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Establishing the impacts of freshwater aquaculture in tropical Asia: the potential role of palaeolimnology

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Freshwater aquaculture is an important source of protein worldwide. Over-exploitation of fisheries can, however, add severely to pressures on ecosystem functioning and services. In Southeast Asia, aquaculture in freshwater lakes contributes significantly to the economy and to reductions in poverty and nutritional insecurity. However, overstocking and excessive feeding of fish can lead to a degradation of affected water bodies, manifest as eutrophication, toxic algal blooms, losses of biodiversity and amenity, anoxia and, in extreme cases, collapse of fisheries. Projected increased warming and storminess associated with global climate change are likely to magnify existing problems. Matching levels of aquaculture production with ecological carrying capacity is therefore likely to become increasingly challenging, requiring levels of data and understanding that are rarely available, a problem that is impossible to rectify in the short term using standard limnological approaches. This paper reviews the development of freshwater aquaculture in the Philippines, associated environmental impacts, and relevant environmental regulations and regulatory bodies. The potential role of palaeolimnology, a science that is relatively under-utilised in the tropics generally and in tropical Asia in particular, in complementing extant datasets, including monitoring records, is highlighted through reference to a preliminary study at Lake Mohicap. Lake Mohicap currently supports aquaculture and is one of a cluster of seven volcanic crater lakes on Luzon, the largest of the archipelago of islands forming the Philippines.

Key words Philippines; palaeolimnology; eutrophication; aquaculture

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Introduction

Globally, more than two billion people are exposed to diseases linked to water supplies, through the consumption of polluted drinking water or food that has been contaminated by water-borne pollutants (Gleick 2011; Prüss-Ustün *et al*. 2014). The problem is acute in parts of Asia, where a combination of factors has severely jeopardised water resources (Chellaney 2011) and the ecosystem services provided (Clausen and York 2008). The challenge of meeting the demand for aquatic ecosystem services in Asia, where abstraction rates are already the highest in the world, is likely to increase in coming years, owing to projected changes in climate and consumption, and the cumulative and combined effects of pollution (Evans *et al.* 2012; Vorosmarty *et al.* 2013).

Environmental pollution is a major problem throughout Asia (Evans *et al.* 2012), as is evident from an escalation in accounts of the effects of pollution, such as harmful algal blooms (Glibert 2013), toxic air

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(Zhou *et al.* 2015) and contaminated soils (Zhao *et al.* 2015). Long-term monitoring of ecological systems in tropical Asia has tended to focus on rainforests and coral reefs: relatively little research has been devoted to understanding the ecological and chemical status and functioning of freshwater bodies (Biswas and Seetharam 2008). For example, of the lakes included in the International Long Term Ecological Research (ILTER) network, set up in 1993 to monitor environmental change impacts on ecological and socioeconomic systems, only three are located in Asia (Donghu and Taihu in China and Yuan-Yang in Taiwan). Both Taihu and Yuan-Yang also feature in the Global Lake Ecological Observatory Network (GLEON), along with Lake Soyang (South Korea). The four lakes featured are all subtropical, while Lake Soyang – which is a reservoir – formed behind a dam in the early 1970s. Lakes in tropical Asia fare are similarly under-represented in the GloboLakes (2015) database, which was set up to provide a basis for investigating the state of lakes and their response to climatic and other environmental drivers of change using a combination of *in situ* and remotely sensed data: of a total of 991 lakes in the database, only 12 (i.e. less than 1.5%) are located in tropical Asia. Therefore, a shortage of data constrains the design of effective measures for reducing or reversing aquatic degradation and provides for only the most fragile and superficial of platforms upon which to base assessments of the extent of human perturbation and the effects of pollution on lake functioning. Detecting change or impact in freshwater ecosystems is dependent upon being able to determine the amplitude of natural variability, and therefore the extent by which this has been exceeded by anthropogenic activity, and the determination of baseline (or pre-impact) conditions. Defining this envelope of variability can also help to identify when ecosystem thresholds or carrying capacities have been exceeded (Dalton *et al.* 2009).

The archipelago of islands comprising the Philippines is relatively lake-rich when compared with other parts of tropical Asia (69 freshwater lakes). Many of the lakes support fish farms that, although important economically and for food security, can be major sources of pollution (Edwards 2015). In an effort to mitigate negative environmental impacts arising from aquaculture and other water-based or focused activities, the Republic Act (RA) No. 9275 (The Philippine Clean Water Act (CWA) of 2004) was implemented. The aims of the CWA include the restoration and rehabilitation of impacted ecosystems, the latter in part through the promotion and acceleration of relevant research (DENR-EMB 2014). However, implementation of the CWA has been compromised by a dearth of long-term monitoring data and relevant ecological studies. Indeed, lake-based studies are rare in the Philippines, beyond a few basic ecological surveys and research aimed at improving aquaculture productivity (Papa and Mamaril 2011).

This paper contextualises concerns regarding the risks to human and environmental health, and to economic development, posed by the rapid expansion of lake-based aquaculture and associated pollution in the Philippines, and reviews the regulatory response. Lake Mohicap, one of the seven crater lakes of San Pablo, Laguna, on the island of Luzon, is a particular focus of the paper. The island of Luzon is a centre for lake-based aquaculture: the cluster of crater lakes that includes Lake Mohicap is currently associated with a high

Figure 1 Aquaculture, pollution and cyanobacteria (*Microcystis spp.*) blooms at the Seven Crater Lakes of San Pablo
Source: Photo by D. Taylor, May 2014

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intensity of fish farming that has greatly contributed to the deterioration of water quality in the lakes (Figure 1). The results of a preliminary palaeolimnological analysis of a sediment core from Lake Mohicap are discussed in the context of aquaculture and relatively recent changes in sedimentation and water quality.

Aquaculture and water quality

Aquaculture is currently the fastest growing sector in livestock production globally (Sampels 2014), and fish protein is important for the nutritional security of a substantial proportion of the world's population (Kawarzuka and Béné 2011). Aquaculture worldwide produced over 58 million tonnes of fish products and generated an estimated US$144.4 billion in 2012, growing at an average rate annually of over 12% between 1976 and 2012 (Krause *et al.* 2015). Asian countries account for by far the largest share of production – well over 80% according to the FAO (2014). The total quantity of fish from aquaculture is projected to reach 93.6 million tonnes by 2030, with China and Southeast Asian countries the main producers (World Bank 2013). Aquaculture also provides employment and a reliable income, often in communities where both are otherwise difficult to secure (Pant *et al.* 2014). Historically the number of people employed in fisheries has grown more quickly than global population, with employment levels in aquaculture in Asia more than doubling over the last c. 15 years to more than 18 million, or greater than 95% of the total employed in the industry globally (FAO 2014).

Pollution associated with aquaculture is a significant problem, but economic and social effects are also a concern. In Asia, productivity per fish farmer is lower than in any other region of the world, being c. 60% of that in Africa and only c. 5% of that in North America (FAO 2014). Moreover, doubts have emerged over the ability of small-scale or low-technology aquaculture to act as a basis for economic development in rural areas (Stevenson and Irz 2009), in part because of low survival rates among farmed fish, a reliance on labour from unpaid family members, and pressure to export nutritious produce beyond the local area (Gehab *et al.* 2008; Jolly *et al.* 2009). Although relevant empirical studies are few, particularly with regard to freshwater aquaculture, there is evidence that fish farming can have negative social effects, particularly among the most vulnerable communities (Irz *et al.* 2007). A paradox exists: while the benefits of expanded aquaculture may have helped alleviate poverty among some communities, the costs of fish farming in terms of resources consumed (including land for fishponds), disrupted ecosystem functioning and reduced ecosystem services (Figure 2), and the risks posed to health through farmed fish contaminated by harmful pollutants entering the food chain, may be more widely felt (Törnqvist *et al.* 2011).

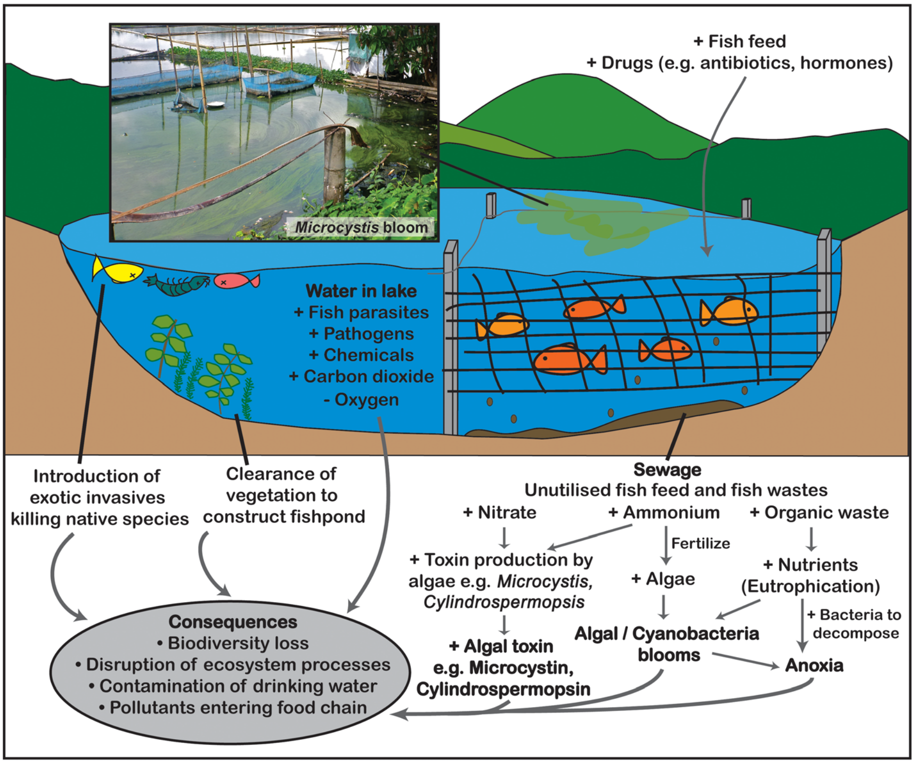

Figure 2 Schematic representation of fish farming and its environmental impact

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In the Philippines, a presidential decree (PD) by President Marcos in 1973 (PD 43-A) targeting the construction of small fishponds, later consolidated with other related decrees into PD 704 (1975), sanctioned an accelerated development of fisheries resources. A boost in production from fish farms ensued. Production of farmed fish has continued to climb, despite increased intensity of aquaculture being implicated as a cause of periodic mass die-offs of farmed fish (Jacinto 2011; Magcale-Macandog *et al.* 2014), growing by more than 10% between 2007 and 2012 (DA-BFAR 2012). Tilapia (*Oreochromis niloticus*) and milkfish (*Chanos chanos*) are the most important farmed fish in, respectively, lakes/ponds and brackish/marine waters (ADB 1996; Cruz 2007; FAO 2009). This rapid rate of development has not been without its environmental costs, however. Environmental degradation linked to fish farming, in the form of clearance of vegetation to construct fishponds, contamination of drinking water supplies and the food chain (for example, by environmental hormones), eutrophication (due to high densities of fish and low feed conversion ratios), introduced pathogens and exotic invasive species, potentially undermines the long-term sustainability of fish farming. In such situations, aquaculture may end up reducing resilience, particularly among the most vulnerable members of a community (Troell *et al.* 2014). Negative environmental impacts associated with aquaculture are set to deepen in the future, in the absence of mitigating and adaptive measures, as a result of climate change-driven warmer waters, increased hypoxia, raised pollutant toxicities and rates of bioaccumulation of toxins in farmed fish, and the emergence or re-emergence of pathogens (Ficke *et al.* 2007; De Silva and Soto 2009; Porter *et al.* 2014).

Of 69 freshwater lakes in the Philippines, 36 are classed in accordance with criteria laid out in DENR Administrative Order No. 34, Series of 1990 (Guerrero 1999) into three categories: good lakes are regarded as having water quality within acceptable standards and no evidence of stress from overexploitation of fisheries; threatened lakes show moderate pollution, sedimentation and ecological stress; while critically endangered lakes are associated with heavy pollution and overfishing. Twenty-seven of the lakes classified are associated with water quality problems linked to aquaculture. Laguna de Bay – lake number 18 in Table I (Figure 3) – is a prime if perhaps an extreme example. The lake provides a wide range of ecosystem services to central Luzon, including to residents of the capital Metropolitan Manila. Overexploitation and unsustainable aquaculture practices have contributed to a marked decline in water quality, biodiversity, and productivity (Zafaralla *et al*. 2002; Santos-Borja and Nepomuceno 2006). Laguna de Bay has also been categorised as a critically endangered lake, despite being part of a candidate key biodiversity area (CKBA). Key biodiversity areas (KBAs) build upon the National Integrated Protected Areas System (NIPAS), were set up in the early 1990s under the administration of the Department of Environment and Natural Resources (DENR), and aim to ensure the landscape-based conservation of globally important biodiversity. Areas that are suspected of supporting globally important biodiversity, but for which there is no conclusive supporting data, are designated CKBAs and are regarded as priorities for research in the Philippines. A perhaps less extreme and therefore more representative example of the aquatic impacts of aquaculture is provided by several of the lakes grouped as the Seven Crater Lakes of San Pablo, which also form part of a CKBA and are associated with high levels of pollution and occasional mass die-offs of fish (Global Nature Fund 2015). Fish farming and human settlement are the main sources of pollution.

Towards a more ecologically sustainable lake-based aquaculture: institutional and regulatory responses to declining water quality in the Philippines

Legislation implemented in different countries around the world in response to a widespread degradation of water bodies has tended to target levels of a relatively narrow range of pollutants. Only rarely do water pollution regulations adopt a whole catchment approach, cover all forms of water bodies and seek to put in place mechanisms that will enable restoration or rehabilitation of damaged ecosystems. The Water Framework Directive (WFD) (2000) is an example of such all-encompassing legislation, requiring that all water bodies in European Union (EU) member states reach at least 'good' water quality status, or show little or no human impact, by the end of the first implementation period (2015) (Kirilova *et al.* 2010) or six-year targeted cycles thereafter. However, development and effective implementation of environmental legislation require not only strong political will and buy-in from the main interested parties, but also the availability of relevant data (including datasets from long-term monitoring studies) and a high level of understanding of the pressures on water bodies and their effects, and range of possible appropriate responses (Rola *et al.* 2004).

In the Philippines, growing concerns regarding the overexploitation of natural resources and environmental degradation allied to increased parliamentary democracy provided the context for the creation in 1987 of the DENR (BFAR-PHILMINAQ 2007). The Environmental Management Bureau (EMB), the enforcement arm of the DENR, is responsible *inter alia* for regulating the environment through close monitoring sources of pollution and mitigate its effects to health and environment

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Table I The 69 major freshwater lakes in the Philippines

General area of Philippines	Lake #	Lake name	Region/province	Coordinates (N, E)	Depth (m)	Governing bodies	Protective status	Class	Condition of the lake
Northern and Western Philippines	1	Alindayat*	III, Zambales	15° 36’ 38", 119° 56’ 34"	DD	BFAR	NP	NC	T
	2	Bangalau	II, Cagayan	18° 14’ 57.76", 121° 54’ 13.37"	2.5	NS	NP	NC	NS
	3	Baao	V, Camarines Sur	13° 27’ 49.5138", 123° 18’ 57.5388"	DD	NS	NP	NC	NS
	4	Bato*	V, Camarines Sur	13° 19’ 54.9984”, 123° 21’ 32.0004”	4.5	DENR-BMB	NIPAS	B	T
	5	Buhi*	V, Camarines Sur	13° 27’ 24.9984”, 123° 30’ 51.0012”	7	BFAR	NP	B	T
	6	Bulusan	V, Sorsogon	12°45’ 41.688", 124° 5’ 29.781"	DD	DENR	NIPAS	NC	NS
	7	Bunot *	IV, Laguna	14° 4’ 59.9982”, 121° 20’ 59.9994”	23	LLDA-BFARMC	CKBA	NC	T
	8	Cabalangan*	II, Cagayan	18° 10’ 59.99", 121° 45’ 0"	DD	NS	NP	NC	NS
	9	Calibato*	IV, Laguna	14° 6’ 15.0012”, 121° 22’ 37.9992”	156	LLDA-BFARMC	CKBA	NC	T
	10	Calig	II, Cagayan	18° 12’ 29.88", 121° 49’ 18.12"	DD	NS	NP	NC	NS
	11	Caliraya	IV, Laguna	14° 18’ 11.3178”	DD	NS	NS	NC	NS
	12	Caluangan*	IV, Oriental Mindoro	13° 22’ 00.0120", 121° 07’ 59.9880"	DD	BFAR	NIPAS	NC	T
	13	Cansiritan	II, Cagayan	17° 54’ 7.56”, 121° 42’ 2.71”	DD	NS	NP	NC	NS
	14	Cassily	II, Cagayan	17° 40’ 19”, 121° 30’ 48”	DD	NS	NP	NC	NS
	15	Danao*	V, Camarines Sur	13° 21’ 33”, 123° 34’ 24”	DD	NS	NP	NC	NS
	16	Danum	CAR	17° 5’ 39.41", 120°53’ 4.97"	DD	NS	NP	NC	NS
	17	Kayangan	IV, Palawan	11°57’ 12.40", 120°13’ 24.62"	DD	NS	NP	NC	NS
	18	Laguna de Bay*	IV, Laguna, Metro Manila and Rizal	14° 23’ 7.6812", 121° 17’ 4.9698"	2.8	LLDA-BFARMC	CKBA	NC	CE
	19	Lumot-Mahipon*	IV, Laguna	14° 15’ 20.934", 121° 32’ 49.0884”	DD	NS	NS	NC	NS
	20	Malbato	IV, Palawan	12° 01’ 48.1008", 120° 06’ 59.9004"	DD	NS	NP	NC	NS
	21	Manguao	IV, Palawan	10° 46’ 00.1200", 119° 33’ 00.0000"	DD	DENR-BMB	NIPAS-KBA	NC	G
	22	Mapanuepe	III, Zambales	14° 59’ 2.22", 120° 17’ 40.33"	DD	NS	NP	NC	NS
	23	Mohicap*	IV, Laguna	14° 7’ 22.53”, 121° 20’ 2.4318”	30^{m}	LLDA-BFARMC	CKBA	NC	T
	24	Nagatutuan	II, Cagayan	18° 3’ 46.36”, 121° 39’ 47.52”	DD	NS	NP	NC	NS
	25	Nalbuan	II, Cagayan	18° 13’ 26”, 121° 46’ 51”	DD	NS	NP	NC	NS
	26	Naujan*	IV, Oriental Mindoro	13° 10’ 10.9992”, 121° 20’ 54.9996”	19	DENR-PAWB	NIPAS	B	G
	27	Paitan*	III, Nueva Ecija	15° 49’ 59.99" ,120° 43’ 59.99"	DD	NS	NP	NC	T

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	28	Palakpakin*	IV, Laguna	14° 6’ 40.2798”, 121° 20’ 19.8378”	8	LLDA-BFARMC	CKBA	NC	T
	29	Pandin*	IV, Laguna	14° 7’ 0.0006”, 121° 22’ 0.0012”	62	LLDA-BFARMC	CKBA	NC	T
	30	Pantabangan	III, Nueva Ecija	15° 48’ 59.58”, 121° 8’ 58.31”	DD	NS	NP	NC	NS
	31	Paoay*	I, Ilocos Norte	18° 7’ 16.2474”, 120° 32’ 25.728”	3-5	DENR-PAMB	NIPAS	NC	T
	32	Pinatubo crater lake	III, Zambales	14° 59’ 2.22”, 120° 17’ 40.33”	DD	NS	NP	NC	NS
	33	Sampaloc*	IV, Laguna	18° 7’ 16.2474”, 120° 32’ 25.728”	25	LLDA-BFARMC	CKBA	NC	T
	34	Taal*	IV, Batangas	13° 56’ 54.999”, 121° 0’ 26.9994”	90	PAWB-PPCT	NIPAS-KBA	NC	T
	35	Tadlak*	IV, Laguna	14° 10’ 57.3528”, 121° 12’ 23.3244”	58	LLDA-BFARMC	CKBA	NC	NS
	36	Tambo	III, Tarlac	15° 17’ 45.87”, 120° 22’ 19.17”	DD	NS	NP	NC	NS
	37	Yambo*	IV, Laguna	14° 11’ 66.667”, 121° 36’ 66.667”	40^{m}	LLDA-BFARMC	CKBA	NC	T
Central Philippines	38	Balinsasayaw*	VII, Negros Oriental	9° 21’ 59.1042”, 123° 9’ 18.9036”	134^{m}	DENR-PAWB	NP	NC	G
	39	Bito*	VIII, Leyte	10° 47’ 19”, 124° 58’ 49”	DD	NS	NP	NC	T
	40	Danao*	VII, Cebu	10° 40’ 35.274”, 124° 20’ 34.299”	0.91–54.9	NS	NP	NC	G
	41	Danao*	VIII, Leyte	10° 52’ 5.001”, 124° 51’ 20.9988”	DD	NS	NP	A	T
	42	Danao*	VII, Negros Oriental	9° 21’ 2.001”, 123° 10’ 59.9988”	DD	NS	NP	NP	NS
	43	Kabalin-an*	VII, Negros Oriental	9° 21’ 11”, 123° 9’ 45”	DD	NS	NP	NP	NS
	44	Lanao	VII, Calibao Island - Bohol	9° 52’ 47”, 123° 45’ 51”	DD	NS	NP	A	T
	45	Mantohod*	VII, Negros Oriental	10° 10’ 60”, 123° 13’ 1”	DD	NS	NP	NC	G
Southern Philippines	46	Apo	X, Bukidnon	7° 52’ 50.10”, 125° 0’ 23.25”	DD	NS	NP	NC	NS
	47	Bulut	XII, North Cotabato	7° 18’ 09.0000”, 124° 17’ 35.0160”	DD	NS	NP	NC	G
	48	Blingkong	XII, North Cotabato	6° 39’ 0”, 124° 55’ 0.02”	DD	NS	NP	NC	G
	49	Buluan	ARMM, Maguindanao	6° 38’ 42”, 124° 49’ 38”	DD	NS	NP	NC	G
	50	Butig	ARMM, Lanao del Sur	7° 44’ 2”, 124° 17’ 27”	DD	NS	NP	NC	G
	51	Danao	X, Misamis Oriental	8° 39’ 48.9996”, 124° 46’ 48.2988”	DD	NS	NP	NC	NS
	52	Dapao	ARMM, Lanao del Sur	7° 47’ 12”, 124° 2’ 36”	DD	NS	NP	NC	G
	53	Gumaod	X, Misamis Oriental	8° 39’ 7.14”, 124° 48’ 24.74”	DD	NS	NP	NC	NS
	54	Labas	XII, North Cotabato	7° 15’ 00.0000”, 124° 30’ 00.0000”	DD	NS	NP	NC	G
	55	Lahit	XII, South Cotabato	6° 15’ 6.9978”, 124° 42’ 54”	DD	NS	NP	NC	NS

(*Continues*)

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Table I. (Continued)

General area of Philippines	Lake #	Lake name	Region/province	Coordinates (N, E)	Depth (m)	Governing bodies	Protective status	Class	Condition of the lake
	56	Lanao*	ARMM, Lanao del Sur	7° 51' 00.0000", 124° 15' 00.0000"	DD	DENR-BMB	NIPAS-KBA	NC	T
	57	Mainit*	XIII, Surigao del Norte-Agusan	9° 26' 2.0004", 125° 31' 59.9982"	128	LMDA	NIPAS-CKBA	A	T
	58	Malinao	XII, North Cotabato	7° 16' 39.0000", 124° 19' 06.9600"	DD	NS	NP	NC	G
	59	Maughan	XII, South Cotabato	6° 6' 5", 124° 53' 20"	DD	NS	NP	NC	T
	60	Napalit	X, Bukidnon	7° 52' 5.59", 124° 47' 3.97"	DD	NS	NP	NC	NS
	61	Nunungan	X, Lanao del Norte	7° 49' 21", 123° 57' 19"	DD	NS	NP	NC	G
	62	Pagusi	XIII, Agusan	9° 18' 0", 125° 33' 0.01"	DD	NS	NP	NC	G
	63	Pinamaloy	X, Bukidnon	7° 40' 16.13", 124° 59' 58.35"	DD	NS	NP	NC	NS
	64	Pulangi	X, Bukidnon	7° 48' 27.13", 125° 1' 59.69"	DD	NS	NP	NC	NS
	65	Putian	ARMM, Lanao del Sur	7° 48' 24.012", 124 34' 3"	DD	NS	NP	NC	T
	66	Sebu	XII, South Cotabato	6° 13' 27.0006", 124° 42' 11.9988"	5	NS	NP	B/C	NS
	67	Siloton	XII, South Cotabato	6° 13' 33.1896", 124° 43' 51.657"	DD	NS	NP	NC	NS
	68	Tutay	X, Bukidnon	7° 40' 00.8004", 125° 01' 40.1988"	DD	NS	NP	NC	NS
	69	Wood	IX, Zambonga del Sur	7° 50' 40", 123° 9' 54"	DD	NS	NP	NC	T

Source: Information from Guerrero (1999), Papa *et al*. (2012), Pascual *et al*. (2014) and DENR-EMB (2014)

Abbreviations: *Lakes with aquaculture; A, class A, B, class B, C, class C (see Table II); CE, critically endangered lakes (are associated with heavy pollution and overfishing); CKBA, candidate key biodiversity area; DD, data deficient; G, good conditioned lakes (having water quality within acceptable standards and no evidence of stress from overexploitation of fisheries); KBA, key biodiversity area; ^{m}, max; NC, not classified; NIPAS, National Integrated Protected Areas System; NP, not protected; NS, not specified; T, threatened lakes (show moderate pollution, sedimentation and ecological stress).

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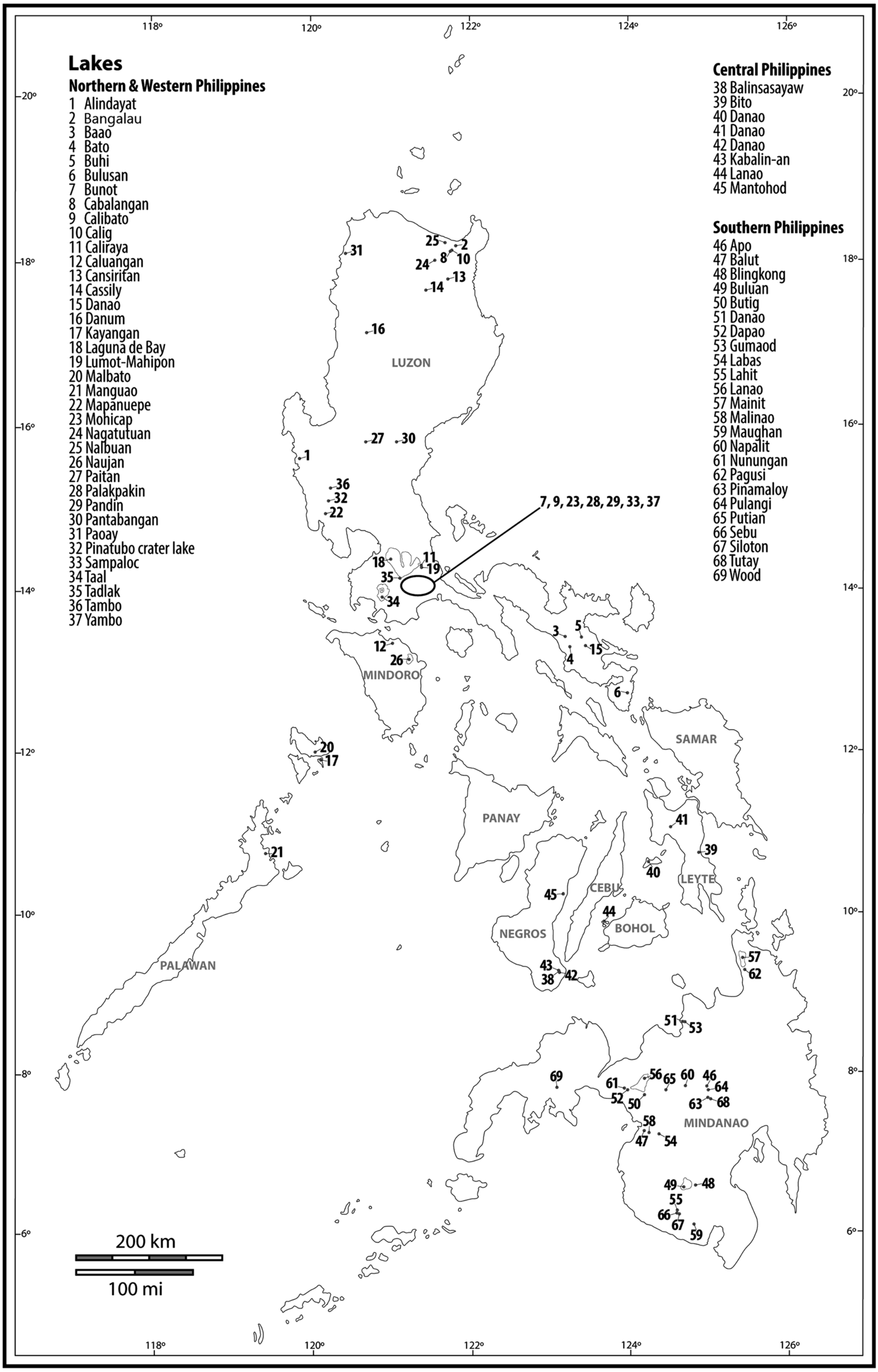

Figure 3 Philippine map showing the 69 freshwater lakes (information from Guerrero 1999; Papa *et al*. 2012; DENR-EMB 2014; Pascual *et al*. 2014). For information on their protective status and water classification, see Table I

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(White 2009) using DENR Administrative Orders (DAOs) (Figure 4). In addition to the DENR, aquaculture activities are regulated through Fisheries Administrative Orders (FAOs) and the RA No. 8550 (Fisheries Code of 1998) which are administered by the Bureau of Fisheries and Aquatic Resources (BFAR), the government agency responsible for overseeing the country's fisheries and aquatic resources, and under the Department of Agriculture (Guerrero 1999; DA 2012).

Activities of the BFAR from the 1970s brought significant developments to fisheries in the Philippines and led the establishment of lake-based aquaculture management programs (BFAR-PHILMINAQ 2007). The campaign to improve lake management and address problems of declining water quality intensified on the island of Luzon during the 1990s upon the formation of specialised management bodies for Laguna de Bay, the Seven Crater Lakes of San Pablo, and Lake Taal. For Laguna de Bay, the proclamation of RA No. 4850 in 1996 paved the way for the establishment of the Laguna Lake Development Authority (LLDA), under the supervision of the DENR, and implemented

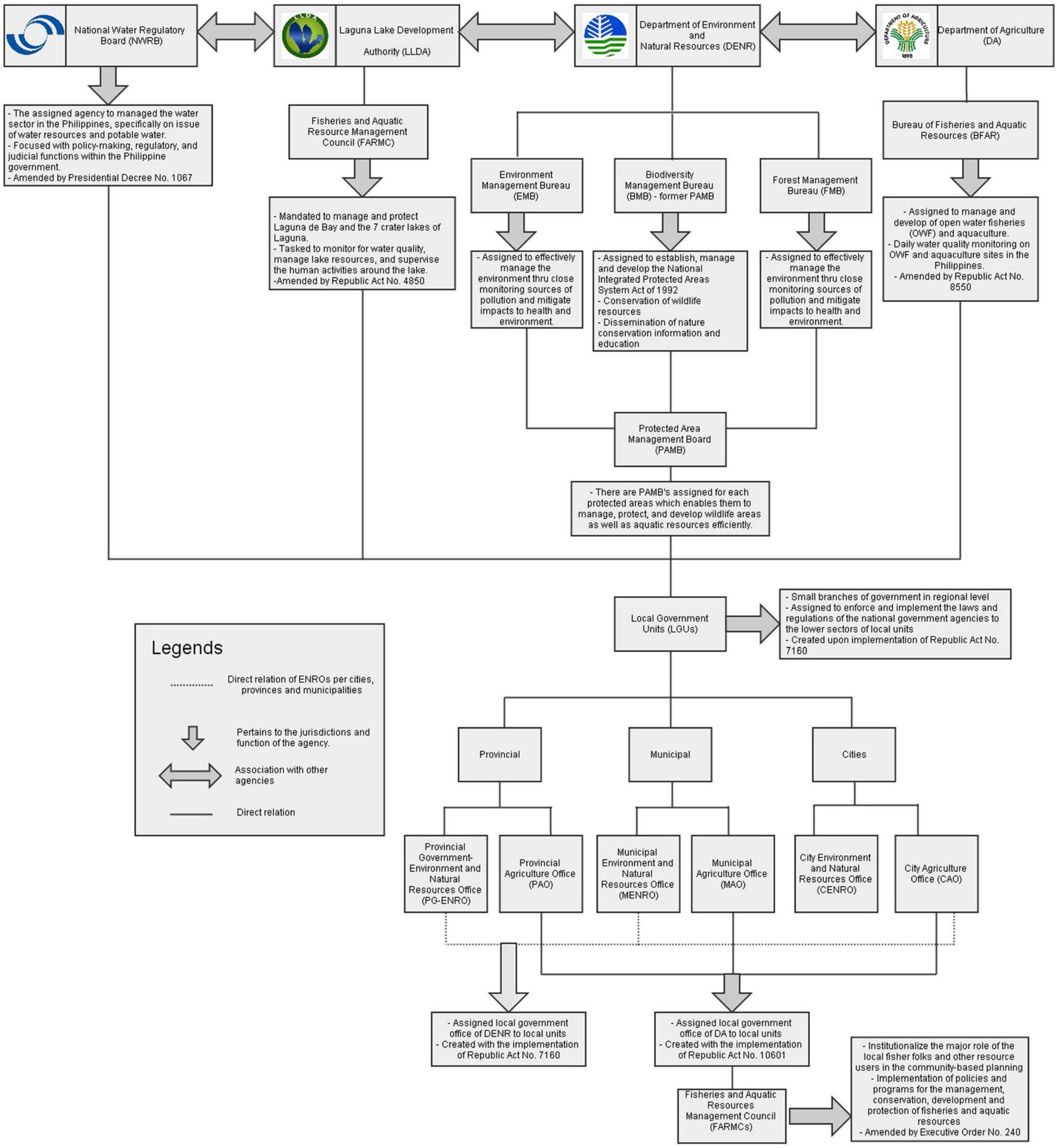

Figure 4 **Schematic diagram of the key policymakers in the Philippines for water and environmental management (Makil 1984; AFMA 2004; COA 2014; Rola *et al.* 2004; DA 2012; FTTC-AP 2013; DENR-EMB 2014; DENR 2015; LLDA 2015)**

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an integrated lake basin management approach to the management of the lake that included a levying of fees on those responsible for discharging effluents to the lake in proportion to the level of pollutants (Santos-Borja and Nepomuceno 2006; LLDA 2015). Aside from Laguna de Bay, LLDA has also taken on the responsibility for managing the Seven Crater Lakes of San Pablo with the assistance from the San Pablo City Government and non-governmental organisations (Santos-Borja 1997; Zafaralla *et al*. 2002; Santos-Borja and Nepomuceno 2006). Lake Taal was previously under the jurisdiction of the Presidential Commission on Tagaytay-Taal (PCTT), created under Executive Order (EO) No. 84 in 1993 (TVPL-PAMB 2009; COA 2014). Implementation of FAOs allowed for establishment of a fish sanctuary in Lake Taal and the prohibition of certain fishing technologies. In order to facilitate management, aquaculture was restricted to particular parts of the lake (Santos-Borja and Nepomuceno 2006). Since 2008, a management plan for Lake Taal was put into effect, and mandated new regulations for fisheries, such as limiting the number of fish cages in the aquaculture sites, introducing new methods of licensing and taxing fish farms, and managing effluent inputs (TVPL-PAMB 2009).

Implementation of the CWA (2004), and its Implementing Rules and Regulations (IRR) by the EMB sought to minimise human impacts and to facilitate improved understanding of aquatic ecosystems as a basis for their rehabilitation, restoration and protection (DENR-EMB 2014) using the water standard parameters listed in DENR Administrative Order (DAO) Series No. 34 of 1990. The water standard parameters provide a baseline against which future changes in water quality, including those arising from the implementation of measures aimed at curbing pollution inputs, can be assessed. Implementation followed on from RA No. 7160 (Local Government Code of 1991), RA No. 8435 (Agriculture and Fisheries Modernisation Act of 1997) and RA 8550 (Fisheries Code of 1998) (AFMA 2004; DA 2012; DENR 2015). The 27 lakes supporting aquaculture mentioned previously are among the 69 freshwater lakes monitored as part of implementation of the CWA (Tables I and II). These freshwater lakes are classed into one of five categories, according to their use (AA, A, B, C and D), with AA and A grouping those that are used for drinking water supplies, while B, C and D represent those that are primarily used for recreation, fisheries and agriculture/irrigation/industrial purposes, respectively. In total, region IV-A to the south and east of Metropolitan Manila in the central part of the island of Luzon has the largest number of water bodies, mainly composed of principal rivers, ponds, streams and lakes, and are (67) classified under this system (DENR-EMB 2014). However, to date, lentic (lake/pond) environments have received relatively little attention, with the focus largely being on rivers: more than 75% of inland water bodies classified under the CWA are lotic (flowing water) ecosystems (Table II).

Both DENR and the National Water Resources Board oversee implementation of the CWA. Actual responsibilities for regulation, however, are divided among several institutions, such as government-owned and -controlled corporations and local government units (LGUs) of cities, provincial, and municipal sectors under RA No. 7160 (DENR-EMB 2014; DENR 2015). Problems over implementation of the CWA and associated regulations have been attributed to a lack of coherence and coordination between the various organisations with regulatory responsibilities (Rola *et al.* 2004). For instance, DENR has no explicit links to other local government units under its jurisdiction, such as the Forest Management Bureau which is responsible for management of catchment forests under the PD No. 705 (The Revised Forest Code of the Philippines of 1975)

Table II Classification and usage of inland water bodies (DENR Administrative Order No. 34, Series of 1990)

For inland water bodies		
Classification	Number of classified inland water bodies	Usage
AA: public water supply	5	Waters that require disinfection to meet the National Standards for Drinking Water (NSDW)
A: public water supply	234	Waters that require complete treatment to meet the NSDW
B: recreational water	197	Waters for primary contact recreation (e.g. bathing, swimming, skin diving, etc.)
C	333	Water for fishery production; Recreational Water Class II[a]; Industrial Water Supply Class I[b]
D	27	For agriculture, irrigation, livestock watering; Industrial Water Supply Class II[c]

[a]Recreational Water Class II (used for boating and tourism purposes).
[b]Industrial Water Supply Class I (used for manufacturing processes after treatment and water supply for industrial sectors).
[c]Industrial Water Supply Class II (used for cooling of industrial machinery after manufacturing processes).

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(Makil 1984; Rola *et al.* 2004). Problems also exist in the crucial activity of monitoring water quality, where there is little coordination of activities or uniformity of methodologies and standards among agencies, despite enactment of DAO 34, and frequent calls for the contrary (DENR-EMB 2014).

Improving the long-term prospects of aquaculture in the Philippines requires an integrative approach to management, extending beyond the fish pond to include broader considerations concerning social inequalities, access to resources and environmental quality (Costa-Pierce 2010; FAO 2010) and avoiding degradation of ecosystem function and services beyond their resilience. At the local level, attempts have been made to incorporate the fundamental principles of ecologically more sustainable forms of aquaculture in the management plans of bodies such as the LLDA. One limiting factor, however, has been a dearth of relevant scientific data (Santos-Borja and Nepomuceno 2006). Despite scientific advancements in recent decades, limnological research and understanding in the Philippines remains relatively poorly funded and developed, and has primarily focused on increasing levels of aquatic productivity (Papa and Mamaril 2011), with a much smaller number of studies examining the socio-economics of fish farming (e.g. Krause *et al.* 2015). By comparison, relatively little research has been carried out on variations in water quality over time, and the levels of aquaculture and other activities that a water body might be able to support without long-term damage to ecosystem status and functioning. Moreover, because of a shortage of long time-series of monitoring data, little is known regarding the extent to which aquatic conditions may have been modified by recent human activity. By providing information that enhances ecological understanding, research on long-term variations in (and drivers of) water quality can support decisionmaking and facilitate a more ecologically sustainable approach to lake management (Sayer *et al.* 2012; Spruijt *et al.* 2014).

Palaeolimnological and limnological research on Lake Mohicap

Lake sediments often comprise datable accumulations of material that can be used as indicators, or proxies, of past environmental conditions in the lake and surrounding area. Palaeolimnology is the scientific study of lake sediments and associated sources of information: where long, complete time-series datasets are rare, palaeolimnology has been useful as a source of information on decadal-scale ecosystem variation and on the extent of anthropogenic impact (Scheffer and Carpenter 2003; Parr *et al.* 2003; Leira *et al.* 2006; Bennion *et al.* 2011). Evidence derived from palaeolimnological techniques has been used to extend or to close gaps in monitoring records (Smol 2008; Battarbee *et al.* 2012), and has the potential to address key questions relating to biodiversity, conservation and ecosystem restoration (Seddon *et al.* 2014). Lake sediments also preserve the isotopic (or radiometric) basis for establishing absolute ages for, or dates of, the reconstructed environments and for establishing past rates of change (e.g. ^{14}C and ^{210}Pb) (Dalton *et al.* 2009). The following section provides a brief example of the use of palaeolimnology, in combination with more conventional limnological studies, aimed at improving understanding of temporal variations in lake water quality in the Philippines over the period that includes the more intense exploitation of aquatic resources that characterises the last few decades. The section focuses on Lake Mohicap (Figure 5), one of the Seven Crater Lakes of San Pablo on the island of Luzon.

Figure 5 Lake Mohicap, one of the Seven Crater Lakes of San Pablo
Source: Photo by D. Taylor, May 2014

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Lake Mohicap (altitude ~99 m above sea level, surface area ~229 000 m^2, maximum depth ~30 m, lake number 23 on Table I and Figure 3) has supported aquaculture since the early 1970s. Tilapia is the main species of fish farmed in the lake. The lake is considered a CKBA. Eutrophication is, however, clearly evident – see Tables II and III, with a combination of waste from aquaculture and from huts belonging to fish farmers that fringe part of the lake the most likely sources of excess nutrient inputs. Along with measurements of water chemistry, limnological research has to date largely focused on zooplankton and phytoplankton distribution and community structure with a total of 86 taxa recorded in the lake (Papa *et al.* 2012; Cordero *et al.* 2014; Pascual *et al.* 2014). The presence of *Arctodiaptomus dorsalis* – an invasive calanoid species – and rotifers (including members of the genera *Brachionus, Filinia* and *Keratella*) suggest that the lake is currently in an enhanced productive state (Berzins and Pejler 1989; Papa *et al.* 2012).

In order to complement existing limnological data, a 95 cm long sediment core was collected from the deepest point in Lake Mohicap using an UWITEC gravity corer. The core was sectioned in the field and sediment samples placed in labelled zip-lock bags and refrigerated in the dark for subsequent laboratory analysis. Laboratory analysis focused on determining the time period covered by the sediment core and on using sedimentary evidence to reconstruct past variations in water quality. A common exploratory approach to palaeolimnological studies was adopted, involving the investigation of sediment-based water quality proxies in core bottom, middle and top samples, to determine the nature of variations over the period of time recorded by the sediments (Smol 2008).

The time period covered by the sediment core was estimated from a single radiocarbon (^{14}C) date obtained on plant macrofossils from a depth of 94–95 cm using accelerated mass spectrometry (AMS). Radiocarbon analysis gave a date of 260 ± 30 years (Beta Analytic, US, Laboratory Reference number = 379190), which when calibrated using Calib 7.1 and the IntCal13 calibration curve, yielded a median date of 1645 years AD. The sediments in this core therefore were deposited over the last c. 370 years. Isotopes with a shorter half-life than ^{14}C (^{210}Pb, ^{137}Cs, ^{241}Am) were used to establish the rate of sedimentation in the upper-most part of the core. Thus the sample depths of 41.5 cm, 29.5 cm and 11.5 cm were dated at, respectively, c. 1946, c. 1976 and c. 2007. This suggests both a high rate of sedimentation overall and an acceleration in sediment accumulation over the last 60–70 years, with both characteristics presumably linked to catchment disturbance leading to sediment inwash and increased productivity of the lake itself.

Given that the age of the sediment core from Mohicap spans approximately the last 370 years, we were able to test the hypothesis that recent changes in trophic status of the lake have occurred, and that changes in trophic status can be inferred from a number of different sediment-based proxies and linked to particular potential drivers of variations in water quality. Loss on ignition (LOI), a proxy for total organic matter in lake sediments, was measured from 4 cm to 96 cm (Dean 1974). Percentage total organic carbon (%TOC), percentage total nitrogen (%TN) and ratios of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes were measured in three samples from the sediment core (Meyers and Teranes 2001). Diatom sample preparation followed standard procedures (Battarbee 2001), and abundances expressed as percentage relative to the total number of valves counted in each sample. Concentrations of algal chlorophyll and carotenoid pigments preserved in sediment samples were established using high performance liquid chromatography (McGowan 2013) and are generally assumed to represent production of different algal groups and, including zeaxanthin from cyanobacteria, important bloom-forming and potentially toxic taxa (Taranu *et al.* 2015). Chlorophyll a (Chl-*a*), which is produced by all algal groups, was used as an integrated metric for algal production (McGowan *et al.* 2012).

Palaeolimnological results, summarised in Figure 6, confirm the hypothesis that underpinned the preliminary palaeolimnological research at the lake. High relative abundances of *Aulacoseira granulata* towards the

Table III Summary of the physico-chemical variables data (with mean value and ranges) evaluated during the wet and dry season in Lake Mohicap, San Pablo City, Laguna, Philippines (Cordero *et al.* 2014)

Physico-chemical factors	Rainy season (Jun–Nov)	Cool dry season (Dec–Feb)	Hot dry season (Mar–May)
Rainfall[a] (mm)	417.55 (318.30–682.1)	81.1 (30–192.1)	75.23 (2–132.6)
Conductivity (us/cm)	471.52 (391.83–560.33)	469.79 (358.50–560.42)	458.83 (326.00–506.75)
pH	6.77 (5.72–7.55)	7.37 (7.12–7.57)	7.62 (7.22–7.93)
Temperature (°C)	28.3 (27.76–29.19)	26.84 (25.75–27.66)	28.64 (26.79–30.05)
Secchi disk transparency (m)	2.9 (2.04–4.11)	2.06 (1.51–3.96)	1.87 (1.38–2.42)
Dissolved oxygen (μg/l)	6.36(5.33–7.57)	4.59 (3.27–5.81)	6.39 (5.83–7.52)
Phosphates (mg/l)	1.53 (1.12–2.37)	0.97 (0.75–1.21)	1.33 (0.82–1.86)
Nitrates (mg/l)	10.1 (3.31–25.75)	3.6 (3.24–4.04)	16.08 (4.02–25.10)

[a]Rainfall data are from Climate and Agromet Data Section, Climatology and Agro Meteorology Division, PAGASA-DOST, Quezon City.

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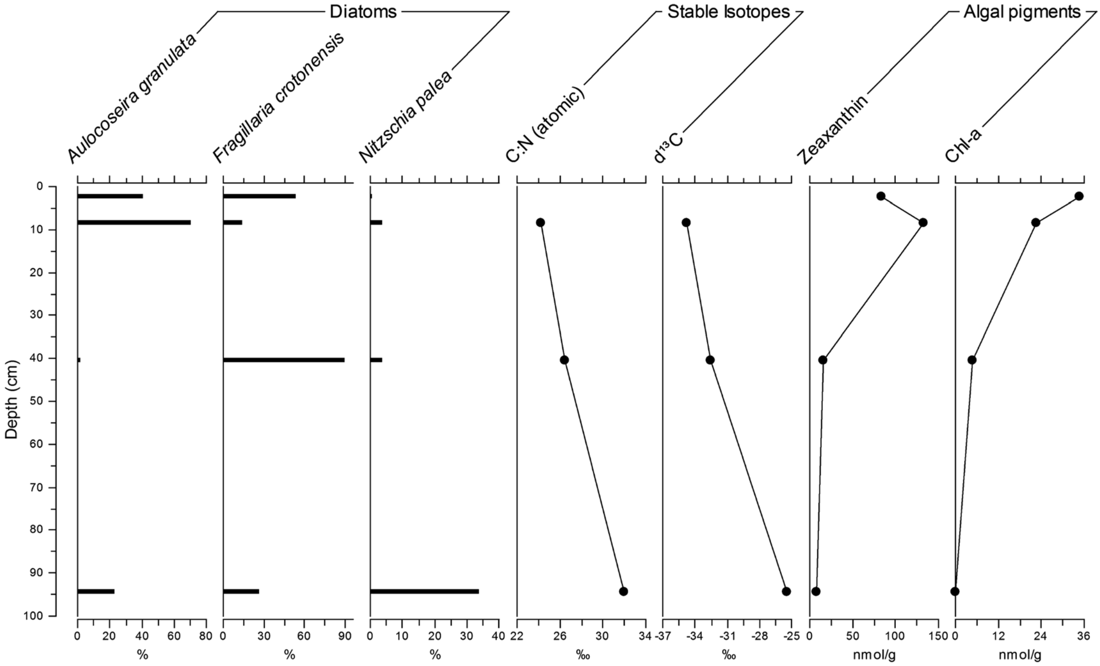

Figure 6 Multiproxy analyses of Lake Mohicap using diatom, stable isotopes, and algal pigments

top of the core suggest that the lake may have become hyper-eutrophic over the last c. 60–70 years (Alakananda *et al.* 2010). Nutrient enrichment during this time is confirmed by high concentrations of zeaxanthin and Chl-*a* pigment remains, indicating high algal production, especially from potentially bloom-forming cyanobacteria. Diatom analysis suggests that Lake Mohicap has been productive throughout the time period covered by the sediment record (i.e. the past c. 370 years). However, during the early part of the record, benthic habitats for diatoms disappeared, resulting in a flora dominated by only planktonic taxa. Nutrient enrichment, through its influence on enhanced productivity in the photic zone in particular and a resultant shading of deeper habitats, may have driven an increased prominence of planktonic over benthic diatom taxa.

The stable isotope (^{13}C and ^{15}N) data are intriguing. High C:N values throughout the core suggest that the catchment is a major source of carbon inputs to the lake, although the proportion of carbon from algal production shows a gradual increase (Araullo 2001; Meyers and Teranes 2001). Changes in land use therefore likely have an important impact on ecosystem function of Lake Mohicap. Without more data, we can only speculate as to the cause of declining $\delta^{13}C$ values between the bottom and top of the core. In warm, strongly stratified lakes, observed at Lake Mohicap, CO_2 exchange between the lake and the atmosphere is probably restricted and in-lake processing of organic carbon by bacteria and other heterotrophic organisms probably very intense (Boehrer and Schultze 2008). $\delta^{13}C$ values in the sediment core may therefore be largely controlled by microbial processing in the lake, but more work is needed to develop and test this idea (Torres *et al.* 2011).

Clearly, more research in Lake Mohicap and other sites of freshwater aquaculture in the Philippines and tropical Asia is required. That said, the preliminary data reported here suggest that Lake Mohicap has long been in a relatively productive state, possibly because of local (volcanic) geological conditions or due to a prolonged period of human inputs from the catchment. However, according to the sedimentary record, productivity has increased dramatically in recent decades, particularly following the introduction of caged fish-based aquaculture in the early 1970s. Thus a realistic pre-significant human impact baseline at Lake Mohicap would appear to be before c. 1970. Establishing in greater detail what those conditions entailed, and the influence of past water quality fluctuations of more broadly based processes, such as those occurring in the catchment (e.g. soil erosion) and farther afield (e.g. climate change), and/or of other in-lake changes in physical conditions (e.g. variations in the degree of water column mixing), ought to be a focus of further more detailed palaeolimnological and limnological research.

Conclusion

Freshwater aquaculture in tropical systems has brought economic benefits and increased food security to many

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communities. However, the practice is also associated with negative environmental impacts that could jeopardise future sustainability. This is particularly the case in the Philippines, where government policies and decrees have actively encouraged fish farming over the past four decades or so. A substantial proportion of lakes in the Philippines generally and the island of Luzon in particular now support aquaculture, with the lakeshores often inhabited by local communities. Many of these lakes provide important ecosystem services beyond the protein and income from farmed fish and most are suffering from excessive nutrient inputs despite a regulatory infrastructure being in place that aims to ensure environmentally relatively benign forms of management. Also, despite their significance (and importance as sentinels of environmental change processes and impacts), almost all lakes in the Philippines are understudied, especially when compared with lotic and marine ecosystems. To strengthen sustainability objectives in terms of economic development and wider ecosystems services provision, there is a clear need for policymakers to consider the use of scientific evaluations generated by long-term monitoring studies, or adequate replacements for or complements to these, and the application of novel techniques enabling the restoration of degraded ecosystems.

To achieve this, and being cognisant of the lack of long-term lake monitoring studies in the wider tropics, palaeolimnology is proposed as a promising tool in both applied and systematic sciences to augment existing knowledge. For example, the application of palaeolimnological techniques in the Lake Mohicap pilot study in this review has been very useful in determining its baseline condition and the extent of change in the past 370 years. In 2014 Lake Mohicap, along with the other Seven Crater Lakes of San Pablo, was regarded as threatened; the pilot study described here confirmed the lake to have been long enriched with nutrients but also suggested further increased pressure from nutrient enrichment in recent decades, leading to the current hyper-eutrophic conditions. With such diagnoses here and across the tropics where freshwater aquaculture is practiced or planned, additional work brings a little closer the creation of sustainable and efficient environmental policies and implementation of appropriate, evidence-based responses that together can prevent the further degradation of lake water quality. Moreover, the same approach has the potential to provide information on baseline (pre human impact conditions) that can underpin the restoration of already degraded habitats and the recovery of ecosystem services.

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