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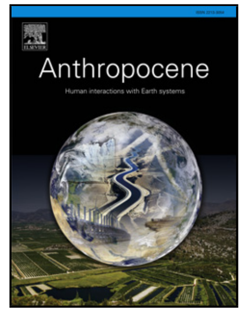

Title: Ecosystem impacts of feral rabbits on World Heritage sub-Antarctic Macquarie Island: a palaeoecological perspective

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Highlights

· World Heritage Macquarie Island is severely damaged by introduced invasive rabbits
· Palaeoecological tools identify ~7100 years of natural catchment and lake variability
· Large unprecedented ecosystem changes in just 100 years followed rabbit introduction
· Baselines for assessingecosystemrecoveryafter rabbit eradication are identified
· Case study for the use of palaeoecologicalmethods in invasive species management

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Abstract

The introduction and establishment of non-indigenousspecies through human activities often posesa major threat to natural biodiversity. In many parts of the world management efforts are therefore focused on their eradication. The environment of World Heritage sub-Antarctic Macquarie Island has been severelydamaged by non-indigenous species including rabbits, rats and mice, introduced from the late AD 1800s. An extensive eradication programme is now underway which aims to remove all rabbits and rodents. To provide a long-term context for assessingthe Island'spre-invasion state, invasion impacts, and to provide a baseline for monitoring its recovery, we undertook a palaeoecological study usingproxies in a lake sediment core. Sedimentological and diatom analyses revealed an unproductive catchment and lake environment persisted for ca. 7100 years prior to the introduction of the invasive species.After ca. AD 1898, unprecedented and statistically significant environmental changes occurred. Lake sediment accumulation ratesincreased >100 timesdue toenhanced catchment inputs and within-lake production. Total carbon and total nitrogen contents of the sediments increased by a factor of four. The diatom flora became dominated by two previously rare species.The results strongly suggest a causal link between the anthropogenic introduction of rabbits and the changes identified in the lake sediments.This study provides an example of how palaeoecology may be used to determine baseline conditions prior to the introduction of non-indigenous species,

quantify the timing and extent of changes, and help monitor therecovery of the ecosystem and natural biodiversityfollowing successfulnon-indigenous species eradication programmes.

Keywords: diatoms, invasive species,lake sediments, management, paleoecology,pest eradication

1. Introduction

Impacts of non-indigenous species can be ecologically devastatingand are a major threat to global biodiversity (IUCN, 2013). Oceanic islands are particularly vulnerable as they often have a large proportion of endemicspecies with limited resilience tonon-indigenousones, and a lack of native predators to keep invasive non-indigenous speciesunder control (Lebouvier et al. 2011). Human visitation and colonisation of remote oceanic islands and subsequent deliberate or unintended introductions of invasive non-indigenousspecies have, in many cases,drastically modified their natural ecosystems (Connor et al. 2012). For example, the introduction of rabbits has led to catastrophic ecosystem changes through overgrazing, increased soil erosion and vegetation changeson many islands around the world (Bonnaud and Courchamp, 2011; Cronk, 1997; Hodgson 2009; Towns, 2011), including continental islands such as Australia, where rabbits have had devastating environmental and economic impacts (CSIRO, 2013).

As a result, conservation and management efforts are increasingly focused on the control and/or eradication of invasive non-indigenous species (Bell,2002; McClelland, 2011; Merton et al. 2002; PWS, 2007; SCSSI, 2013). To assess the effectivenessof these measuresit is necessary to determinethe nature, magnitude and spatial extent of the impacts of non-indigenous species in the context of long term natural variability.This includes quantifying the state of the environment prior to and during a non-indigenous species invasion, and its recovery state following their eradication.

This information is not generally available, particularly on oceanic islands with no long-term history of human occupation or scientific monitoring. In the absence of such information, a palaeoecological approach (the study of past environments) may be used.Palaeoecological methods have been extensively used around the world to examine the influence of humans on landscapes including lakes and rivers and their catchments. As a result their value for providing a framework against which to assess ecosystem impacts and response and recovery is well recognised (see Bennion and Battarbee, 2007; Crutzen and Stoermer, 2000; Froyd and Willis, 2008; Smol, 2008 for examples and reviews).

Palaeoecological methods have previously been applied onoceanic islands such as the Galapagos Islands, Hawai‘i’ and the Azoresshowing that theirhighly diverse pre-Anthropocenelandscapes were completely transformed with the arrival of humans and the introduction of non-indigenous species.This in turn caused adecline in biodiversity and the extinction of many native species (Athens,2009; Burney and Burney, 2007; Burney et al. 2001; Connor et al. 2012; van Leeuwen et al. 2008).

Lakes providea particularly useful palaeoecological archive as their sediments accumulate in layers over time and integrateinformation from both the lake and its surrounding catchment (Smol, 2008). These layers of sediment may be dated and changes in a lake and its surrounding environment studiedover time using a range of biological and non-biological proxies. Anthropogenic impacts are often particularly well recorded (Smol and Stoermer, 2010) and lake sediments can therefore provide long-term dataonthe state of the catchment and lake prior to, during and after the introduction of an invasive species (Korosi et al. 2013).These data can include measures of changes in soil erosion rates, vegetation(Restrepo et al. 2012; Sritrairat et al. 2012), andwithin-lake production(Bradbury et al. 2002; Watchorn et al. 2008).

This study presents a palaeoecological study of a lake in a heavily rabbit-impacted area on sub-Antarctic Macquarie Island (54°30’S, 158°57’E, 120 km^2, Fig. 1). A sediment core collected from the bottom of Emerald Lake was analysed to assess changes in sedimentation rates, grain size distribution, geochemical properties and diatom composition over the last ca. 7200 years. The aims were to:(i) determine the characteristics of the lake and its catchment prior to the introduction of rabbits; (ii) determine the onset and impacts of the introduced rabbits on the lake and its catchment; and(iii) provide a long-term perspective or baseline for assessing ecosystem response and recovery following the successful rabbit eradication programme.

2. Briefhistory of human discovery, exploitation and introduction of non-indigenous species on Macquarie Island

Macquarie Island is a United Nations Education and Scientific Organisation (UNESCO) Biosphere Reserve and World Heritage listed for its outstanding geological and natural significance (UNESCO, 2013). Macquarie Island is geologically unique as it is entirely composed of uplifted oceanic crust (Williamson, 1988).Hence, much of the Island is composed of volcanic, sulphur-rich bedrock (primarily pillow basalts) and associated sediments (Cumpston, 1968).

Since its discovery in AD 1810 it has experienced extensive and on-going environmental impacts from exploitation of its native wildlife and from deliberate and inadvertent introductions of invasive species, particularly vertebratesthat have developed feral populations.

Human activities were initially focused on exploiting the abundant seal and penguin populations for oil, leading to their near extinction by the end of the nineteenthcentury (Cumpston, 1968). During this time a number of non-indigenous animals were introduced including cats (in the early nineteenth century as pets); rabbits (in AD 1879 as an additional human food source); and rats and mice, which were inadvertently introduced (Cumpston, 1968).

Together they have had devastating environmental impacts across the Island (PWS, 2007)including degradation of the vegetation, with resulting widespread slope instability and erosion. Secondary impacts also occurredon burrowing seabirds that require vegetation cover around their nesting sites (PWS, 2007). Rodents have also had significant impacts, with ship rats in particular eating the eggs and chicks of burrow-nesting petrels (PWS, 2007). Therefore, the unique natural values that led to Macquarie Island's World Heritage listing were increasingly being threatened (PWS, 2007).

Since AD 1974 the focus on management of both invasive and threatened specieshas changed from collection of baseline data, to integrated control, and now the eradication of feral populations and the development of a natural environment recovery programme (Copson and Whinham, 2001). Control and/or eradication of invasive species began with attempts to control the feral cat population in AD 1975. This was followed by a cat eradicationprogrammewhichbegan in AD 1985 and ended in AD 2000 (PWS, 2007). The control of rabbits using the *Myxamatosis* virus started in AD 1978-79 when the rabbit population was estimated at 150,000 (Copson and Whinham, 2001). By the AD 1980s-1990s numbers dropped to approximately 10 % of the AD 1970 population. From AD 1999-2003, however, their numbers rapidly increased due to the absence of cats, successively warmer winters and growing resistance to the virus which ceased to be deployedin AD 1999 (PWS, 2007, 2013).This significantly increased the damage caused by rabbits across the Island.

The eradication of rabbits and other rodents is now the highest management priority (PWS, 2007). The latest phase of the eradication campaign began in AD 2010-2011 (PWS, 2013).

3. Material and methods

3.1 Study site and materials

Emerald Lake (54°40’22’’S, 158°52’14’’E) is a small, shallow, freshwater lake (maximum depth 1.2 m) located in a heavily rabbit-grazed area in the northwest of Macquarie Island at 170 m above sea level. The lake sits on the western edge of the Island’s plateau. The discontinuous vegetation cover in its catchment is primarily composed of *Stilbocarpa polaris* (Hombr. & Jacquinot ex Hook. F.) A. Grayand*Azorella macquariensis* A.E. Orchard.There is evidence of rabbit grazing and burrowing activity in all parts of the catchment (Fig. 1).

A 50.5 cm long sediment core was collected from the centre of the lake (1.2 m water depth) in AD 2006using a UWITEC gravity corer which is designed to collect intact surface sediments without compaction.The core was photographed, extruded on-site and sub-sampledat 0.5 cm intervals.

3.2 Dating and mass accumulation rates

Catchment erosion rates and changes in production can be inferred from changes in sediment composition and mass accumulation rates. The latter are measured by dating successive layers of the accumulated sediment (Rose et al. 2011) using^{210}Pb and ^{14}C dating methods (Appleby and Oldfield, 1978; Robbins, 1978; Ramsey, 2008).

^{210}Pb methods were used to date recent (up to 120 years old) sediments. Unsupported ^{210}Pb activities were measured in bulk sediment samples using alpha spectroscopy, following

Harrison et al. (2003) at the Australian Nuclear Science and Technology Organisation (ANSTO, Australia). Ages and mass accumulation rates were determined using the Constant Initial Concentration (CIC) (Appleby and Oldfield, 1978) and Constant Rate of Supply (CRS) models (Appleby, 2001). The CIC model was selected because catchment disturbances have occurred (Appleby, 2008; Appleby and Oldfield, 1978). ^{210}Pb derived dates are cited in calendar years (AD). ^{137}Cs was also measured, but was below detection limits.

^{14}C dating was used to date older sediments. Bulk sediments were analysed by ANSTO and Rafter Radiocarbon (New Zealand) using Accelerator Mass Spectrometry. The surface sample indicated there was a minor radiocarbon reservoir effect (198 ± 30 ^{14}C yr BP). All dates were corrected for this and calibrated in OxCal (Ramsey, 2012) using the Southern Hemisphere calibration curve (ShCal04; McCormac et al. 2004). ^{14}C derived dates are quoted as calibrated years before present (cal yr BP) where 'present' is AD 1950. When the ^{210}Pb and calibrated ^{14}C ages were combined into a final age-depth model, calibrated ^{14}C dates were converted into calendar years (AD/BC).

3.2 Sedimentwater content and input of plant macrofossils

Overgrazing and burrowing activities by rabbits can not only cause increased erosion rates, but also lead to slope instability, and disturbance of natural vegetation which in turn cause a higher proportion of inorganicand terrestrial plant macrofossils to enterthe lake and become incorporated into the sediments.

Sediment water content (which is normally inversely related to inorganic inputs) was determined by weighing the original wet samples, freeze-drying them (-80 °C) for three days and then re-weighing them (Menounos, 1997).To investigate changes in the proportion of plantmacrofossils vs. coarse grained inorganic sedimentsentering the lake, dried bulk sediment samples were sieved at600 µm. The samples were then submerged in water and the floating (organic macrofossil) and sinking (inorganic, coarse grains) fractions separated. The organic macrofossil fraction was dried, weighed and expressedas a percentage of the original total sample mass.

3.3 Lake sediment geochemistry

The ratio between total carbon and total nitrogen (TC:TN)may be used as an indicator of whether the organic matter is primarily aquatic (TC:TN < 10) or terrestrial (TC:TN > 10) in origin (Meyers and Teranes, 2001). Hence, TC:TN ratios can be used to study changes in the source of the organic material present in the sediment.

TC and TN were measured at 0.5 cm intervals using 20-60 mg of sediment with a Macro Vario elemental analyser. The TC and TN contents of the organic macrofossils were also measured. Total sulphur (TS)was measured at 5 cm intervals using approximately 2 g dried sediment with a LECO CNS 2000 analyser.

3.4 Diatomchanges

Diatoms are one of the most commonly used biological indicators of aquatic ecosystem changes (Smol, 2008). They are highly sensitive and respond rapidly to changes in their environment (e.g. light, nutrients, pH, salinity, sediment supply and temperature; Smol and Stoermer,2010).

Diatoms were analysed at 0.5 cm intervals using standard methods (Battarbee et al. 2001). At least 400 valves were counted per sample, using phase contrast and oil immersion at 1000 x magnification on a Zeiss Z20 light microscope. The relative abundance of all species (including unidentified forms) was recorded as a percentage of the total number of valves counted (Battarbee et al. 2001). Taxonomy was principally based on sub-Antarctic (Van de Vijver et al. 2002), Antarctic (Roberts and McMinn, 1999) and Australian taxonomic literature (Vyverman et al. 1995; Hodgson et al. 1997). All taxa were photographed and are archived, including taxonomic data, with K. Saunders. Species occurring with ≥ 1% relative abundancewere included in this study.

3.5 Data analysis

Separate constrained hierarchical cluster analyses (CONISS; Grimm, 1987) were undertaken on the sedimentological (water content, plant macrofossil, TC, TN, TS) and diatom data to determine the timing of the most significant splits in the data, in particular whether the most significant split coincided with the introduction of rabbits. The broken stick model was used to determine the number of significant splits (Bennett, 1996). This identifies a zone boundary as significant if the explained variance of the zonation exceeds the variance of a zonation in a random dataset with the same parameters (i.e. n and total variance the same as in the actual dataset; Bennett, 1996).

These analyses were performed in R version 15.2 (R Development Core Team, 2009) using the add-on packages Vegan (Oksanen et al. 2007) and Rioja (Juggins, 2012). Stratigraphic plots were developed in C2 version 1.5 (Juggins, 2007).

4. Results

4.1 Dating and mass accumulation rates

Inspection of the sediment core in the field showed an abrupt change in sediment composition between 22.0 cm and 19.5 cm. This change has been observed in other sediment cores from the lake basin and is therefore considered basin wide.

Based on ^{210}Pb and ^{14}C dating, this abrupt change in sediment composition was found to be associated with a large change in sediment accumulation rates(Fig. 2).Between22.0 cm and 50.5 cm the sediment accumulated over ca. 7100 years (6306 ± 40 ^{14}C yr BP/7257 cal yr BP), while between 18.0and 0 cmthe sediment accumulated in just the last ca. 100 years (Fig. 2).Sedimentation rateswere 0.1 mm yr^{-1}from the base of the core to 27.0 cm and declined to 0.04 mm yr^{-1}to 22.0 cm (Fig. 2a). Sedimentation rates in the upper 18.0 cm of the core were more than 10 timeshigher(1.3 mm yr^{-1}) with a period of particularly rapid sedimentation between 10.0 and 6.0 cm (7.4 mm yr^{-1}; Fig. 2b).Extrapolation of the^{210}Pb age-depth model based on the constant sedimentation between 10.0-18.0 cm (Fig. 2b)places the abrupt change in sediment composition at 19.5cmto ca. AD 1898.

4.2 Sediment water content, organic geochemistry and plant macrofossils

Below a transition between 19.5-22.0 cm the sediments were composed of dense predominantly grey clays with relatively low water content (mean 32.9 % below 19.5 cm)and low organic content (mean TC 1.1 % and mean TN 0.1 %). Large plant macrofossils (>600 µm) were rare to absent below 17.5 cm(Fig. 3).

Above 19.5 cm the sediment was much less consolidatedwith a twofold increase in water content (mean 56.6 %) and a fourfold increase in organic content (mean TC 4.2 % and mean TN 0.4 %)reaching maximum values at 13.5 cm (6.6 % and 0.06 %, respectively)(Fig. 3). TC:TN ratios remained relatively stable between of 5.83 (0 cm) to 11.77 (31.0 cm), but showa general shift to a higher and more stable ratio of TC:TN above the transition. TS was very low or undetectable throughout the core, apart from a peak at 18.0 cm (2.1 %). The abundance of large plant macrofossils (>600 µm)increased dramatically above 17.5 cm, peaking at 13.5 cm thenvirtually disappearing above7.0 cm (Fig. 3).

4.4Diatomassemblages

Ninety diatom taxa were identified. Of these, 74 taxa occurred with a relative abundance ≥ 1 % in one or more samples and 14 had maximum relative abundances ≥ 10 % in ≥ 2 samples (Fig. 4). Diatom assemblages were dominated by benthic and epiphytic taxa, and showed clear assemblage shifts through the core.

*Staurosira circuta*Van de Vijver & Beyensand *Staurosira martyi*(Héribaud) Lange-Bertalot dominated the record from the base of the core to 37.0 cm(Fig. 4). A significant change in thespecies' assemblagesoccurred at 37.0cm with the appearance of *Cavinula* *pseudoscutiformis* (Hust.) D.G. Mann & Stickle in Round, Crawford & Mann, and*Fragilaria* sp. 1becoming more abundant and dominant than *Staurosira circuta*and *Staurosira martyi*, apart from a peak in *Staurosira martyi* from 32.0-29.5 cm (Fig. 4). From 29.5-19.5 cm species that were eithernot previously present or were very rare began to increase in abundance, in particular *Staurosira venter*(Ehrenberg) Cleve & Moller, for a brief period, and *Frankophila*cf. *maillardii* (R. Le Cohu) Lange-Bertalot, *Psammothidium abundans*(Manguin)Bukhtiyarova & Roundand *Fragilaria capucina*Desmazieres. The most significant change in the diatom assemblage data occurred above19.5 cm when the diatom assemblage becamedominated by *Fragilaria capucina* and *Psammothidium abundans*(Fig. 4).

5. Discussion

Humans have a pervasive impact on ecosystems, even those that are remote. The adverse and often devastating impactson natural biodiversityfollowing the introduction of non-indigenous species are becoming increasingly common and recognised.

5.1 Emerald Lake palaeoenvironmental record

Overall, all proxies record clearlychanges in the lake and its catchment following the introduction of rabbits. These changes are beyond the ranges of (statistically significant) natural variability and do not correspond to any known climate changes in the region.

For ca. 7100 years Emerald Lake was stable and oligotrophic. It had very low sediment accumulation rates, low sediment organic content and no substantial sediment inputs from the catchment.Sedimentation accumulation rates were just 0.1 mm $yr^{-1}$from ca. 7250 cal yr BP to ca.

4300 cal yr BPand decreased furtherto 0.04 mm $yr^{-1}$from ca. 4300 cal yr BP to AD 1898. The diatom community was dominated by species' assemblages typical of Macquarie Island lakes and ponds (Saunders, 2008; Saunders et al. 2009), with changes in their relative abundances related primarily to changing sea spray inputs together with secondary impacts of changes in pH and temperature(Saunders et al. 2009).

From the late AD 1800s Emerald Lake and its catchment experienced an abrupt regime shift. There were rapid, large changes in all proxies, with most substantially exceeding their natural ranges of variability over the previous ca. 7100 years (Figs. 2 and 3). Sediment accumulation rates increased by over 100 times (from ca. 0.04 mm yr^{-1} to a maximum of 7.4 mm yr^{-1}) as a result of a rapid increase in catchment inputs and erosion rates (Fig. 2) and an increase in within-lake production. Sediment water content increased twofold and TC, TN by a factor of four with their ratio (>10) showing a shift towards more terrestrial organic inputs(Meyers and Teranes, 2001)concomitant with an increase in the abundance of large plant macrofossils. TS alsoincreased from the early AD 1900s onwards, reaching values not previously recorded (Fig. 3).This could be associated with a reduction in hypolimnetic oxygen or an increase in the reducing capacity of the sediments, both of which accompany increases in lake productivity (Boyle et al.2001). Total sulphur can also be enriched through increased inputs and diagenesis of sulphur-rich humic substances (Ferdelman et al. 1991). The latter would be consistent with the wide-scale slope instability and landslips observed on Macquarie Island as a result of the grazing and burrowing activities of rabbits (Scott, 1988). Direct evidence of this is present in the catchment of Emerald Lake (Fig. 1) in the increase in terrestrial inputs and the peak in plant macrofossils, TC and TN ca. AD 1935 (Fig. 3). Landslips can also occur as a result of tectonic activity. Four earthquakes in the AD 1920s and AD 1930s with magnitudes ≥ 7.5 have been recorded (Jones and McCue, 1988). Heavy rainfall may also cause landslips (Taylor, 1955), but the low slope angles in the catchment of the lake and geomorphological evidence suggest that the activity of rabbits grazing and causing disturbance of surface soils through burrowingis the most likely cause. Significant changes in diatom species composition were also recordedfromthe late AD 1800s. This involved a shift to two dominant taxa;*Psammothidium abundans* and *Fragilaria capucina*, which were previously at very low abundances in the lake, and the concurrent absence of at least eight species that were commonpreviously (Fig. 4).*Fragilaria* species are a pioneer species well adapted to high sedimentation rates (Lotter and Bigler, 2000; Van de Vijver et al. 2002) and have been found to be more responsive to catchment-related rather than climate-related variables (Schmidt et al. 2004). This suggests that the diatom communityresponded rapidly tothe shift in nutrient status and changes in the sediment inputs from the catchment.

Collectively all of these changes directly followed the introduction of rabbits in AD 1879 (Cumptson, 1968).With no natural predator, the rabbit population quickly became established. By AD 1880 they were reported as 'swarming' on the northern part of the Island, which is where Emerald Lake is located (Scott,1882; Fig. 1).Their rapid establishment in the vicinity of Emerald Lake is reflected by the regime shift in the palaeoecological record with broken-stick analyses showing that changes in both the sedimentological proxies and diatom composition in the late AD 1800s were statistically significant and unprecedented in the sedimentary record (Figs. 3 and 4).

Some observational records of changing rabbit populations exist for the late 19th and early to mid 20th centuries (Mawson, 1943; Taylor, 1955; Cumpston, 1968). While rabbits were widespread in the northern part of the Island in the late AD 1800s, no rabbits were observed in AD 1923 (Cumpston, 1968). From AD 1948 to the AD 1960s rabbits were again abundant in the north (Taylor, 1955; Scott, 1988). These observations are broadly consistent with the increases in sediment accumulation rates recorded in the late AD 1800s and from the mid AD 1950s to early AD 1960s (Fig. 2b) reflecting increased sediment inputs from the catchment.

The*Myxomatosis* virus was introduced in AD 1978 to control the rabbit population (PWS, 2007). This led to a marked decrease in rabbit numbers and signs of vegetation recovery during the AD 1980s and AD 1990s (PWS, 2007; Scott, 1988; Scott and Kirkpatrick, 2007). The re-establishment of vegetation and reducederosion from grazing likely led to thedecline in the volume of material entering Emerald Lake and the decrease in the sedimentation rate from ca. AD 1970 onwards (Fig. 3b). The TC:TN ratio also decreased, indicating less terrestrially-derived organic matter entering the lake (Meyers and Teranes, 2001; Fig. 3), consistent with decreased erosion rates.Following withdrawal of the *Myxomatosis* virus rabbit numbers rapidly increased again from AD 1999-2003, this time with well-documented evidence of their environmental impacts (PWS, 2007, 2013).

This study shows a very close agreement between the timing of the introduction and expansion of the rabbit population and the changes in the lake ecosystem. The results therefore strongly suggest a causal link between the anthropogenic introduction of rabbits and the statistically significant changes identified in the lake sediments.

5.2 Implications and future work

This study is particularly timely as theseven year pest eradication programmeaimed at restoring the island’s biodiversity,is now coming to an end on Macquarie Island. This has been the world’s largest eradication programmeinvolving three species (rabbits, cats, mice) at one time. It has included the introduction of calicivirus, aerial baiting, and a ground follow up phase (hunting with dogs, shooting, fumigating burrows, trapping) during which the team has covered more than 80,000 kilometres on foot, equivalent to almost two circumnavigations of the Earth. As no pests have been reported in the last two years there will be a new shift in research priorities from monitoring impacts to measuring ecosystem response and recovery (PWS, 2013). This can only be done sensibly if long-term natural baselines of ecosystem parameters prior to the introduction of rabbits are taken into account.

Emerald Lake is a small lake with a small, simple catchment. This means it was considered likely to be responsive to within lake and catchment changes compared to larger lakes in larger catchments. Nevertheless an extended sampling campaign of other lakes on the island would allow a more thorough spatial assessment of the timing, extent and types of changes associated with the rabbits. Similarly a range of additional proxies could be analysed in lake sediments to provide a more complete picture of pre-and post-impact states of the environment. For example the pollen and plant macrofossil record in lake and peat sediments could provide important information on changes in plant communities, supporting the main aim of the eradication programmewhich is restoration of the Island's vegetation (PWS, 2007). Previous work has demonstrated the potential of analysing both these proxies in palaeolake and peat deposits from Macquarie Island (Bergstrom, 1986; Bergstrom et al. 2002; Keenan, 1995; Selkirk et al. 1988).

Further understanding of aquatic community responses to environmental impacts could include analysis of other biological proxies in the lake sedimentssuch asinvertebrate remains (Smol et al. 2001), complementing existing freshwater invertebrate surveys of lakes on Macquarie Island (Dartnell et al. 2005). Surveys of stream invertebrates in AD 1992, 2008 and

2010 have already reported large compositional changes at sites exposed to grazing by rabbits (Marchant et al. 2011).

In a wider context,the eradication of invasive species is increasingly becoming the goal of conservation managementon other sub-Antarctic and oceanic islands around the world (DOC, 2013; SGSSI, 2013; SANAP, 2013). In all these cases a palaeoecological approach can provide an invaluable long-term perspective for quantifyingecosystem response and recovery after the eradication of the invasive species(Burney and Burney, 2007; Connor et al. 2012).

6. Conclusion

This study has demonstrated that the introduction of rabbits on Macquarie Island led to unprecedented and statistically significant changes in Emerald Lake and its catchment from around the late AD 1800s. The scale and magnitude of these changes is unprecedented in at least thelast ca. 7200 years. Sediment accumulation rates increased by> 100 times due to increases in catchment erosionand within-lake production,and were accompanied by a fourfold increase in the total carbon and total nitrogen content of the sediments. A diverse diatom community was replaced by just two previously rare diatom species *Fragilaria capucina* and *Psammothidium abundans*;pioneer coloniserscharacteristic of rapidly changing environments. This study provides information on the scale of the impact together with one baseline against which the effectiveness of the remedial management, including thevery successful invasive species eradication programme, can be assessed. As similar eradication programmes are becoming increasingly common on sub-Antarctic islands, and islands elsewhere, this study demonstrates how palaeoecological methods may be used to provide a long-term perspective onboth natural and

Anthropogenic forcing of ecosystems, the impact of invasive species and the effectiveness of management programmes aimed at restoring natural biodiversity.

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Figure captions

Fig.1. (a) Location of Macquarie Island and Emerald Lake (inset); (b) Emerald Lake and its catchment at the time that the sediment core was collected; (c) An example of the damage caused by rabbits to nearby hillsides.

Fig. 2. (a) Combined ^{210}Pb and ^{14}C age-depth model for Emerald Lake. The upper 18.25 cm was dated using ^{210}Pb. ^{14}C dating was used to date sediments below 22.0 cm (dates are reservoir corrected, and error bars and the 95.4 % probability distribution of each sample are provided). Grey circle indicates extrapolated ^{210}Pb date. Dashed line indicates period between the two; (b) CIC-based ^{210}Pb model with extrapolated ^{210}Pb date to 19.0 cm.

Fig. 3. Sedimentological data. TC/TN is the total carbon to total nitrogen ratio. ^{210}Pb derived dates are on the y axis with extrapolated ^{210}Pb date to ca. AD 1900 in grey. Grey dashed lines indicate significant zones, as determined by broken-stick analyses. Black dashed line indicates the boundary between the most significant zones.

Fig. 4. Dominant diatoms (≥ 10 % relative abundance in ≥ 2 samples). Species in greypositively respond to large-scale catchment changes and increases in sediment input. ^{210}Pb derived dates are on the y axis with extrapolated ^{210}Pb date to ca. AD 1900 in grey. Grey dashed lines indicate significant zones, as determined by broken-stick analyses. Black dashed line indicates the boundary between the most significant zones.

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Figure 1

Figure 2

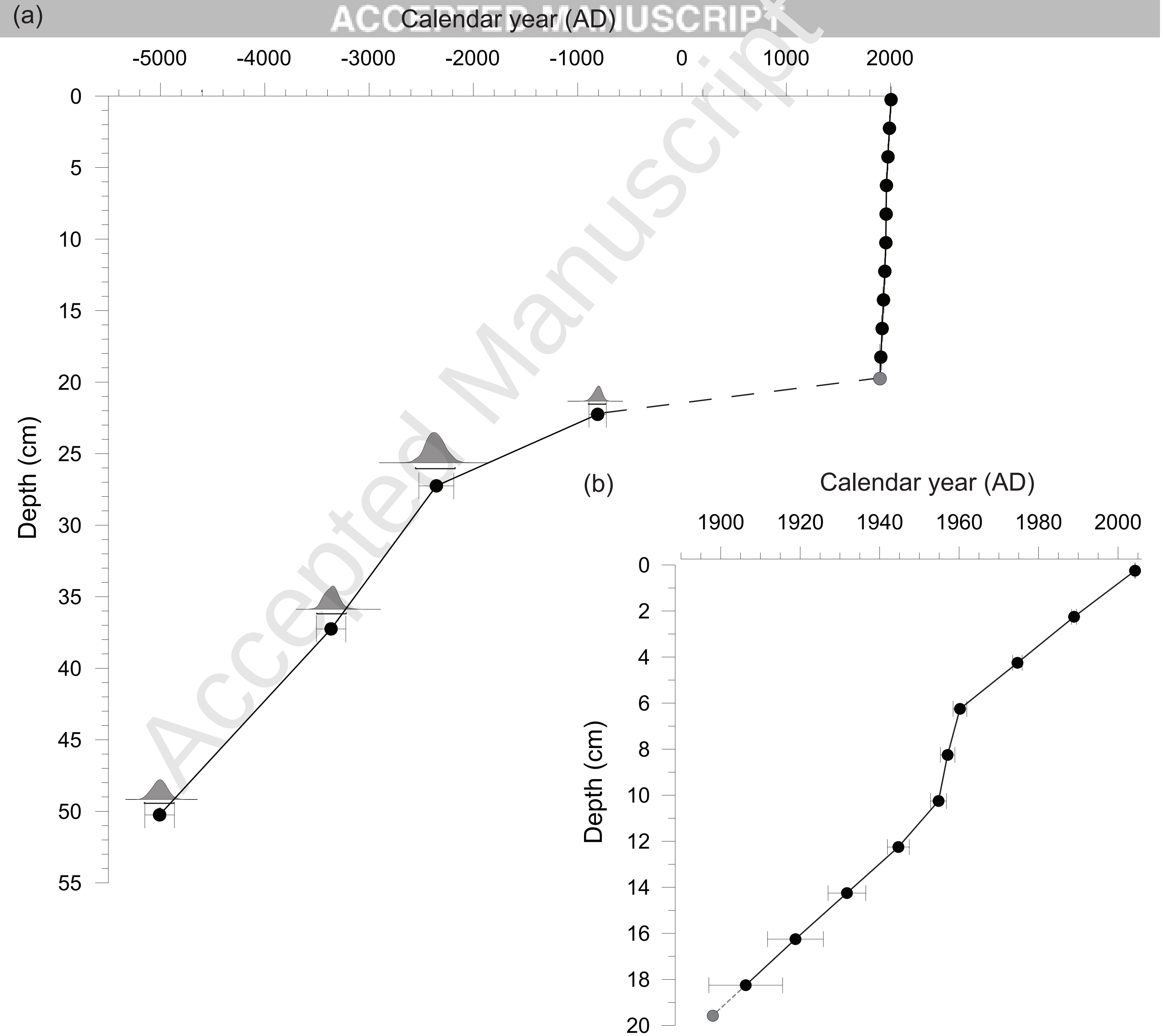
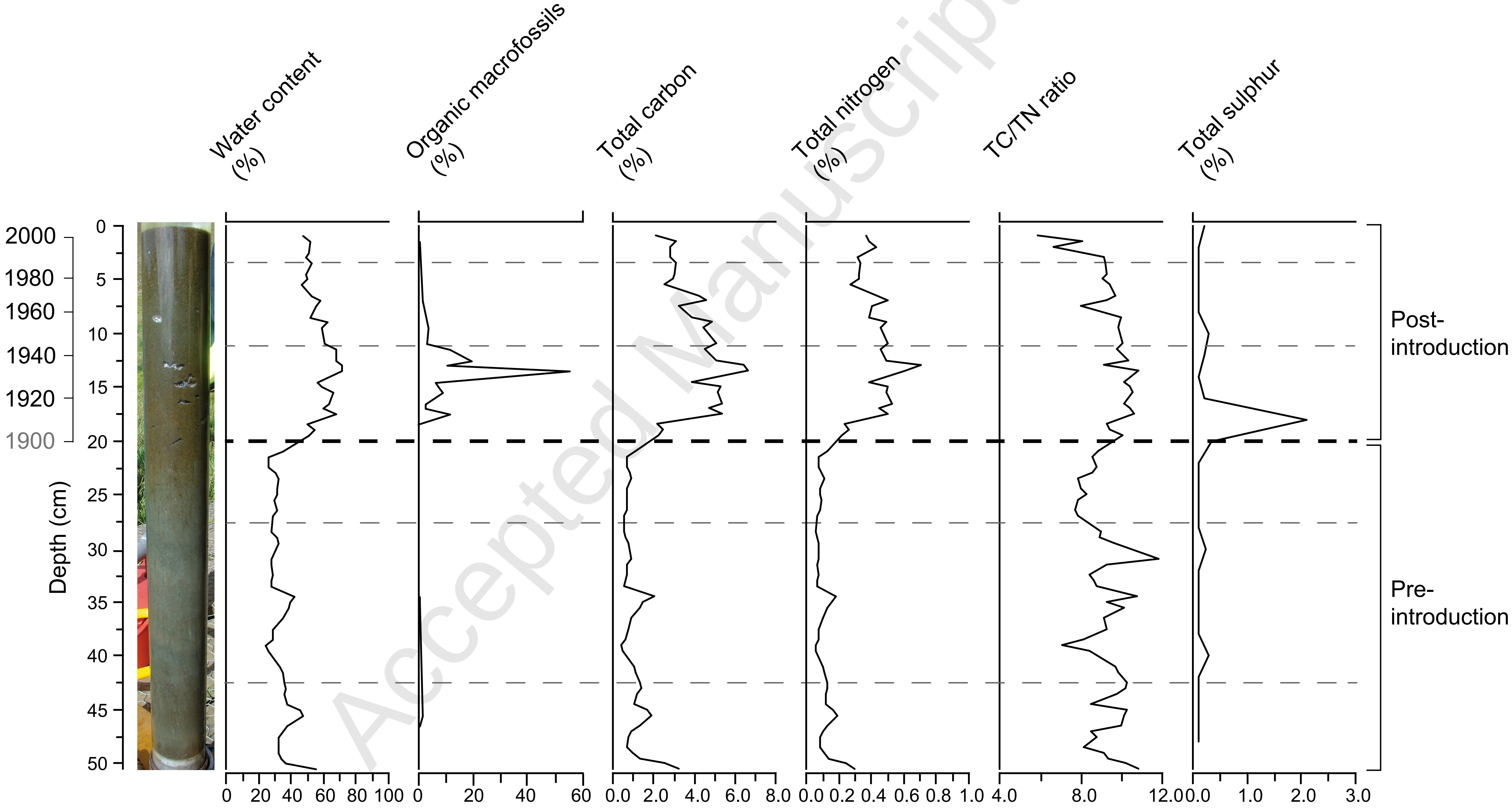
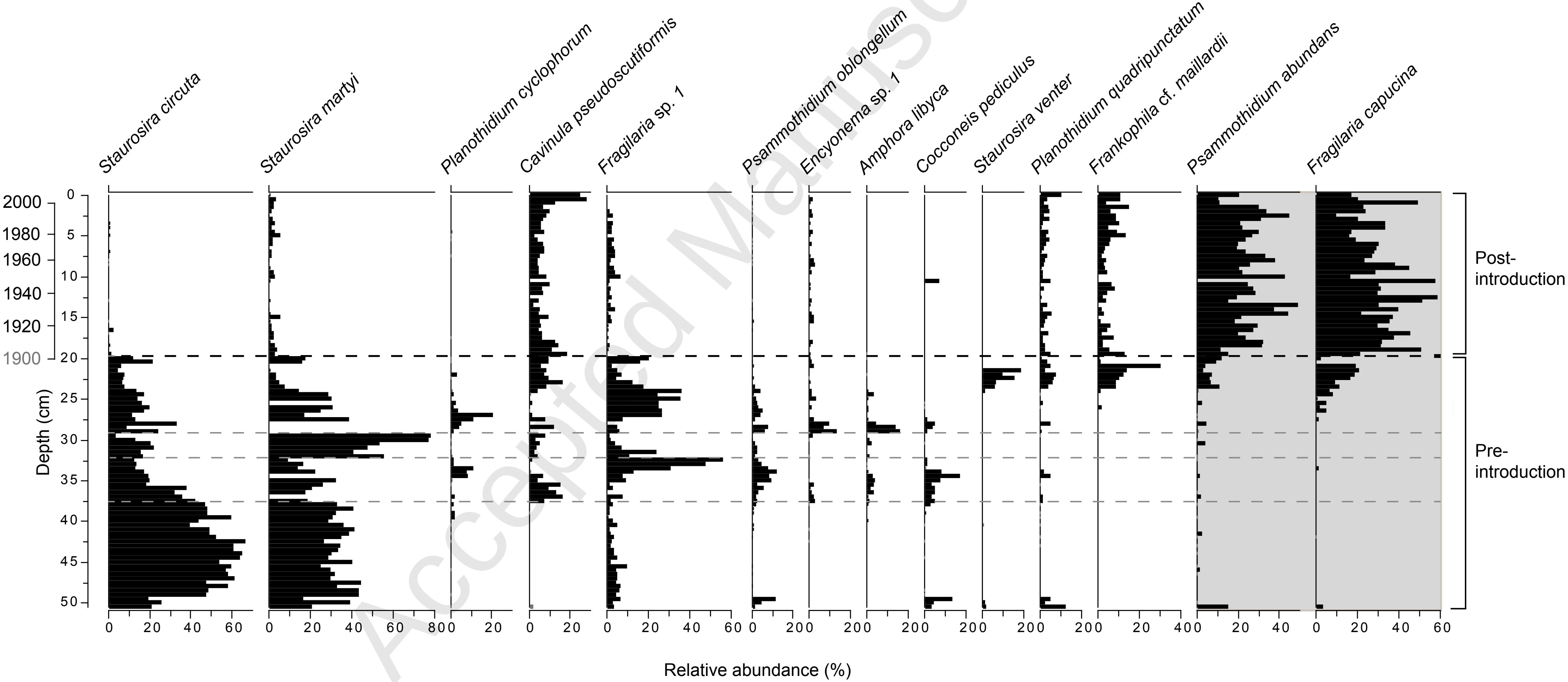

(a)
Calendar year (AD)
-5000
-4000
-3000
-2000
-1000
0
1000
2000
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
55
(b)
Calendar year (AD)
1900
1920
1940
1960
1980
2000
Depth (cm)
0
2
4
6
8
10
12
14
16
18
20

Figure 3



Water content (%)
Organic macrofossils (%)
Total carbon (%)
Total nitrogen (%)
TC/TN ratio
Total sulphur (%)
2000
1980
1960
1940
1920
1900
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
Post-introduction
Pre-introduction
0 20 40 60 80 100
0 20 40 60
0.0 2.0 4.0 6.0 8.0
0.0 0.2 0.4 0.6 0.8 1.0
4.0 8.0 12.0
0.0 1.0 2.0 3.0

Figure 4



Staurosira circuta
Staurosira martyi
Planothidium cyclophorum
Cavinula pseudoscutiformis
Fragilaria sp. 1
Psammothidium oblongellum
Encyonema sp. 1
Amphora libyca
Cocconeis pediculus
Staurosira venter
Planothidium quadripunctatum
Frankophila cf. maillardii
Psammothidium abundans
Fragilaria capucina
2000
1980
1960
1940
1920
1900
Depth (cm)
Post-introduction
Pre-introduction
Relative abundance (%)