had recently decreased in the Edku, Burullus and Bokka cores. The onset of pesticide contamination was earlier in Tunisia than in Morocco. Sediment records indicated that pesticide usage has diminished in Tunisia but not in Morocco where levels at two sites give cause for concern. The most complete

pesticide record for Egypt was in Manzala but levels of contamination were not particularly high compared with some non-African sites. The source of pesticides in Chitane is questionable since the catchment is still mainly semi-natural vegetation with only one small recently cultivated field. Consequently, atmospheric transport of pesticide residues into this site could be occurring, possibly from Europe.

Numerical analysis

Numerical analysis of the palaeoecological data was used to detect trends and periods of rapid biological change through the recent past (Birks et al., 2001b). Estimating disturbance can be difficult in field situations but Birks et al. (2001b) also show how community disturbance (the amount of change through time) can be estimated at all the CASSARINA sites using ordination techniques and species turnover times. During the recent past marked community change has occurred at all nine sites.

Discussion

Despite some problems with sediment dating and microfossil preservation and a general lack of documentary records, biological changes at the CASSARINA sites have been generally well recorded during the 20th century by palaeolimnology. Without the techniques employed in CASSARINA, many of the longer term (>3 y) trends and fluctuations in biogeochemistry of the sites would be unrecognised. More specifically, palaeoecology offers the only way to reveal past aquatic ecosystem changes and trends at the species level for unmonitored sites (cf. Smol, 1992). On the other hand, some biological attributes cannot be obtained from sediment records and some aspects of contemporary diversity were established by the modern surveys.

Understanding the nature and pace of past ecosystem change is fundamental to the assessment of wetland lake status. CASSARINA has shown that the main drivers of change at the species level are salinity (related mainly to freshwater availability and changes in regional hydrology) and land reclamation for agriculture. The main 20th century environmental changes, based largely on sediment records, at all nine CASSARINA sites are summarised in the Appendix (Tables 1A–3A). Combining the results of

palaeolimnology with those of modern survey permits an integrated assessment of recent environmental change and its significance. It is convenient to consider this assessment from several aspects, aquatic ecosystem change and stress, biodiversity and biogeography, ecosystem resilience and future implications.

Change and stress

All forms of rapid environmental change can be considered as stressors for aquatic ecosystems yet inherent resilience means that in many cases lake biota can either recover or be transformed into a species different state. Although biological and chemical monitoring of the nine CASSARINA lakes has enabled setting of ecological baselines for the late 20th century, evidence for ecosystem stress trends must be sought in the sediment record. Palaeoecological studies have shown that aquatic ecosystems are never stable if considered over a long enough time period (Birks, 1996) but aquatic communities can adapt and maintain diversity if the rate of change is not excessive or sustained. For the CASSARINA sites, sediment records indicated major species changes but, with the exception of Bokka, ecosystem functionality is generally maintained, albeit in an altered state (Birks et al., 2001b).

Irrespective of a lake's biological attributes and even of moderate pollution, all lakes fundamentally require an adequate water supply. Twentieth century variations in the supply of freshwater has been the single most important factor affecting all the CASSARINA sites. Changes in hydrology can however be complex and Ichkeul, Bokka and Zerga all experienced enhanced freshwater supply during the early or middle 20th century. However, post-1980, this trend has tended to reverse; acutely so at Bokka where land drainage and water stress culminated in the extinction of all aquatic life by late 1998. The southern part of Zerga was a saline lagoon (Ramdani et al., 2001a) with hard compacted marine shell-rich sediment before the Nador Canal winter flood control scheme began delivering fresh water and silt to the site in the mid 1950s. More flourishing growth of emergent aquatic macrophytes in this southern region after the 1950s is probably prevented by live-stock grazing. Conversely, in the north-east, the Oued Drader inflow has been much reduced in recent decades by water abstraction. Of all the CASSARINA sites, Sidi Bou Rhaba is the only lake where the 20th century sediment record does not indicate major changes. Siltation is accelerating

but sedimentary diatoms and ostracods indicate only a gradual increase in salinity whereas aquatic plant changes suggest some eutrophication (Birks et al., 2001a).

In Tunisia, the Ichkeul cores offer evidence of past fresher phases. In the 19th century the lake was predominantly fresh in the winter months but widening of the connection with the Mediterranean in the 1890s led to a small increase in salinity that promoted growth of mainly *Potamogeton* taxa (Stevenson & Battarbee, 1991). In the 1940s *Phragmites* expanded and later freshwater Cladocera appeared indicating fresher conditions (possibly a prolonged low salinity winter phase as irrigation/river canalization schemes promoted freshwater runoff). In the 1980s, a higher salinity regime began to prevail as freshwater inflows were barraged and salinization occurred to such an extent that by the early 1990s the emergent macrophyte beds catastrophically declined, invertebrate communities changed, and the large over-wintering bird populations, especially geese, diminished. Chitane has also experienced reduced freshwater supply in the late 20th century following exploitation of the inflow stream for local crop irrigation. Despite past erosion and recent eutrophication, reduced freshwater supply has exerted high stress on this lake. The lake was dry for several months in 1996 and the sediment core lithostratigraphy indicated that this was the first complete desiccation episode in recent times. At the other Tunisian site, Korba, freshwater runoff has been curtailed by water abstraction for agriculture but the sediment record indicates relatively small aquatic community changes.

The Delta lakes provide different histories of water availability and quality but all show some trend towards declining salinity during the 20th century. Here increased irrigation for agricultural purposes (Shahin, 1985) has clearly promoted freshwater input and this has affected the molluscan fauna (Bernasconi & Stanely, 1993), especially after Aswan High Dam construction (Banoub, 1979). Some of the ecological effects of this change are clearly seen in the Delta lake biostratigraphies (Flower et al., 2001, Ramdani et al., 2001c; Birks et al., 2001a,b). Biota more typical of saline or fluctuating conditions (*Burullus* and *Manzala*) or of reed bed-salt marsh communities (*Edku*) persisted at the beginning of the 20th century but in recent decades species typical of more open freshwater conditions colonized these lakes. This is particularly marked in the zooplankton record for Manzala (Ram-

dani et al., 2001c) where a clear trend towards fresher conditions appeared well before the Aswan High Dam was built and has persisted through most of the 20th century. Interestingly, Stanley and Warne (1993) predicted that the Delta lakes will become increasingly marine due to subsidence and sea-level rise. The small increase in halophilous species in several core tops (Flower et al., 2001) may be an indication of this prediction.

Environmental change records for the CASSARINA sites can be summarized according to four main 20th century scenarios: (i) where freshwater supply has been promoted artificially during the 20th century by irrigation schemes (the Delta lakes); (ii) where freshwater supply was temporarily increased by land drainage and canalization schemes but diminished in late 20th century, leading to loss of open water (Bokka) or increasing salinity (Zerga and particularly Ichkeul); (iii) where recent water abstraction has reduced water level and quality (Chitane); (iv) where previously moderate or high salinities have persisted with only small changes or fluctuations (Korba and Sidi Bou Rhaba). These four scenarios mainly concern changes in hydrology, however, pollution can also stress aquatic systems and trace metals and pesticide levels are relatively high at several sites. There is no biostratigraphic evidence that their effects are at present greater than those being caused by reclamation or water abstraction. Where extreme pollution has occurred such as in Delta Lake Maryut (e.g., Saad et al., 1985), fisheries are lost and biological recovery is not possible without redeveloping the ecosystem entirely. The CASSARINA Delta lakes do receive high pollution loadings but in the regions where sampling was performed contamination was often remarkably low. Pollution is a major problem in Manzala (e.g., Seigal et al., 1994; Drainage Research Institute, 1997) yet it tends to be localized in the eastern region by reed beds. Reed beds should be actively managed for waste water control (cf., Duning et al., 1998). Industrial pollution is apparently not a major problem in the CASSARINA lake regions. The elevated sedimentary lead concentrations in Korba and Burullus (Birks et al., 2000) are probably from waste water but values are not high compared with some European sites (e.g., Renberg et al., 1994).

Biodiversity

Species diversity is one way to assess the quality or value of an aquatic ecosystem but number of species is often a poor measure of important (key, rare or endemic) taxa (Gaston, 1994; Tokeshi, 1999). Furthermore, diversity itself is a problematic measure and diversity indices are of questionable value (Rosenzweig, 1995). During modern sampling in CASSARINA, several biological groups (phytoplankton, zooplankton, diatoms and aquatic plants) were surveyed. Species richness (number of taxa per standard sample) is a convenient indicator of diversity and there is a clear trend for the Delta lakes to be more speciose for algae (Figure 2) but this is not so for zooplankton (Ramdani et al., 2001b). Physico-chemical conditions do not appear to be very different at the Egyptian sites (Fathi et al., 2001) but they are generally less saline than the western sites. They are by far the largest sites and habitat size is a frequent determinant of diversity (Rosenzweig, 1995) but because of the constraints on aquatic diversity between lakes with different water quality, species-area curves are not generally applicable to lake biota comparisons. Nevertheless, high diversity for some groups in the Delta lakes is doubtless linked with both water quality and evolutionary ecology (see below) as well as with food-web relationships.

Brackish conditions ($5\text{--}10\text{ g l}^{-1}$) are well known to support low diversity (e.g., Wetzel, 1975) but those CASSARINA sites with sea connections exhibit significant spatial gradients in salinity. Increasing salinity can moderate the effects of some pollutants (Hall & Anderson, 1995) but intra-site spatial effects are beyond the scope of the present study. Clearly, sampling strategies used in this project must under-estimate whole basin diversity and this is especially so for the larger sites (Zerga, Ichkeul and the Delta lakes). At these sites marine invertebrates typically occupy the confluent zones (e.g., Hollis, 1992). Despite this restriction, the CASSARINA point sampling data can be used comparatively in simple correlation analysis of taxon richness with water quality to show a strong negative influence of site salinity on taxon diversity of diatoms (epiphyton and in surface sediment) and of aquatic vegetation (Table 1). Positive correlations are also indicated between phytoplankton and diatom epiphyton diversity, diatoms in surface sediment and aquatic vegetation, and with fish and submerged vegetation. These relationships indicate significant biotic

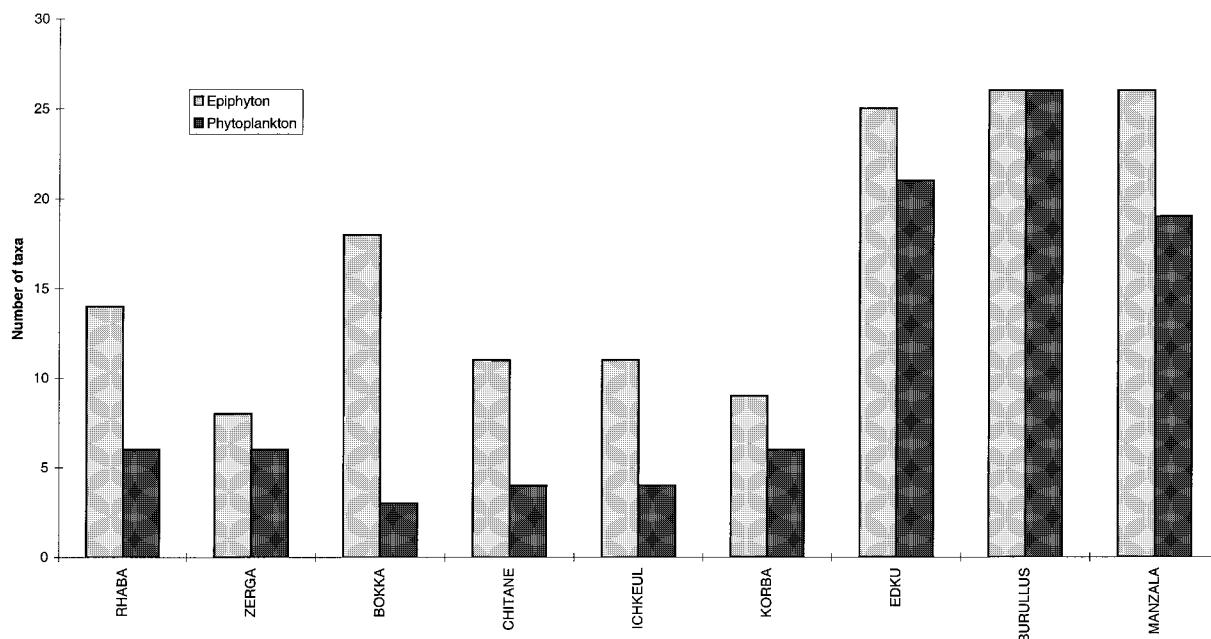


Figure 2. Total numbers of algal taxa occurring in phytoplankton samples and of diatom taxa in epiphyton samples at the nine CASSARINA sites (data from Fathi et al., 2001; Flower & Patrick, 2000). See Figure 1 for site names in full.

links but more robust testing is clearly needed to verify these interactions using a larger suite of sample sites.

Palaeoecological analysis of species abundance changes usually provides the best records of environmental change in poorly monitored lakes. However, sediment records will always underestimate contemporary aquatic diversity because of sampling and preservational constraints. Nevertheless, quantitative changes in numbers of taxa can provide useful information about diversity trends. Estimating numbers of taxa in sediment samples pose comparability problems but, if time periods rather than depths are examined and sampling intensity is standardized, then these are reduced. Numbers of microinvertebrate, diatom, mollusc and aquatic plant taxa occurring in CASSARINA cores can be allocated to three time periods, late 19th century–1920s, 1920s–1950s, and 1960s–late 1990s (Table 2). Mean numbers of different taxa per period are used in Table 2 but even so, differences in core sampling intervals, total number of levels counted at each site (sampling intensity), preservational problems (particularly diatom species in the lower sections of the Delta lake cores and most or all of the Ichkeul and Korba cores) and missing periods limit interpretation. Some general inferences can however be made. Diversity has changed both positively and negatively,

depending on site and on biological group, as the environment changed. Thus, freshening of the Delta lakes has tended to increase diversity in some but not all groups. Where group diversity has remained fairly stable species have often changed considerably (e.g., zooplankton at Edku, macrofossil taxa at Burullus and Manzala). At the Tunisian sites, some declines in aquatic taxa occurred in Korba, possibly due to pollution, but in Ichkeul, where 20th century salinity has varied, taxa generally increased since ca. 1900. In acidic Chitane (enriched after ca. 1960) diatom diversity was high but declined since the 1920s–1950s period whereas zooplankton taxa increased. At the Moroccan lakes, diversity in Bokka fluctuated with numbers of mollusc and diatom taxa declining as aquatic plants and zooplankton taxa increased after the 1920s as agriculture intensified. Overall diversity has tended to increase in Sidi Bou Rhaba but the short Zerga record indicates variable changes including a notable decline in mollusc taxa since ca. 1960.

Concordance in species richness values for each groups between sites (for the post 1960 period) or between periods is not generally demonstrated (Table 2). Although all these comparisons are strongly limited by comparability problems, the taxon sums in each period must reflect, to some extent, the floristic

Table 1. Simple correlation matrix for data collected during environmental monitoring of the nine North African CASSARINA lakes. The data comprise total numbers of open water zooplankton species, diatoms taxa in epiphyton, diatom taxa in surface sediment*, open water phytoplankton species, fish species, vegetation (aquatic plant species), vegetation* (including ruderal plant species) and site mean salinity (1998) and phytoplankton biomass*. Data sources: Birks et al., 2001a; Fathi et al., 2001; Flower & Patrick, 2000; Flower et al., 2001; Ramdani et al., 2001a,b). Significance at $p = 0.95$ is underlined

	Zooplankton	Diatoms	Diatoms*	Phytoplankton	Phytoplankton*	Fish	Vegetation	Vegetation*
Diatoms	0.41							
Diatoms*	0.02	0.55						
Phytoplankton	0.00	<u>0.87</u>	0.47					
Phytoplankton*	0.00	0.35	−0.23	0.53				
Fish	−0.44	0.03	−0.34	0.18	0.00			
Vegetation	−0.20	0.26	<u>0.70</u>	0.26	−0.16	−0.20		
Vegetation*	−0.48	−0.33	−0.38	−0.28	−0.20	<u>0.68</u>	−0.14	
Salinity	−0.43	− <u>0.65</u>	− <u>0.72</u>	−0.41	0.26	0.24	− <u>0.70</u>	0.40

Table 2. Diversity (number of taxa) for each biological assemblage group recorded in different time periods within each of the CASSARINA sediment cores (Figure 1 for full site names). Where sediment records permitted, species are allocated to three time periods broadly representative of the 20th century (see text). Note, (i) that no useful diatom diversity records for the 20th period were available for Ichkeul or Korba (see text), (ii) that in the Zerga and Chitane cores sediment dates were restricted to the latter two 20th century periods elsewhere dates for the early 20th century period were by extropolation (from Appebly et al., 2001). Taxon richness for each group is given as the mean number of different taxa for each time period, numbers in bold indicate the total number of taxa in each assemblage group in the whole core and those within bold parentheses are the total number of taxa in post 1960s sediment. Zero indicates no taxa present, nc indicates not counted, – indicates absence of sediment, * indicates the marginal core from Burullus lake (see text)

		Sediment cores									
		RHAB2	ZERG1	BOKK1	CHITAN1	ICHK1	KORB1	EDKU1	BULR1	BULR2*	MANZ1
1960s–1990s	Zooplankton	20	14	15	12	13	13	13	11	nc	17
1920s–1950s	Zooplankton	17	13	14	11	9	15	12	14	nc	17
Pre-1900–ca. 1920s	Zooplankton	19	–	12	–	8	15	7	11	nc	12
total taxa		22(22)	16(16)	17(16)	16(16)	18(18)	16(14)	18(16)	16(12)		19(17)
1960s–1990s	Diatoms	19	19	22	31	7	0	36	27	20	26
1920s–1950s	Diatoms	12	0	25	38	0	0	31	15	12	34
Pre-1900–ca. 1920s	Diatoms	14	–	26	–	0	0	0	0	19	0
total taxa		75(62)	43(43)	63(30)	128(86)	7(7)		91(40)	63(49)	50(34)	64(40)
1960s–1990s	Molluscs	2	4	3	0	3	2	13	3	8	10
1920s–1950s	Molluscs	2	6	6	0	3	2	11	2	7	10
Pre-1900–ca. 1920s	Molluscs	2	0	6	–	3	4	8	0	5	5
total taxa		4(4)	6(4)	6(3)	0	3(3)	4(3)	19(16)	3(3)	14(11)	12(11)
1960s–1990s	Macrophytes	5	8	9	8	3	6	9	nc	4	8
1920s–1950s	Macrophytes	4	4	7	6	3	5	8	nc	7	5
Pre-1900–ca. 1920s	Macrophytes	3	–	6	–	1	8	8	nc	9	3
total taxa		10(7)	15(13)	18(11)	13(12)	9(4)	15(6)	24(15)		18(5)	13(10)

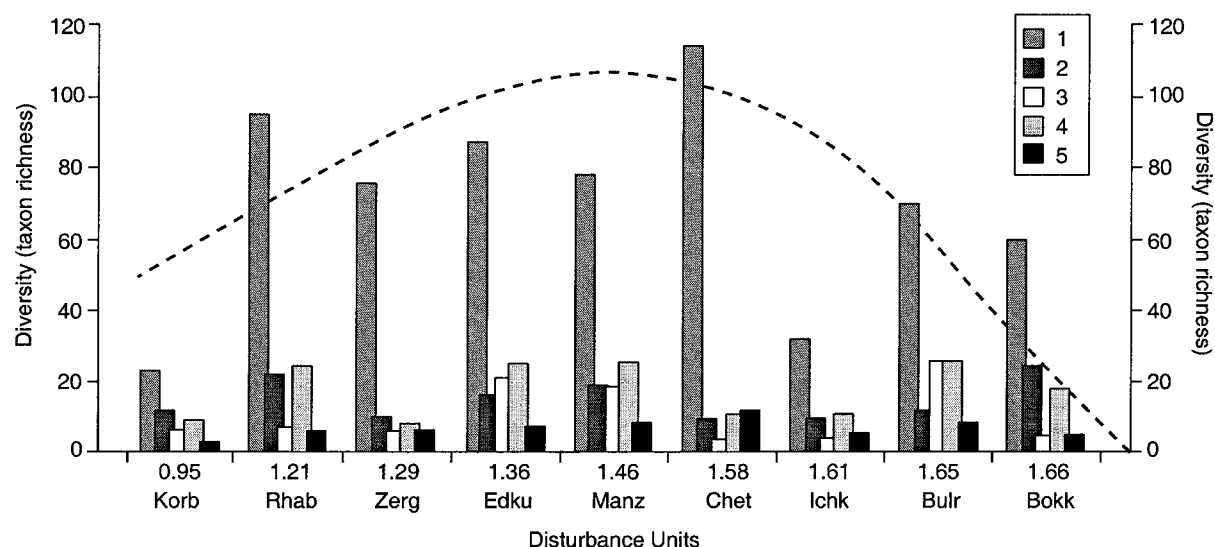


Figure 3. Species diversity (taxon richness) and disturbance intensity inferred from species compositional changes (as standard deviation units, see text and Birks et al., 2000b) in each CASSARINA sediment core. Diversity at each site is estimated in several ways: (1) the total number of taxa (all micro- and macrofossil taxa) recorded in post 1960s sediment in each sediment core (see Table 2); (2) total modern zooplankton taxa (Ramdani et al., 2001b); (3) total modern phytoplankton taxa (Fathi et al., 2001a); (4) total modern epiphytic diatom taxa (Flower & Patrick, 2000) and (5) total of modern aquatic macrophyte taxa (Ramdani et al., 2001a). The dotted curve is a hypothetical representation of the relationship between diversity and disturbance from Connell (1987). See Figure 1 for site names in full.

and faunistic changes experienced at each site. The amount of down-core compositional change in each biological assemblage group can be estimated using species turnover measures (as standard deviation units on species ordination axis estimates, see Birks et al., 2001b). This approach offers a useful way of quantifying the influence of past disturbance on species diversity recorded within and between the CASSARINA sites. At each site, biological disturbance (as a mean of the total amounts of compositional change (SD units) for each fossil group in each core) during a period approximating to the 20th century is compared with several estimates of species diversity (from cores and from modern sampling) in Figure 3. Diversity theory suggests that intermediate disturbance promotes high diversity (Connell, 1978) and the least and most disturbed CASSARINA sites do indicate only a weak correspondence with the hypothetical diversity relationship (Figure 3) according to taxon (diatoms, zooplankton and animal and plant macrofossils) totals recorded in recent (post-1960) sediment. Furthermore, high or low initial diversity (as assessed for the earlier periods, Table 2) does not seem to confer any relative resistance to subsequent diversity changes. There is however no obvious relationship between past disturbance and the diversity of biologi-

cal sub-components (plankton, epiphyton and aquatic plants) recorded during modern sampling (Figure 3). This could indicate the wider diversity of assemblage groups examined in the sediment cores as well as limitations of modern spot sampling. Both modern and palaeo approaches suffer from problems of representativity and comparability (see above and Haywood, 1995). Nevertheless, combining the two (using adequate spacio-temporal sampling and securely dated, contiguous sediment samples) offers a promising way to improve assessment of biodiversity change trends and species inventories in lakes.

Although species numbers are useful guide to aquatic community quality (Haywood, 1995), the presence of individual species is also an important indicator of site status (Gaston, 1994). Some of the species present at the CASSARINA sites are very rare, either nationally or in North Africa generally. Excepting several acid pools and streams (Ben Khalifa, 1987) Megene Chitane is the only acid wetland lake in North Africa. It has high diversity for diatoms but low for zooplankton and molluscs (Table 2, Figure 3). The diatom flora is unique for a Tunisian lake, being composed of *Eunotia* species and other acidophilous taxa (Flower et al., 2001). It is also only the second recorded Tunisian site for the cladoceran cold-water

preferring copepod *Diaptomus cyaneus* and the benthic aquatic pteridophyte, *Isoetes velata* and is the only Tunisian site for the charophyte *Nitella opaca* (Ramdani et al., 2000). These species are often common in softwater European lakes but they make the Tunisian site of national significance for aquatic biodiversity despite the recent disturbance problems (Birks et al., 2001a; Flower et al., 2001). The Delta lakes have some unusual features in their halophilous diatom floras, including planktonic *Cyclotella choctawatcheeana* and the neritic *Pleurosira laevis* and *Hylodiscus scoticus* (Flower et al., 2001). Unusual taxa are not exclusive to the Delta lakes and Chitane. An endemic species variety of copepod is known in Sidi Bou Rhaba (Ramdani, 1988) and Bokka was one of two natural localities in Morocco for *Nymphaea alba* (Fennane et al., 1999).

Biogeographic factors, in addition to those of water quality, are important influence on the occurrences of some aquatic species at some CASSARINA sites. The Delta lakes form a distinct group biologically being characterized by different fish species (differentiated at the family level) and some benthic invertebrates and aquatic higher plants of freshwater origin. The common Delta lake fish genera (*Tilapia*, *Oreochromis* spp.) and the Nile Perch (*Lates niloticus*) are endemic within the Nile system where fish speciation has been exceptional (Talling & Leomalle, 1998). There are also several species of freshwater gastropod mollusc that have recently invaded the Delta lakes (Birks et al., 2001) and these are endemic to the Nile system (Brown, 1994). By contrast, faunal species from marine habitats, for example fish and bivalve molluscs, are common in other North African lagoons. The 20th century introductions of exotic water plants, notably include the water hyacinth (*Eichhornia crassipes*) and the water fern (*Azolla filiculoides*), have proliferated in all three Delta lakes. On the other hand, *Papyrus* and *Azolla niloticus* have become extinct in the Delta region (Tackholme & Drar, 1950; Birks et al., 2001a) since Pharonic times.

Resilience and recovery

Aquatic ecosystem resilience can be defined in various ways and one way is to consider that an aquatic ecosystem is resilient if biological changes in response to perceived disturbance are small. Measuring disturbance pressure in field situations is however difficult (see Tokeshi, 1999). The concept of ecological 'sensitivity' of lake communities to water quality

changes offers another way of assessing resilience, through multivariate analysis of sedimentary assemblage changes (Birks, 1996), particularly for acid lakes (Battarbee et al., 1991). Since species *per se* are more sensitive indicators of water quality change than are functional attributes (e.g., Schindler, 1986), past species changes provide a useful approach to ecosystem response/resilience issues. Aquatic ecosystem resilience is ultimately a function of species environmental tolerances and those CASSARINA sites that remain biologically diverse, despite pollution, salinity change, lake area loss, and intensive fishing, must contain many resilient species. The Delta lake are good examples of very resilient ecosystems. They continue to support significant fisheries, abundant water bird populations and extensive reed beds. Nevertheless, fishery yields and open water areas are currently declining as disturbance pressure rises. These undoubtedly degraded lakes still possess centres of high value diversity in their least damaged regions. These centres represent species refugia that are of vital future importance for potential recruitment if detrimental processes are mitigated.

The palaeo-records indicate that species abundances fluctuate on a range of time-scales (cf., Birks, 1996) and recovery from some large disturbance events can be rapid. Sediment core biostratigraphies can be used to estimate resilience by considering species turnover and time-tracks for recovery (Birks et al., 2001b) and these identify clearly the sites with greatest overall recent biological change (Zerga, Bokka, Ichkeul, Chitane and the Delta lakes). Despite these changes, the Chitane and Burullus (marginal) cores indicate that some biological recovery has occurred but where disturbance has been more sustained significant recovery will require major intervention (Ichkeul) or complete site redevelopment (Bokka). In Ichkeul, biostratigraphic interpretation of very recent changes is problematic (Appleby et al., 2001) but loss of freshwater supply has caused a critical reduction of the winter low salinity phase and summer hyposalinities. The potential for biological recovery does exist (given re-established freshwater inflows), as indicated by unsustained spring growth of *Phragmites* still occurring in the late 1990s. In Merja Bokka, however, resilience mechanisms (species tolerances) were overwhelmed as standing water receded to zero in 1998. In the unlikely event that this site is restored, re-establishing the hydrology and importing key aquatic

organisms is required. In this case, the CASSARINA palaeo-data provide the only source of information on the aquatic species that were formerly present. In Zerga and the Delta sites sediment records indicate that in the early 20th century marine influences were generally more pronounced than today. This suggests that reduced freshwater supply is needed to restore 'naturalness'. For the Delta lakes, the pre-Aswan High Dam seasonality regime provided by river floods is now lost and any future management is perhaps best focused on maintaining current diversity.

Future issues

Environmental degradation is a major challenge facing many African countries (GEO 2000). In North Africa the ever increasing and largely unplanned demand for water will inevitably continue to diminish wetland lake ecosystems. Only through the greater appreciation of biodiversity and the importance of aquatic ecosystems can wetland conservation be promoted in developing countries (Wetzel & Gopal, 1999). The MedWet Programme has made exemplary progress in promoting Mediterranean wetland values and stimulating local appreciation of environmental issues, particularly in North Africa (e.g., Skinner & Zalewski, 1995; Pearce, 1996). However, basic research on how environmental change has affected the structure and function of the aquatic ecosystems that sustain each wetland lake is fundamental for effective long-term management policy.

Although necessarily selective, CASSARINA has revealed the intensity of 20th century change that has occurred in North African wetland lakes and has established modern late 20th century base-lines for water quality, littoral macrophytes, plankton and fish. All are undergoing rapid change and although future climate and, for the Delta lakes, subsidence give cause for concern, it is the short time-scale (<10 y) human driven changes that are punitive. Increasing land-use intensification and hydrological disturbance constitute the imminent threat to wetland sustainability in the region. Land-use related changes in the 1990s have led directly to the loss of Merja Bokka and the impoverishment of Megene Chitane. Other sites are clearly being degraded yet a detailed recent national inventory of wetland sites exists only for one North African country (Hughes et al., 1997). This Tunisian report is already partly out of date and many of the smaller

inland sites listed are now lost through recent water abstraction for agriculture (cf., El Amani, 1977).

Multiple use of several CASSARINA sites as bird reserves and/or as profitable fisheries together with waste disposal and land reclamation is clearly unsustainable. Some selective management is practised but is rarely the result of a balanced appreciation of the competing economic, societal and ecological values involved. Wider issues of site usage should be addressed but the sustainable management of these valuable North African lakes must be founded on the results of essential and urgent chemical and biological monitoring programmes. Greater emphasis on monitoring spatial aspects of water and sediment quality together with whole lake vegetation cover is required for the larger sites. Remote sensing is an obvious tool in such work (Flower et al., 1998). Also, maintaining monitoring continuity, especially at the species level, is a major priority if biology is to be incorporated into effective dynamic environmental projection models. These multi-component studies are expensive yet continuity in long-term international collaboration and support is essential.

Increasing human usage of freshwaters through expanding agriculture is inevitable and in the next 50 years the global effects may rival that of climate change (Tilman et al., 2001). Human pressures on natural resources in North Africa are already intense, particularly in the Egyptian Delta region (Biswas, 1993; Sultan, 1999). Nevertheless, the resilience of several CASSARINA sites has imparted sufficient tolerance to environmental change that the aquatic ecosystems still retain considerable diversity. Without effective conservation controls however, prosperity-led development in North Africa during the 21st century will surely bring about the elimination of those remaining wetland lakes that are not maintained artificially or by seawater inflow. Adequate water supply is an essential basic requirement for lake functionality (Moss, 2000) but aquatic diversity and habitat quality are important and site management must ensure that ecological tolerances are not exceeded for valued species. Thresholds cannot at present be defined precisely but are primarily related to excessive loss of lake area and to water quality extremes (salinity and pollution). Achieving sustainability for North African wetland lakes is a compelling reason to introduce effective minimum management but societal responses are often slow compared with the rates of environmental degradation.

This time constraint could lead to irreversible loss of options for mitigation strategies (Kasperson & Timer, 1999) making sustainable development more difficult.

Where problems are recognised and finance is available, restoration management can be achieved as exemplified by Louisiana's Mississippi Delta Lakes Project (Boesch et al., 1994; Van Heerden, 1994). Enhanced societal aspirations can be compatible with wetland conservation objectives and, in the long term, natural and cultural heritage values will be given equal importance. Conservation values are part of pan African policy (UNECA, 1991; GEO 2000) but realistically, achieving protection for wetland biodiversity will need not only international effort and support but also the commitment at national level to implement appropriate management. Wetland lakes are a rapidly disappearing resource in North Africa and CASSARINA has perhaps provided a foundation stone for tackling this problem at the aquatic community level. The work raises important issues about aquatic biodiversity *per se* and about national obligations to biodiversity yet, ultimately, only through a wider appreciation of the conservation ethic will the true societal value of these wetland lakes be fully recognised.

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Appendix: Summaries of the main 20th century changes recorded at each of the nine CASSARINA sites (Tables 1A–3A)

Table 1A. The main 20th century environmental change events recorded at the three Moroccan CASSARINA sites. Inferences are made from the past to the present using multi-proxy biostratigraphic and documentary evidence (see Birks et al., 2001, Flower et al., 2001 and Ramdani et al., 2001a, c). N/A indicates absence of data. Note: pre 1950s sediment record dates for Bokka are by extrapolation, SAR indicates sediment accumulation rate

Period	M. Sidi Bou Rhaba	Merja Zerga	Merja Bokka
ca. 1960–late 1990	Gramineae decline and pesticides increase; overall salinity increase (but declines in 1960s); <i>Chydorus</i> peaks in 1990s and 1960s; SAR increases; <i>Salicornia</i> appears; south part of lake became dry	Cereal pollen and pesticides increase; salinity increases post mid-1980s; <i>Ruppia</i> and molluscs decline, diatoms indicate finer grained siltation post 1980; <i>Potamocypis</i> increases; SAR stable; over exploitation of ground water and marginal vegetation	Salinity increases, rapid mineral soil siltation; marked ostracod changes; molluscs, aquatic plants and carbonates decline; pesticides increase; in 1994 water very turbid, level reduced to <20 cm and amphibians common; no open water in late 1998 and crop plants present
1920s–ca. 1960	Pesticides present in 1950s, trees stable (<i>Eucalyptus</i> pollen present), salinity stable; SAR increases; carp introduced; aquatic plants and microinvertebrates decline, eutrophication likely	Mid 1950s salinity lower but still strongly brackish, decline in some forams, ostracods and marine molluscs in the 1950s; Nador land drainage canal operational in 1950s; probable SAR increase but pre-1950s sediment not dated	Freshwater molluscs decline; <i>Zamichellia</i> , ruderal and emergent plants increase; chenopods and sediment carbonates decline; periodic flooding by Sebou River; fringing macrophytes (<i>Typha</i>) and epiphytic diatoms increase; hydrology less stable
ca. 1900–1920s	Arboreal pollen increase as Gramineae and Characeae decline, aquatics stable; salinity increases; <i>Eucalyptus</i> planted in 1920s; slight increase in eutrophication/disturbance and SAR	Documentary records of <i>Salicornia</i> marsh and abundant marine molluscs	Open freshwater, increasing Cladocera, ostracods, molluscs, aquatic plants and sediment carbonates; in ca. 1900 agriculture increases and molluscs indicate possibly flowing water and diatoms slightly brackish water with shallow sediments

Table 2A. The main 20th century environmental change events recorded at the three Tunisian CASSARINA sites. Inferences are made from the past to the present using multi-proxy biostratigraphic and documentary evidence. Note that because of poor preservation diatom based inferences for Korba and Ichkeul are absent. SAR indicates sediment accumulation rate

Period	Megene Chitane	Garaet El Ichkeul	Lac De Korba
ca. 1960–late 1990s	Decline in water acidity and sediment accumulation, eutrophication begins, diatoms and cladocera change, <i>Isoetes</i> recovered; emergent plants increase; higher SAR and salinity period in 1960s and enrichment indicating diatoms; pesticides decline in 1990s, catchment partly protected	Hydrological changes; post 1980 inflows restriction and salinity increases, <i>Ruppia</i> and SAR increases but <i>Scirpus</i> and <i>Phragmites</i> decline; forams, marine molluscs decline; ostracods and pesticides increase; sediment mixing problems but Cladocera indicate fresher conditions in 1960s.	Seasonally hypersaline; fairly stable conditions but Pb contamination increasing; pesticides peak in the 1980s; Characeae decline, few marine molluscs; green algae common; local agriculture intensified; low SAR; sebkha salt marsh; no diatom record; probable enrichment
1920s–ca. 1960	Acid oligotrophy persists but major increase in sediment accumulation in 1940s; organic remains (<i>Juncus</i> and <i>Nymphaea</i>) abundant, <i>Isoetes</i> and some Cladocera decline; pesticide contamination begins	Salinity, SAR, marine molluscs and forams increase; ostracods change; trees stable (<i>Eucalyptus</i> present) <i>Ruppia</i> & <i>Potamogeton</i> and fringing emergent plants abundant and increasing; pesticide contamination starts; freshwater inflows canalised	Decline in marine molluscs; contamination begins as Pb then pesticides increase in 1950s; probable abstraction of freshwater inflows; low SAR; sebkha salt marsh; local agriculture expanding
ca. 1900–1920s	Oligotrophy, acid indicating diatoms, aquatic plants (<i>Nymphaea</i> and <i>Nitella</i>) and Cladocera abundant; trees increase; acidophilous benthic diatoms abundant	Ostracods and forams change; <i>Potamogeton</i> appears and increases; sediment carbonates decline; SAR and salinity increases; no diatom record and few molluscs and aquatic plants	Low SAR; marine molluscs but changes in forams; Characeae common possibly fresher seasonal conditions; chenopods more common ca. 1900; sebkha salt marsh

Table 3A. The main 20th century environmental change events recorded at the three Egyptian CASSARINA sites. Inferences are made from the past to the present using primarily multi-proxy biostratigraphic but also documentary evidence. Because of poor diatom preservation diatom, records of salinity are absent for the lower sections of cores from these sites. SAR indicates sediment accumulation rate

Period	Edku Lake	Burullus Lake	Manzala Lake
ca. 1960–late 1990s	Salinity declines; marked increases in freshwater molluscs; forams and marine molluscs become scarce; aquatic plants (<i>Typha</i> and <i>Azolla filiculoides</i>) increase but <i>Potamogeton</i> declines post 1980s, cladocera common; diatoms and SAR stable; active reclamation and intensive local cultivation.	Low but still mixed salinity regime; diatoms indicate increasing eutrophication; marine Mollusca remain common and freshwater molluscs persist; <i>Typha</i> and <i>Potamogeton</i> increase further but <i>Ruppia</i> declines; cladocerans decline further; SAR stable; active reclamation	Low salinity but diatoms indicate a small post late 1970s increase; epiphytic diatoms common; <i>Typha</i> and submerged aquatics abundant; high organic sediment; sediment carbonates decline; forams scarce; freshwater molluscs increase; SAR low; active reclamation; intensive agriculture
Late 1920s–ca. 1960	Mixed salinity regime with overall decline in salinity; freshwater Mollusca and Cladocera increase, strongly after the 1940s; aquatic plants increase; exotic trees planted; <i>Eichhornia crassipes</i> begins to increase; small increase in attached freshwater diatoms; local reclamation; SAR declines	Salinity declines; marine mollusca reduced; <i>Typha</i> , <i>Potamogeton</i> and sediment carbonate increase; freshwater mollusca appear; sediment dwelling diatoms indicate a mixed salinity regime; SAR declines; local reclamation; exotic trees planting	Salinity declines; <i>Typha</i> and submerged aquatics, especially <i>Ruppia</i> , cladocerans and some ostracods increase; forams and marine mollusca decline further; freshwater mollusca and diatoms begin to increase; SAR stable; canalization active, exotic tree planting
ca. 1900–1920s	Mixed salinity regime but strongly brackish; decline in forams; <i>Azolla nilotica</i> common; increases in <i>Potamogeton</i> , cladocera, marine molluscs and some ostracods; salt marsh plants and then <i>Phragmites</i> decline; sediment calcareous	Marine salinity regime with marine Mollusca and forams abundant; <i>Ruppia</i> and other aquatic plants increase; Gramineae and cladocerans decline and ostracods increase; diatoms not present	Mixed but strongly saline regime; low organic sediment, carbonates increase; <i>Ruppia Potamogeton</i> and <i>Ceratophyllum</i> present; Gramineae decline as chenopods increase; forams common but cladocerans are few