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ORIGINAL ARTICLE

Contemporary changes in open water surface area of Lake Inle, Myanmar

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Abstract From 1935 to 2000, the net open water area of Inle Lake in Central Shan State, Myanmar decreased from 69.10 to 46.69 km^2, a loss of 32.4% during this 65-year period. Local beliefs are that losses in lake area have been even greater within the last 100–200 years. Various activities, including timber removal, shifting agriculture in the uplands by various ethnic groups, and unsustainable cultivation practices on the low- and mid-level hillslopes around the lake, have been blamed for both historical and ongoing sedimentation. We take issue with attributing loss of lake area to these activities, and propose instead that ongoing "in-lake" and "near-lake" agricultural practices are the main sources of contemporary sediment and loss of open water area. About 93% (i.e., 20.84 km^2) of the recent loss in open water area of the lake is due to the development of floating garden agriculture, largely along the west side of the lake. Direct environmental impacts associated with this practice and with other agriculture activities within the wetlands and margins of the lake include sedimentation, eutrophication, and pollution. Whilst the sustainability of hillslope agriculture and past forestry practices can indeed be questioned, a more urgent need is to address these "in-lake" and "near-lake" practices.

Keywords Sedimentation · Erosion · Floating gardens · Shifting cultivation · Deforestation · Tourism

Introduction

Inle Lake in the Southern Shan State of Myanmar (Fig. 1) has been the site of recent development projects conducted by the United Nations Development Programme (UNDP) and the Food and Agriculture Organization (FAO). A common goal of these projects is to improve quality of life for local inhabitants, in part by implementing sustainable environmental and land management practices in the contributing catchment of Inle Lake. Nevertheless, some of these recent investigations and interests appear to be associated with the increasing tourism in the area. Several FAO/UNDP reports and overview studies note the dramatic infilling of the lake with sediment, a process that threatens the lake ecosystem, as well as the local economy (e.g., Volk et al. 1996; Su and Jassby 2000). For example, populations of Inle carp (*Cyprinus carpio intha*) are believed to be declining due to decreased water clarity levels associated with suspended sediment and eutrophication (Su and Jassby 2000).

The length of the lake has reportedly declined from roughly 58 km to 18 km and its maximum width has decreased from 13 km to 6.5 km during the past 100–200 years, although the earlier dimensions are believed

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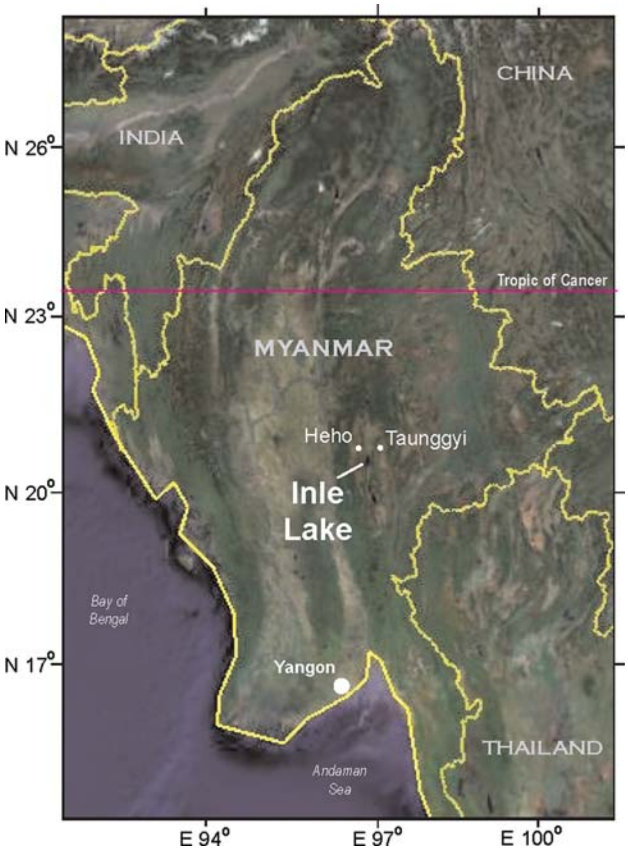

Fig. 1 Map of the region showing the general location of Inle Lake, Southern Shan State, Myanmar

to be overestimates (Ngwe Sint and Catalan 2000). Nevertheless, it has been noted that the true lake area is difficult to assess because the limnetic region gradually blends with the littoral zone and eventually swamps and wetlands, and the annual lake level may fluctuate by as much as 3 m between wet and dry seasons (Su and Jassby 2000). Reductions are often reported for wetland areas occurring at the northern periphery of the lake and for particular sections along the east and west sides of the lake (Fig. 2). Because methods used to compute these changes have not been documented to our knowledge, it is not clear what criteria have been used for delineating spatial changes in lake extent. Dimensions of the lake prior to 1935 and land cover pre-dating the recent FAO investigation (ca. 1996) both seem to be speculative. Also speculative is the role of the land cover/land use contributing to sedimentation, both historically and at present. Nevertheless, the current perception is that land-use and land-cover changes have accelerated, and are continuing to accelerate, sediment transport into the lake (e.g., Su and Jassby 2000). Another perception is that ‘deforestation’ and ‘shifting cultivation’ in the mountains around the lake have contributed significantly to the sedimentation problem (e.g., Marshall 1999; Ngwe Sint and Catalan 2000; Su and Jassby 2000); however, no studies have identified such sediment linkages, nor have these land use terms been consistently used in reports from the region.

The purpose of this paper is to verify the changes in lake surface area and dimensions for the contemporary period, describe various observed processes contributing to present day sedimentation, and discuss issues related to the sustainable development of the landscape around the lake and within the lake. These latter discussions are supported by field observations obtained during several visits to the areas surrounding the lake, discussions with local and regional experts, and analysis of 2000 Landsat and 2004 1-m IKONOS imagery compared with 1935–1937 topographic maps of the region.

Inle Lake environment

Inle Lake lies about 420 km northeast of Yangon within Nyaung Shwe township in the southern Shan State of Myanmar (Fig. 1). The basin is within the Shan Plateau, about 50 km east of the tectonically active Saigang fault and faults along the Shan scarp (Vigny et al. 2003). The formation of the basin was presumably controlled by active faulting, with the lake oriented north–south and bounded on the east by the steep linear front of the Sinduang Range. Although bathymetric surveys have not been published for Inle Lake, the deepest parts are reported to vary between 4 and 6 m (Ngwe Sint and Catalan 2000); however, we found many parts of the mid-lake water body to be <4 m and much of the lake margin was much shallower. The main stream draining into the lake is the Nanlit Chuang, which flows from north to south with headwaters 16 km north of the inlet to the lake (Fig. 2). The elevation of the lake is 890 m a.s.l.; the Sindaung range to the east and the more extensive Letmaunggwe, Thandaung and Udaung ranges to the west of the lake rise to nearly 1,900 m. The foot of these mountains typically sets from 1 to several kilometers back from the lake. The relatively flat lands adjacent to the lake are cultivated, as are most of the lower foot slopes and wetlands along the lake margins. The drainage area and storage capacity of the lake have been estimated at 5,612 km^2 and 3.5×10^7 m^3, respectively, while annual inflow and water residence time are estimated as 1.1×10^8 m^3 $year^{-1}$ and 0.32 year (Volk et al. 1996; Ngwe Sint and Catalan 2000; Su and Jassby 2000). The outlet of the lake is the Nan Pilu at the south end, which flows through a 16-km long swamp south of the

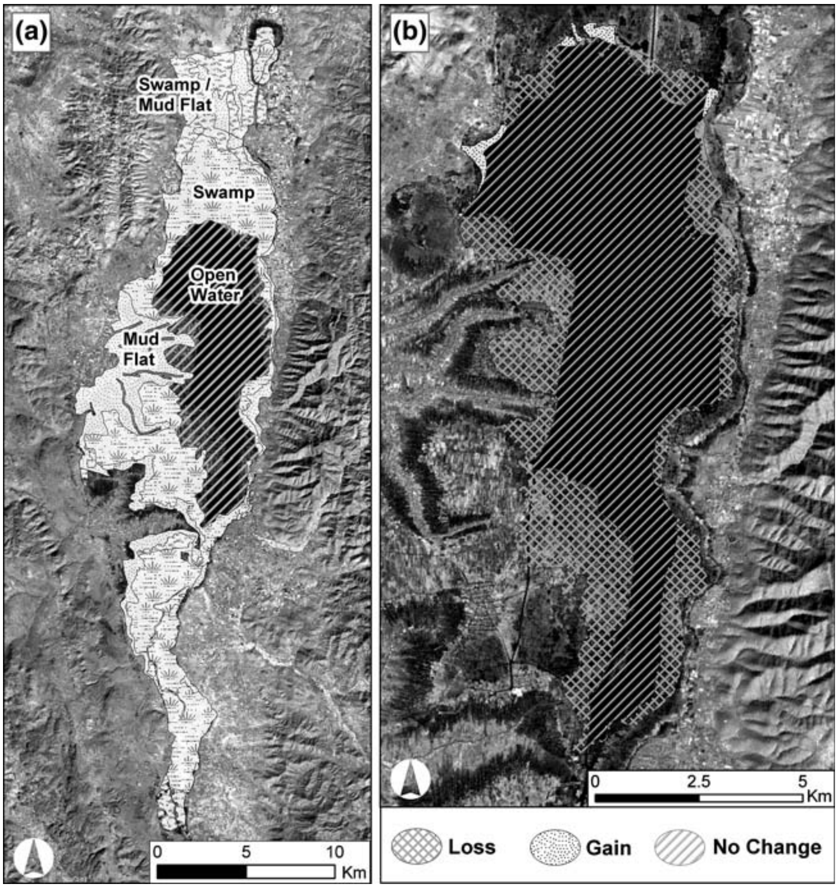

Fig. 2 **a** Open water, mud flats, swamp, and swamp/mud flat mixture land-cover categories identified on the 1:63,360, 1935/1937 'Inle Lake region of Burma' maps (Couchman 1937; Lewis 1938); the terrain in the background is 15 m resolution panchromatic band of a Landsat Enhanced Thematic Mapper + image acquired on 24 January 2000. **b** Estimated open water area change in Inle Lake between 1935/1936 and 2000

lake and then 10 km to the upstream end of a large reservoir behind Mobye Dam where the Lawpita hydroelectric power station was built in the 1960s. This power station provides most of the electricity used in Yangon (170–198 Mw), and supplies about 15% of Myanmar's electric power. However, the facility is in poor repair and low-water conditions, particularly in 1998, have made it an unreliable source and a cause of power failures in southern Myanmar.

Mean air temperature near the lake ranges from 16.9 to 31.5°C. Mean annual rainfall is 920 mm, generally occurring on 70–75 individual days (Fig. 3). The area experiences strong seasonal wet and dry periods; approximately 70% of the annual rainfall occurs during the months of July, August, and September. This monsoon season is when most of the soil erosion likely occurs.

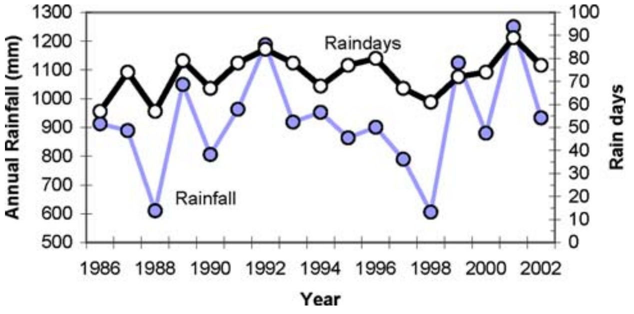

Fig. 3 Annual rainfall and rain day totals for a 17-year period at Inle Lake (data from Khaing Wah Wah Maw, Integrated Community Development Project, Inle Lake)

Soils on the lower hillslopes around the north part of the lake are rather thin and somewhat poorly structured. Typical soil profiles consist of a relatively thin A horizon (several to 10 cm deep) with an underlying clayey Bt horizon that grades into a B/C horizon of clay loam texture at a depth of about 40–45 cm (Table 1). Soils in this area have previously been described as Acrisols and red-brown soils (Volk et al. 1996; Su and Jassby 2000). On lower slopes, the underlying surface bedrock (≈50–60 cm deep) is largely limestone and calcareous sandstone and siltstone (Fig. 4a; Su and Jassby 2000). At higher elevations, bedrock is low-grade metamorphosed sandstone with quartz veins. Bedrock on the east side of the lake strikes slightly northeast and dips westward at 10–15°. Some localized peaks of resistant, coarse-grained metamorphosed sandstone are scattered throughout the lower floodplain and on hills adjoining the major tributaries entering the lake from the west along with outcrops of

Table 1 Soil description for profile along the road to the Forestry Monestary above Maing Thauk. *OC* Organic carbon, *TN* total nitrogen

Horizon	A	Bt	B/C
Depth (cm)	0–8	8–42	42–55
pH (H_2O)	6.81	5.75	6.23
pH (KCl)	6.22	3.88	4.85
OC (g/100 g)	1.47	0.23	0.29
TN (g/100 g)	0.12	0.04	0.04
C/N	12.0	5.5	7.4
K [cmol(+)/kg]	0.479	0.516	0.796
Ca [cmol(+)/kg]	9.581	4.294	5.015
Mg [cmol(+)/kg]	0.693	0.449	0.263
Na [cmol(+)/kg]	1.856	1.807	2.953
CEC [cmol(+)/kg]	9.01	5.12	7.36
Sand (%)	47.4	36.3	42.6
Silt (%)	28.6	20.4	29.9
Clay (%)	24.0	43.3	27.6
Texture	Loam	Clay	Clay loam
Particle density (g/cc)	2.52	2.59	2.6
Bulk density (g/cc)	1.39	1.33	1.67
Organic matter	Fine roots	Max roots	Roots
Stone/rocks	Many	Pebbles/stones	Sandstone

limestone (Fig. 4a; Volk et al. 1996; Ngwe and Catalan 2000; Su and Jassby 2000).

The population in and around Inle Lake has been growing steadily over the past 25 years. In the 1,450 km^2 area constituting the wetlands and upland village tracts around the lake as well as villages in the lake itself, the total population estimate for 2005 was 143,793 (Asian Development Bank 2006); a large proportion (about 90%) of these households are considered rural. Inn Tar forms the largest cultural group (70%) followed by the Shan (15%), Pach (10%), and Myanmar (3%) ethnic groups. Half the total income in the township is derived from agricultural activities; the remaining income is generated from small-scale production/manufacturing, local business, trading, and fisheries (30, 10, 7, and 3%, respectively; Khaing Wah Wah Maw, Integrated Community Development Project, Inle Lake, personal communication, 2003). Tourism is not considered a separate category in these statistics; thus the recent surge in income from tourism is likely under-represented. Many sites on the lower hillslopes have been heavily cultivated (Fig. 4b). Reported agricultural land use in Nyaung Shwe township for 2003 was as follows: paddy fields 12,970 ha, potato 4,330 ha, groundnut 1,620 ha, sesame 400 ha, coffee 190 ha, sugar cane 130 ha, and tea plantations 4,240 ha (Khaing Wah Wah Maw, Integrated Community Development Project, Inle Lake, personal communication, 2003). More than 55,000 of the people in this region reside in 15 scattered villages built within Inle Lake, where their livelihood is supported largely by agricultural production from floating gardens (Fig. 4c) and, to a lesser extent, fishing (Ngwe Sint and Catalan 2000).

In the mid-1900s some of the upper mountain slopes surrounding the lake were cleared by indigenous people and crops such as potato, ginger, bean, and garlic were planted (Marshall 1999; Ngwe Sint and Catalan 2000; Su and Jassby 2000); however, it is not clear if the previous forest that occupied the hillslopes near the lake was merely scrub forest or if it contained large trees. Currently, there is no indication (e.g., large stumps, logging disturbances) that dense stands of large trees occupied these slopes. Some of these lands have remained cultivated, but others have since been abandoned. A rather extensive agricultural area is currently located about 13–15 km west of the lake at higher elevations (1,240–1,480 m). The widespread commercial logging in the region mentioned by others (e.g., Volk et al. 1996; Marshall 1999; Ngwe Sint and Catalan 2000) appeared not to have occurred near the lake.

Floating gardens were introduced in the early 1960s after the military government took power (Figs. 4c, 5c). Before that time, most agriculture was practiced in the wetlands around the lake and on the lower hillslopes. Floating gardens consist of large blocks of organic-rich soils of low bulk density (i.e., less than water) that are excavated from wetlands around the lake (Fig. 5c). Dense thickets of *kaing* grass grow in these swampy areas, allowing organic materials to accumulate. Blocks of these organic soils about 2 × 40 m are cut and transported into places along the lake margin where they are staked by bamboo poles (Su and Jassby 2000). The organic blocks are typically ≤1 m deep, with the upper surface extending 10–20 cm above the water. Major crops grown in floating gardens include tomatoes, potatoes, beans, garlic, and flowers. The floating gardens are now popular tourist attractions. To maintain the productivity of the gardens, pesticides, fertilizer and fungicides are applied; given the hydroponic nature of the cultivation these chemicals easily find their way into the lake (Myo Myint 2000). A common practice is to 'transport' the floating gardens to the perimeter of the lake once their fertility is exhausted; normally this is about a 3-year period (Fig. 4d). Thus, this practice contributes to the apparent disappearance of the lake surface.

Contemporary change in lake dimensions

Two adjacent 1:63,360 topographic maps covering the 'Inle Lake region of Burma' were scanned at 300 dpi.

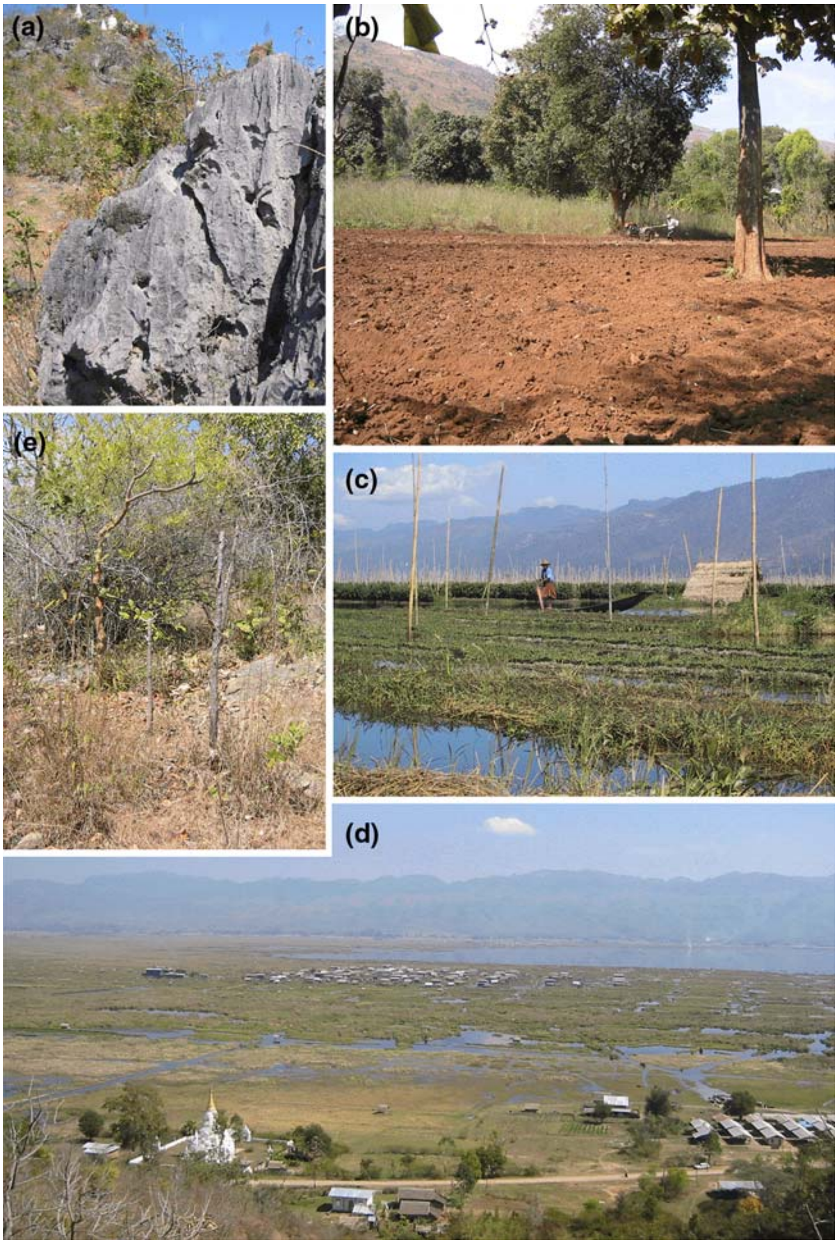

Fig. 4 **a** Exposed outcrops of coarse-grained metamorphosed sandstone and limestone in the hills on the west side of the lake; **b** cultivated fields in the foothills near the west side of the lake; **c** actively managed floating gardens; **d** dense concentrations of floating gardens converted from wetlands and also abandoned floating gardens along the west side of the lake (note the village amongst the floating gardens); and **e** typical scrub forest cover in the low hills around the lake; some minor erosion evident but no extensive rills or gullies

The maps, identified as nos. 93D/14 and 93D/15 of the Southern Shan States, were surveyed in 1935–1937 (Couchman 1937; Lewis 1938). The maps clearly show open water margins around the lake, swamps, and mudflats. The boundaries of lake surface water and wetland features were digitized using ERDAS Imagine software and converted from geographic coordinates (decimal degrees) to the universal transverse mercator (UTM) coordinate system and World Geodetic System 1984 (WGS84) datum (in units of meters). Four surface types were identified on the topographic maps: open water, mud flats, swamp, and a swamp/mud flat mixture. The digitized features from both maps were appended to produce a single hydrographic layer of Inle Lake for the 1935–1937 period. The 1935/1937 maps predate floating garden aquaculture.

A Landsat 7 enhanced thematic mapper plus (ETM+) image, acquired on 24 January 2000, was imported into the Imagine image processing software. The image was georeferenced to a UTM coordinate system and WGS84 datum. The open water boundaries of the lake are digitized from the imagery. The open water/lakeshore and open water/floating garden boundaries were distinct in the imagery, with open water pixels substantially darker than the surrounding areas, indicating a relatively deepwater body compared to the shoreline areas. To assess recent change in open water, the 1935/1937 open water polygons were inter-

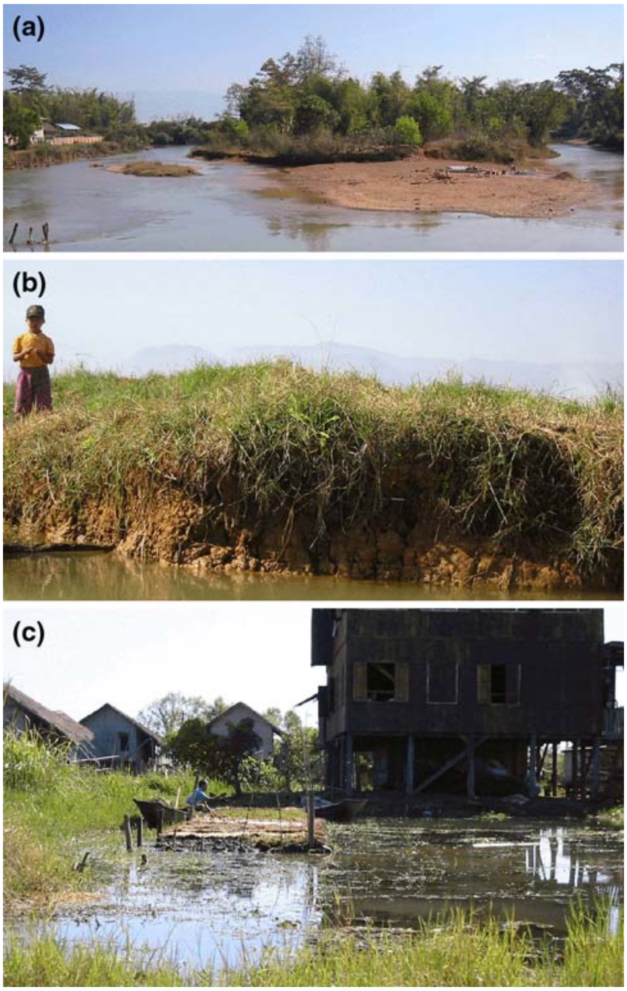

Fig. 5 **a** Sediment and channel conditions in a major tributary discharging into the birdfoot delta along the west side of Inle Lake; note the growth of vegetation on the largest sediment bar indicating that sedimentation has not been extreme in recent years; **b** bank erosion along a channel cut through the wetlands by the lake; and **c** active erosion from a newly prepared floating garden by a village on the lake

sected with the year 2000 open water polygons derived from the 2000 ETM + image. The resulting intersected layer was quantified into loss, gain, and no change categories of open water (Fig. 2).

Based on the 1935/1937 maps, Inle Lake was composed of approximately 69.10 km^2 of open water, not including river channels (Fig. 2a). By 2000, this area had decreased substantially to approximately 45.77 km^2 (Fig. 2b). This equates to a loss of 23.33 km^2 of open water over the 65-year period, a reduction of about 34%. If several small islands visible on the satellite imagery but not on the maps are included (assuming these were present but not shown on the 1935/1937 maps), the loss is slightly reduced to 23.30 km^2. In contrast to the loss in total open water area, the lake has gained 0.89 km^2 in northern locations once reported to be occupied by swamp/mud flats (Fig. 2b); this difference may be attributed partly to water level differences between the earlier surveys (1935/1937) and 2000 Landsat imagery; however, we have no records of the lake water levels during the earlier surveys. Thus, the net open water loss since 1935/1937 is assumed to be 22.41 km^2, or 32.4%, during this 65-year period.

The comparison of lake features based on the 1935/1937 topographic maps versus the 2000 Landsat Enhanced Thematic Mapper + imagery shows that about 93% of the 22.41 km^2 ''loss'' of open water in the 65-year period was attributed to new floating gardens and the transport of depleted floating gardens to the lake margins. These estimates were supported by examination of the detailed 1-m IKONOS imagery acquired in February 2004 (Fig. 6c). Most of the activity associated with floating gardens has occurred since the mid-1960s. For example, the major open water losses around the large birdfoot delta along the western flank of the lake (Fig. 2) are attributed to the recent occupation of thriving or abandoned floating gardens as confirmed on recent 1-m IKONOS and Google Earth imagery (Fig. 6). Thus, much of the apparent disappearance of the lake surface seems to be directly associated with the management of floating gardens, including conversion of adjacent swamp and mudflat areas to floating gardens (Figs. 2, 4d).

Forest conversion and shifting cultivation

Of the prior investigations and reports of factors contributing to the loss of Inle Lake, most have speculated that forest conversion, logging, and shifting cultivation are the primary sources of increased sediment loads and sedimentation in the lake (e.g., Volk et al. 1996; Marshall 1999; Ngwe Sint and Catalan 2000; Su and Jassby 2000). We take issue with those reports, which do not clearly articulate the terms 'deforestation' and 'shifting cultivation'. Herein, we use the more descriptive term 'forest conversion' to denote the permanent removal of forest cover with subsequent replacement by agriculture or grassland. So-called 'degraded' forest conditions, where larger trees were removed and current regrowth consists of scrub forest, is not considered conversion, because much of the inherent rooting strength within the soil mantle is retained and the scrub forest has the potential to evolve with time (Sidle et al. 2006). Shifting cultivation is defined as the clearing of forest patches in the dry season, subsequent burning prior to the rainy period to

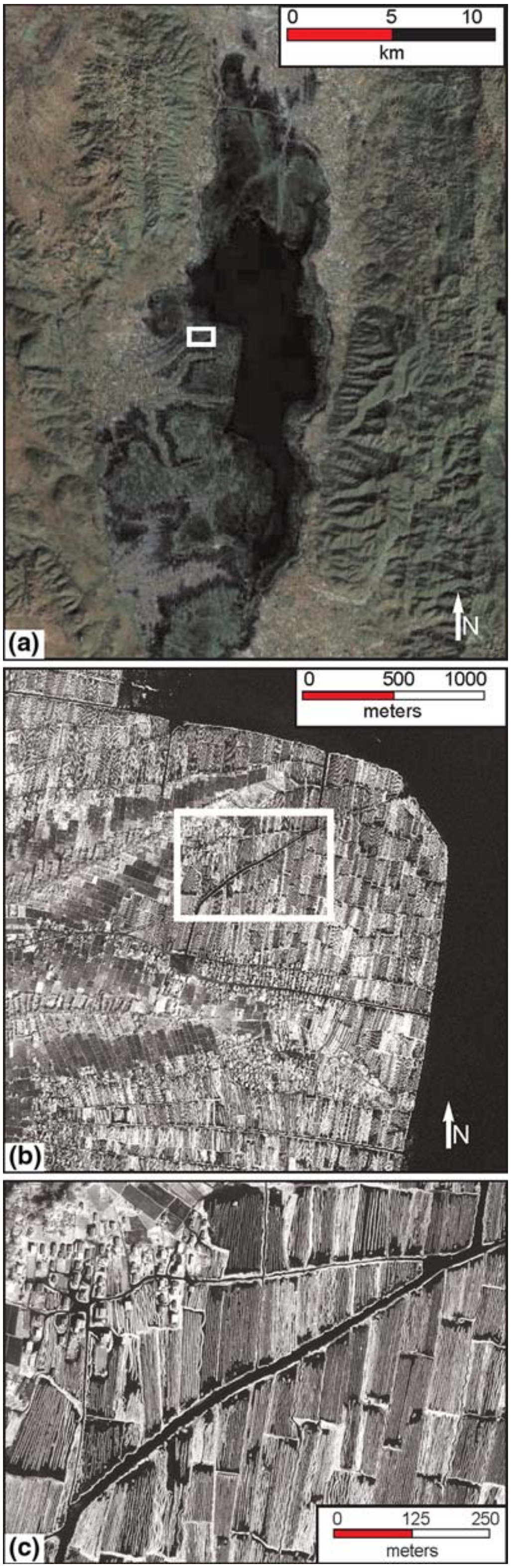

Fig. 6 **a** Inle Lake and surrounding topography (from Google Earth, 58 km altitude); **b** floating garden agriculture area indicated in *white box* in **a**; **c** close-up image of floating gardens shown in **b** (from 1-m IKONOS imagery acquired February 2004)

release nutrients, cultivation of the cleared patch for a period of years, fallowing, and allowing secondary regrowth through various stages of succession (e.g., Spencer 1966; Schmidt-Vogt 1998). Most of these land use conditions are depicted in the general FAO land use map of Nyaung Shwe township (Fig. 7).

Sediment sources and potential contributions to Inle Lake

Widespread gullying in drainages south of the road to Heho has been speculated to be a major source of sediments into Inle Lake (Volk et al. 1996; Marshall 1999); the aforementioned agricultural areas at higher elevations 13–15 km west of the lake and about 18 km southwest of Heho may also contribute sediment. Burning associated with shifting cultivation and grazing have also been implicated as causes of widespread erosion (both sheet erosion and gullies) that contribute sediment to the lake. Nevertheless, no studies have attempted to detail the hydrogeomorphic linkages of these various sediment sources with direct contributions to the lake. Herein, we comment on these hydrogeomorphic processes based on field observations during excursions from 2001 to 2003 as well as analysis of remote images.

On the middle to lower hillslopes along both the northeast and northwest sides of the lake, areas with sparse vegetation cover occasionally exhibited evidence of extensive surface erosion. Widespread rock cover on hillslopes, up to 25% in places, provides protection from raindrop impact (e.g., Poesen et al. 1994); however, the presence of soil pedestals at exposed sites indicate localized splash erosion (e.g., Sidle et al. 2004). Large rills and gullies that would attest to significant sediment transport from these hillslopes were, however, rare. Thus, extensive connectivity between erosion sources and the lake was not obvious.

On the less intensively managed lower slopes on the northeastern side of the lake, there is no evidence (e.g., large stumps, evidence of logging disturbance) of prior harvesting of large trees. Instead, these dry hillslopes and soils appear well adapted to the existing scrub forest vegetation (Figs. 4e, 7). While the lower slopes along the northwest side of the lake have experienced a greater degree of conversion to agriculture, these dry sites do not appear to have been heavily impacted in the past 65 years by commercial harvesting of large trees. Most of the commercial logging appeared to take place in the wetter and more productive forests located

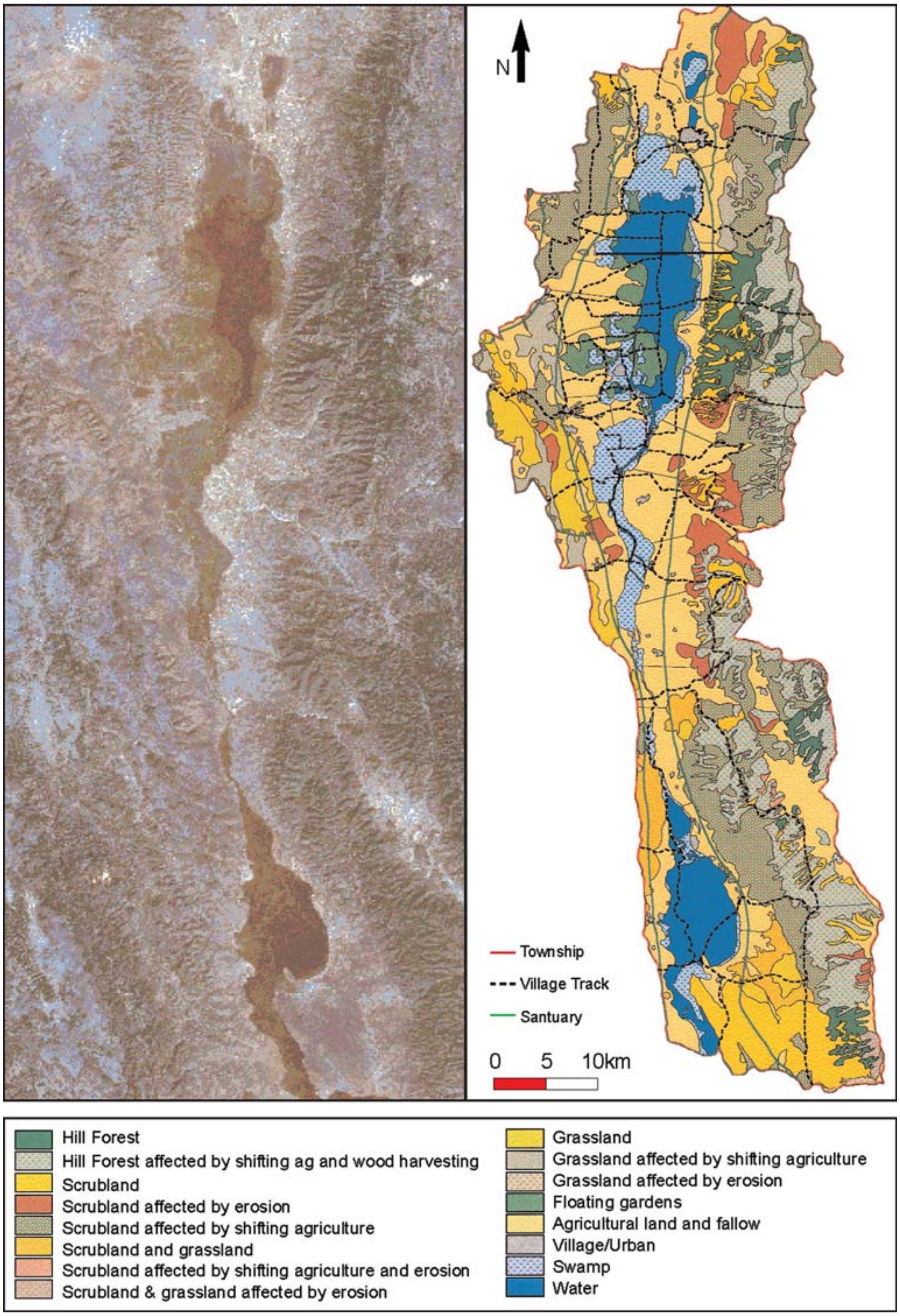

Fig. 7 **a** Natural color Landsat enhanced thematic mapper plus (ETM +) imagery (2000) of the Inle Lake basin; **b** land-use map of Nyaung Shwe township prepared in conjunction with a recent FAO project at Inle Lake (ca. 1996; from Khaing Wah Wah Maw, Integrated Community Development Project, Inle Lake)

at higher elevations many kilometers away from the lake (Fig. 7). Undoubtedly, these earlier disturbances (largely by elephant logging) contributed sediment to the lake via fluvial transport (Ngwe Sint and Catalan 2000). Based on local and anecdotal information, much vegetation conversion and logging may have occurred in the past 65 to >120 years, some of which was associated with shifting cultivation.

At higher elevations, farther removed from the northeast side of the lake, extensive grasslands exist, likely associated with shifting cultivation during an earlier period when this practice was predominant (Fig. 7). Erosion from these areas should follow drainages into the southeastern portion of the lake; however, this is not an area where significant reductions in open water have occurred.

Field inspection of the downstream reaches of several streams entering the lake showed no evidence of recent excessive sediment storage that would characterize systems that were receiving huge inputs of anthropogenically generated sediment—e.g., no large, active gravel/sediment bars or widespread braiding features were present (Fig. 5a; Lisle 1982; Xu 1991; Goswami et al. 1999). Based on comparison of recent satellite images with the 1935/1937 maps, the large birdfoot delta along the west margin of the lake formed due to sedimentation much earlier than 1935. The actual structure of the delta experienced little change during the period from 1935/1937 to 2000 (Fig. 2)—temporal changes (loss of open water) were attributed to occupation by abandoned or active floating gardens (Fig. 6b, c). As noted in studies of other fluvial systems (Brierley and Murn 1997; Knox 2001; Rommens et al. 2006), such downstream sediment effects may lag the original erosion sources by several years to many decades. Thus, some of the logging-related sediment may still reside in headwater channels. However, the absence of dramatic deposition in these downstream reaches suggests that the role of contemporary sediment contributions to losses in lake area have been overstated. Important sources of recent sediment appear to be streambank erosion and excavation and dredging of navigation channels through wetlands to access floating gardens and villages on the lake, but it is difficult to judge relative magnitudes of these contributions (Fig. 5b).

Estimates of sediment delivery to Inle Lake have been reported or summarized from other sources; these range widely from 0.65 million m^3 $year^{-1}$ (Su and Jassby 2000) to 0.8–4.3 million m^3 $year^{-1}$ (Volk et al. 1996) and appear very speculative. If we assume a contributing catchment area to the lake of 5,612 km^2 (Ngwe Sint and Catalan 2000), the average sediment yield is $\approx$1.5–1.8 Mg ha^{-1} $year^{-1}$ for the lower range of these values. Such rates of soil loss, albeit unsubstantiated, fall on the higher end of the spectrum for undisturbed and secondary tropical forests, but are much lower than rates reported for cultivated cropland and agroforestry in the tropics (Sidle et al. 2006).

We propose here that significant contemporary sediment contributions to Inle lake appear to be related to intensive cultivated agriculture in scattered, flat-lying areas near the lake; localized grazing and trampling of stream banks and streams; paths and roads around the lake; residential development; increasing tourism; and, very importantly, "in-lake" disturbances related to the creation of floating gardens. This latter practice of excavating densely rooted *kaing* vegetation together with its organic-rich soil contributes to lake sedimentation (Fig. 5c). Abundant floating gardens are located within and especially along the shallow west side of the lake (Figs. 4d, 6). Soil attached to the massive root systems is loosened and discharged directly into the lake during transport and maintenance (Fig. 5c). Additionally, the densely concentrated floating gardens near the perimeter of the lake may effectively trap incoming sediment, thus redistributing it along the margins of the lake (Fig. 4c, d). Villages constructed on stilts within the lake, which support the floating garden industry, contribute sediment and waste directly into the lake via animal and domestic wastes (Fig. 5c). The floating gardens are one of the main tourist attractions in the lake, and their expansion is apparently encouraged. Such 'in-lake' interactions have not been effectively evaluated relative to sustainable development alternatives.

Intensively cultivated lower hillslopes produce erosion, but sediment may be buffered by existing hedgerows before reaching the floodplain of the lake. Erosion from these hillslopes provides nutrient-laden soil to low-lying, relatively flat agricultural areas where it is extensively reworked on an annual basis. Active soil cultivation on lowlands, particularly the extensive wetlands immediately around the lake, appears to be an important source of sediment and nutrients to the lake. One of the most unsustainable agricultural practices in the region that contributes to soil erosion is land preparation through soil baking coupled with plowing up and down the hillside (Kashio 2000). In this practice, soil is first tilled to a fine powder by cattle traction, then scraped into mounds where a portion of the mound top is scooped out and replaced with cow dung and unconsumed biomass, after which the organic material is ignited and covered with soil. After burning several days the mounds are leveled and cultivated (Kashio 2000). Paths and roads used by residents and tourists are known to contribute to increased runoff and erosion (Sidle et al. 2006), but their extent is very limited in the near-lake area. Shifting cultivation within the lake catchment appears to be spatially limited and practiced at higher elevations far removed from the lake (Fig. 7). While soil erosion does occur in such dispersed sites, there is no strong geomorphic evidence that significant amounts of this eroded soil are being delivered to the streams and rivers discharging directly into Inle Lake. Residential and tourism development immediately around the northern part of the lake appear to produce more sediment due to the level of soil disturbance and their proximity to the lake.

Prior to 1976, land use interactions within the Inle Lake catchment were poorly documented. Evidence of recent large-scale vegetation clearing is not evident. Inspection of recent remote images and our field reconnaissance in 2000–2003 revealed limited areas of clearing on upper slopes >5 km from the lake. Grasslands and scrublands are abundant in many of the high hillslopes along the east and west sides of the lake (Fig. 7). Since many of these grassland settings are elsewhere forested, we suspect that former forest clearing occurred in these areas (although the type of pre-existing forest is uncertain, Fig. 7).

Grazing, which has existed within the catchment for more than a century, has contributed locally to soil erosion. We observed no current evidence of widespread grazing and associated erosion in the immediate vicinity of the lake. However, water buffalo and cattle could be seen trampling banks and congregating in streams near the lake margin, obviously contributing to sedimentation.

Other anthropogenic practices contributing to lake degradation

Other reported impacts on the general health of Inle Lake are largely associated with the floating garden industry and increased tourism (Su and Jassby 2000). These adverse effects include water pollution from fertilizer and pesticide application in and around the lake related to vegetable and flower production, raw sewage disposal, petroleum products, detergents, and waste products related to gold and silversmithing. The expanding aquaculture within Inle Lake itself contributes significantly to lake degradation via sedimentation and turbidity, eutrophication, and pollution (Myo Myint 2000). The large amount of aquatic vegetation growing on the lake bottom is testament to current eutrophication within Inle Lake.

Final remarks and recommendations

The apparent open surface water in Inle Lake has been reduced from 69.1 to 46.7 km^2, or about 22.4 km^2 since 1935 based on comparisons of 1935/1937 topographic maps and recent remote imagery. However, combined field inspection and analysis of detailed 1-m IKONOS imagery showed that most of this apparent loss is associated with establishment of new floating gardens and the relocation of abandoned floating gardens to the shores the lake. In our initial reconnaissance we failed to unequivocally identify the sources of sediment that have been speculated to cause the high levels of sedimentation and lake shrinkage that have occurred over the last 100–200 years. We found no contemporary geomorphic evidence of linkages of past episodes of severe erosion and delivery to the lake. Certainly further investigation is needed, including the development of a complete sediment budget that identifies all potential sediment sources and quantifies their linkage with the lake in time and space. Such studies should include the coring and dating of stable sediment sequences in the lake as well as dating of more contemporary sediment deposits, such as gravel bars and alluvial fans (using dendrochronology and other techniques).

Many investigations in different parts of the world have noted shrinkage of major lakes due to anthropogenic activities (e.g., Du et al. 2001; Yan et al. 2002; Penny and Kealhofer 2005; Legesse and Ayenew 2006). In some cases, sedimentation from land disturbances in the catchment are believed to be major causes of lake shrinkage (e.g., Yan et al. 2002; Penny and Kealhofer 2005), but in other cases littoral land reclamation (e.g., Du et al. 2001) and water abstractions upstream of the lake (e.g., for irrigation; Legesse and Ayenew 2006) are considered to have major impacts. We have not been able to assess the effects of changes in water abstractions upstream of Inle Lake, and we know of no other lakes that can be compared that have the unique interactions with floating gardens observed here. While ‘deforestation’ and shifting cultivation are mentioned as causes of sedimentation by, e.g., Penny and Kealhofer 2005 and Legesse and Ayenew 2006, similar to speculations at Inle Lake, little concrete evidence is presented to substantiate their arguments. We found no evidence to support the widespread perception that the contemporary causes of the shrinkage of Inle Lake are due to recent forest harvesting/conversion and shifting cultivation.

Current recommendations proposed to reduce erosion and sediment inputs should be implemented within the Inle Lake catchment, especially in lands adjoining the lake. These include planting buffers (tree rows, hedgerows, legume crops, and grass strips) along the contours of agricultural fields, composting wastes to mulch soil and replenish organic matter, and encouraging ownership of residents in the planning process to achieve more sustainable agricultural development (e.g., Marshall 1999; Kashio 2000). Promoting land management systems that increase surface runoff (i.e., water harvesting) in this dry region may exacerbate surface erosion and should be used with caution. In steeper sites, it may be necessary to implement measures such as reforestation to protect against mass wasting, although landslides were not a major concern in areas we visited. It appears that the benefits of these erosion control measures to the lake will be more significant if implemented near the lake. The problem of sedimentation associated with the construction and management of floating gardens deserves immediate attention if the open lake area is to be preserved. Depleted floating gardens should not be merely transported to lake margins, but incorporated into near-lake agricultural sites. With respect to ongoing eutrophication and pollution within the lake, it is important to immediately control inputs of chemicals and sediments from within-lake sources and adjacent wetlands, rather than focusing only on hillslope practices.

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