Human impacts and Anthropocene environmental change at Lake Kutubu, a Ramsar wetland in Papua New Guinea

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Edited by Torben C. Rick, Smithsonian Institution, Washington, DC, and accepted by Editorial Board Member Dolores R. Piperno June 12, 2021 (received for review February 1, 2021)

The impacts of human-induced environmental change that characterize the Anthropocene are not felt equally across the globe. In the tropics, the potential for the sudden collapse of ecosystems in response to multiple interacting pressures has been of increasing concern in ecological and conservation research. The tropical ecosystems of Papua New Guinea are areas of diverse rainforest flora and fauna, inhabited by human populations that are equally diverse, both culturally and linguistically. These people and the ecosystems they rely on are being put under increasing pressure from mineral resource extraction, population growth, land clearing, invasive species, and novel pollutants. This study details the last ∼90 y of impacts on ecosystem dynamics in one of the most biologically diverse, yet poorly understood, tropical wetland ecosystems of the region. The lake is listed as a Ramsar wetland of international importance, yet, since initial European contact in the 1930s and the opening of mineral resource extraction facilities in the 1990s, there has been a dramatic increase in deforestation and an influx of people to the area. Using multiproxy paleoenvironmental records from lake sediments, we show how these anthropogenic impacts have transformed Lake Kutubu. The recent collapse of algal communities represents an ecological tipping point that is likely to have ongoing repercussions for this important wetland's ecosystems. We argue that the incorporation of an adequate historical perspective into models for wetland management and conservation is critical in understanding how to mitigate the impacts of ecological catastrophes such as biodiversity loss.

Papua New Guinea | limnology | resource extraction

Wetlands provide a range of benefits to human, animal, and plant life and yet are under increasing threat from industrialization, expanding human populations, and climate change. In 1975, the Ramsar Convention was established to promote the sustainable use of wetlands and halt their decline worldwide (1). One of the commitments that parties to the convention make is to declare as early as possible any changes to the ecological character of Ramsar wetlands as a result of developments, pollution, or other human interference (2). This requires knowledge of the "natural" or "baseline" state of the wetland prior to major human interference (3, 4), as well as ongoing monitoring of the site. In some cases, major alterations to wetlands have occurred prior to Ramsar Convention listing, and so the baseline state is not known. Baseline information can be obtained from a multiproxy analysis of sediment core records that built up prior to the altering event (5). These sediment records can also be used as a cost-effective way to track changes in the ecological health of the site during and after such disturbances (3, 4). Here, we use the case study of Lake Kutubu, a Ramsar site in Papua New Guinea (PNG; Fig. 1), as a demonstration of this approach.

Paleoenvironmental ecological baselines have been successfully developed to define "limits of acceptable change" for Ramsar wetlands in several countries (e.g., refs. 5, 6). The feasibility, cost-effectiveness, and long-term assessment of these baselines allow for any country, independent of economic status, to assess the impacts of resource extraction, other human activities, and climate change on wetland areas. Baselines have the potential to function as ecological tools for environmental justice and to support local communities in tracking the state of their environment. They can also support the Ramsar Convention by providing evidence for ecological impacts and highlighting areas in need of better management.

The Ramsar Convention was adopted in PNG on 16 July 1993, and Lake Kutubu (Ramsar site no. 961) was declared a Ramsar site in 1998 (7), due primarily to its exceptional levels of fish endemism supported by food chains based on unique species of autochthonous primary producers (8). It was determined that significant degradation or loss of the lake would substantially

Significance

Wetland environments are increasingly threatened by climate change, population expansion, resource extraction, forest clearance, and pollution. The Ramsar Convention aims to monitor internationally important wetlands to ensure their ongoing maintenance and survival through wise use and management. However, many wetlands have undergone substantial human-induced changes prior to being listed with Ramsar. In the case of Lake Kutubu, a Ramsar wetland situated in the tropical rainforests of Papua New Guinea, paleoecological indicators preserved in lake sediments have been used to identify baseline conditions and to track anthropogenic impacts over time. This methodology can be applied to wetlands around the world to determine baseline environmental conditions and to track historic ecological changes in areas where constant monitoring has not been possible.

Author contributions: L.S. and S.G.H. designed research; K.E.L., L.S., S.E.C., N.S., J.F., and S.G.H. performed research; G.L.R., A.Z., T.G.E., and J.P.S. contributed new reagents/analytic tools; L.S., S.E.C., J.F., J.P.S., and S.G.H. analyzed data; and K.E.L., L.S., S.E.C., N.S., C.B., and S.G.H. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission. T.C.R. is a guest editor invited by the Editorial Board.

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This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2022216118/-/DCSupplemental.

Published September 27, 2021.

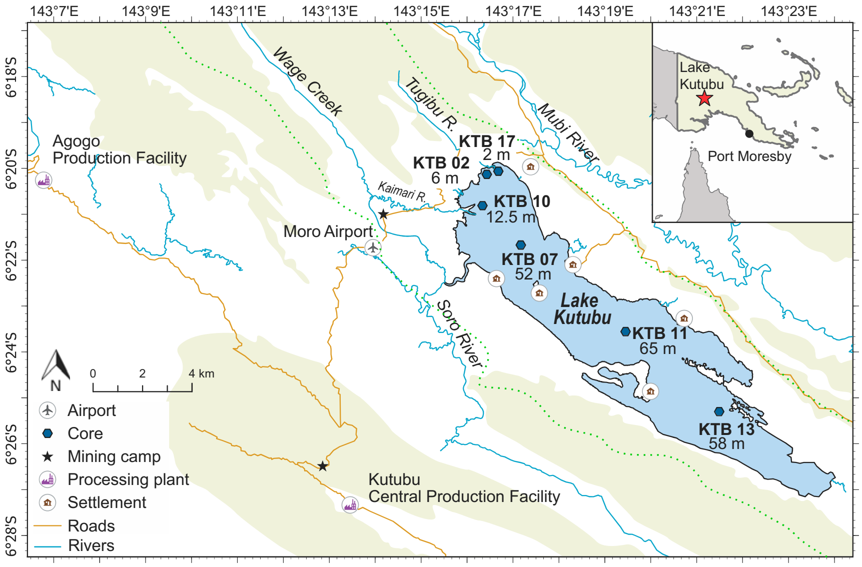

Fig. 1. Sediment cores, resource extraction infrastructure, and settlements at Lake Kutubu, PNG. The green dotted line is the catchment boundary. The shaded areas are 1,000 m contours after Bayly et al. (16). This map was created using ArcGIS software by Esri (http://www.esri.com) and contains information from Humanitarian OpenStreetMap Team Open Street Map (HOTOSM) PNG Waterways (https://data.amerigeoss.org/tl/dataset/hotosm_png_waterways) and PNG roads 2014 (https://png-data.sprep.org/dataset/png-roads/resource/2ea995e6-6483-42db-a71a-ad58f9fbb2de), which is made available under the Open Database License (https://opendatacommons.org/licenses/odbl/1-0/).

reduce the ecological diversity of the region (8). Yet, at the time of listing, the Lake Kutubu region had already been subject to altered scales of human disturbance with the establishment of European administrative bases in the 1930s (9), low-level development from the 1940s to 1970s, and then the much more significant impacts relating to the establishment of petroleum and natural gas projects from the 1980s (10, 11), followed by large-scale land clearance, construction, and immigration into the area (10, 12, 13). A baseline study of the lake's condition prior to these disturbances is needed to understand the scale of change and to provide a restoration target (14). Such targets are essential where ongoing development pressures and environmental governance issues can otherwise lead to long-term degradation of environments and livelihoods. We apply a paleoenvironmental multiproxy approach to assess the history of contamination, ecological impacts, and deforestation in sediments of Lake Kutubu. The identification of detrimental impacts in Lake Kutubu is crucial to provide guidance for the implementation of mitigation measures in tropical lakes under similar modern pollution pressures. This approach includes the analysis of fire and pollution indicators, aquatic algae, chlorophyll-a, and geochemistry in the lake sediments from before and after resource extraction activities commenced, providing a detailed profile of chemical and ecological changes. These data are compared to historic records and observations on the state of the lake prior to and since the start of resource extraction in the 1990s.

Site Description

Lake Kutubu (6°25.79′S, 143°20.22′E, altitude 808 m asl; Fig. 1) in the Southern Highlands Province of PNG has been recognized as one of the most pristine freshwater lakes in the Asia-Pacific region (10). Lake Kutubu is ∼19 km long and 4 km wide. The lake is fed by small creeks and subterranean rivers that flow through and within the surrounding limestone and karst ranges (15). The lake has an estimated area of about 50 km^2 and a volume of 1.825 km^3 (10). Approximately 20 km^2 of wetland reed-beds and swamp forest characterize the lake shore. The surface catchment area is about 260 km^2, covered mainly by tropical rainforest (10).

The lake is thought to have formed when the southeastern end of the valley was blocked by lava flow from Mount Azuma (16) sometime between the late Pliocene and Pleistocene epochs (17). The upland areas of the catchment are a dissected terrain of Darai Limestone (Upper Oligocene to Middle Miocene epoch) with minor interbedded mudstones and sandstones (17). The limestone surface is dominated by numerous sinkholes. The entire lake is flanked by karst landforms; it was the first subterranean karst wetland type to be added to the Ramsar Classification System by Resolution VI.5 (Ramsar site no. 961). Karst (cave) wetland systems are connected to underground rivers and act as recharge areas when the surrounding water table is low and as discharge areas when the water table is high. Activities related to petroleum extraction have affected water quality in Lake Kutubu via these subterranean aquifers (13, 18).

Lake Kutubu is an oligomictic lake that is usually thermally and chemically stratified. Mixing of the anoxic hypolimnion and epilimnion occurs irregularly. When mixing events do occur, they usually only affect one end of the lake and typically only after prolonged periods of cooler weather and stronger winds. These events are typically short lived and can cause fish death by asphyxiation (15).

Apart from these fish deaths that occur with natural mixing events, there have also been fish deaths linked to changes in the water quality. In 2007 there was a fish-kill event with no reported mixing event. Local residents reported that "…suspended material and a yellow chemical 'like sulfur'…" (19) entered the lake, and a range of adverse health effects (i.e., vomiting, skin and eye irritation, and a potential fatality) were linked to consumption of fish and water from the lake at the time (20). In 2013, a plume of suspended material was reported entering the lake from the northern inlets (Kaimari and Tugibu Rivers), coinciding with major drilling and pipe-laying work for the oil and gas project (13, 19). These anthropogenic activities may have caused a breakdown in stratification in the northern area of the lake and upwelling of anoxic water. The event was unusual as it occurred during warm, wet weather, lasted 6 mo, and coincided with an outbreak of epizootic ulcerative syndrome, a disease that had not previously occurred at Lake Kutubu, causing the death of large numbers of fish (13, 19).

Lake Kutubu and its catchment are the traditional lands of the Foi and Fasu people, confirmed by numerous archaeological sites, oral histories, and their continuing connections to the land (8). Population densities are very low, at about 23 persons per square km, and local subsistence and settlement practices and technologies have had only a very limited impact on the environment (21). Although the region was first reached by European explorers in 1911 (22), Lake Kutubu was not known to outsiders until it was seen during an aerial reconnaissance and then visited by government patrol in 1936 (23). A government station, established on the lake shore in 1937, was supplied by seaplane until it was abandoned in 1940; while this was an important base for initial exploration and colonial control of the surrounding region, the station's footprint never exceeded that of a traditional settlement in scale. The government reopened its Lake Kutubu station in 1949, enabling the first Christian missions to be set up in 1951. Under the influence of colonial control and the missions, the dispersed traditional settlements were amalgamated into larger villages, linked by footpaths (24). Geological surveys of the Kutubu area and the wider region intensified during the 1950s and 1960s, supplied by seaplanes landing on the lake. The first airstrip was completed in 1974 (25, 26). The 1970s also saw the introduction of schools and health posts, along with cash crops, small-scale cattle projects, and the first vehicular roads (though there was no external vehicle access). Ongoing geological exploration resulted in a program of test drilling immediately to the south of Lake Kutubu between 1983 and 1986, leading to the issuing of development licenses in 1990 to the Kutubu Petroleum Development Project (25). A brief but intensive construction program involving the expansion of airfields and the road network enabled commercial oil production to begin in 1992. Given the original dense forest in the region, significant deforestation is expected to have occurred, marking a dramatic transformation in the environment, peoples' social life, and local economies. The facilities, which lie just outside the Kutubu surface catchment, include the Kutubu Central Production Facility and Refinery southwest of the lake and the Agogo Production facility further north (Fig. 1). These facilities are each surrounded by around 50 wells (10). More recently, a further intensification of resource extraction has taken place, with the development of natural gas fields in the wider region by the PNG Liquified Natural Gas (PNG LNG) project, which began construction in 2009 and became operational in 2014.

By applying a paleoenvironmental multiproxy method to well-dated sediment cores from Lake Kutubu, we can determine the baseline state of the lake prior to these historic events. In doing so, we assess how recent changes have impacted the ecological state of the lake and the local communities whose health and prosperity are intertwined with the lake's ecology.

Results and Discussion

Age-Depth Model and Sedimentation Rate. Sediment core KTB17 from the northwest part of Lake Kutubu (Fig. 1) exhibited a decay profile of unsupported ^{210}Pb activities with depth and was successfully dated down to 50 cm. Sediment ages were calculated between 0 and 50 cm using the constant flux constant sedimentation (CFCS) dating model, giving a basal age of 1934. The age-depth model for core KTB17 is provided in *SI Appendix*, Dataset S1. The sedimentation flux rate of this core had a mean of 0.4 g cm^2 yr^{-1}, with no major sedimentary changes observed. Given this, erosion and fluvial inputs are unlikely to have overridden the historical signatures of resource extraction activities in this lake catchment. Age-depth models for the other sediment cores referred to here (e.g., KTB02, KTB07, KTB10, KTB11, and KTB13) can be found in previous publications (18, 27).

Geochemical Changes in Lake Sediment. Geochemical trends for Ba, Cd, Co, Cu, Fe, Ni, Pb, and Fe deposition fluxes (Fig. 2 and *SI Appendix*, Dataset S2) show these elements were quite stable prior to 1992. From this date, there is a clear temporal connection between the increase in Ba concentrations and other metals in cores KTB 02, 10, and 17 (Fig. 2) with the start of commercial drilling activities. Geochemical data for KTB02, KTB07, KTB10, KTB11, and KTB13 can be found in previous publications (18, 27).

It is important to note that no other major source of anthropogenic inputs of Ba to the lake is known apart from resource extraction activities. Ba sulfate is widely used in oil and gas drilling to prevent pressure blowouts, and additional geogenic Ba may be produced when processing chemicals react with bedrock (28). In the Lake Kutubu sediments, Ba is the element that best represents a geochemical signature from resource extraction activities (Fig. 2).

Maximum metal deposition fluxes in the lake sediments occurred in 2007 and 2014, corresponding to the occasions when the oil and gas companies were blamed for massive fish kills in Lake Kutubu after toxic chemicals allegedly entered the lake (Fig. 2 and *SI Appendix*, Table S1). Earlier overturning events and fish kills do not coincide with fluctuations in the sediment core geochemistry record, nor do regional droughts.

The increase in population living around Lake Kutubu and the general intensification of associated infrastructure is also expected to have contributed to the increase in metal deposition in the lake. The population living immediately around the lake was estimated at between 300 and 500 in 1936 (23). By the 1980s, on the eve of oilfield development, the Foi and Fasu communities of the wider Kutubu area still numbered only about 5,000 (29). In 2012, the workforce population for the new PNG LNG project added a further 21,220 people to the area (30). Along with this population increase, there has been a rise in traffic along the Kutubu access road and an increase in the use of motorized boats on the lake (10).

Ecological Changes. Paleoecological indicators, namely nonpollen palynomorphs (NPPs), from the sediment core point to a major shift in algal composition in Lake Kutubu in the early 1980s (Fig. 3). *Pediastrum* spp. were the dominant NPP in the sediments prior to c. 1980 but are not recorded more recently (*SI Appendix*, Dataset S3). *Pediastrum–Botryococcus* associations, observed at Lake Kutubu prior to c.1980, generally occur in relatively clear, oligotrophic waters. *Botryococcus* dominance in the absence of other coccal algae, recorded at Lake Kutubu after c. 1980, is frequently linked to changing water quality (31). Lake Kutubu has likely been affected by recent eutrophication. A potential source of this is livestock and habitations, with elevated concentrations of dung-inhabiting fungi in the more recent sediments (e.g., *Sporormiella*, *Sordaria*, and potentially *Potamomyces;* Fig. 3), and the increasing trend in chlorophyll-a, which includes its main diagenetic products (32, 33) (Fig. 3 and *SI Appendix*, Dataset S4), along with the geochemical indicators described above (Fig. 2). The c. 1980 shift in algal communities constitutes a critical transition in the lake's ecology (Kendall's tau: 0.62, *P*: 0.003).

Fire indicators (charcoal) show some burning in the lake catchment during the early to mid-20th century, followed by a major fire peak around 1994 (Fig. 3 and *SI Appendix*, Dataset S3). This fire peak immediately follows an abrupt increase in coprophilous fungal spores (Fig. 3), which suggests increasing human population numbers near the lake. This sequence of events around 1994 likely represents the use of fire for forest clearance during the establishment and expansion of resource extraction operations, agricultural plots, and human settlements rather than a single massive forest fire.

Diatom records from core KTB02 (34) indicate an increase in nutrient concentrations from the late 1970s that correspond

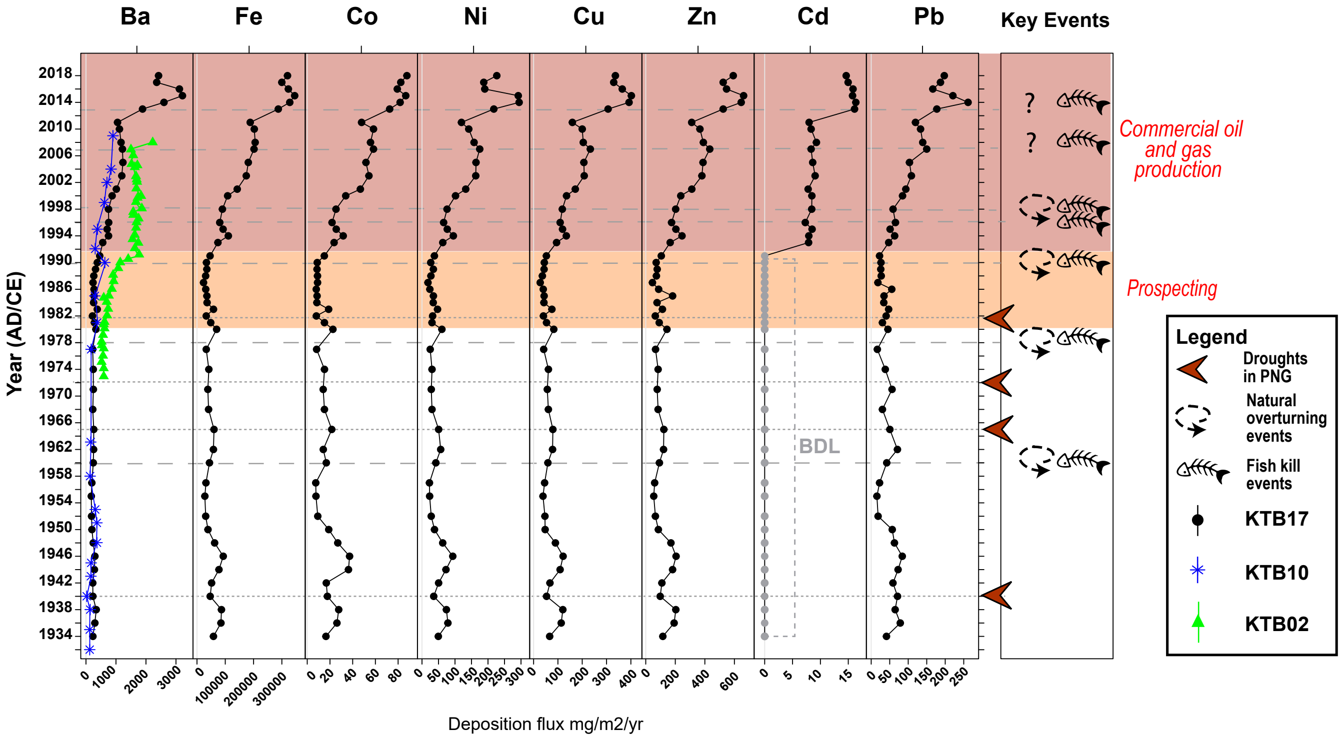

Fig. 2. Lake Kutubu metal (Ba, Fe, Co, Ni, Cu, Zn, Cd, and Pb) deposition fluxes (mg/m^2/yr). Ba deposition fluxes, the main element associated with resource extraction, are shown for cores KBT02, 10, and 17. BDL, below detection limits. Significant resource extraction and reported ecological events noted at the right of the diagram.

closely to the critical transition identified in NPP algal indicators (Fig. 3 and *SI Appendix*, Fig. S1 and Dataset S5). This suggests that the lake's ecosystem was already experiencing significant change prior to oilfield development in the early 1990s. The most significant shift in the diatom record occurs around 1990 when the abundance of epiphytic diatoms, such as *Gomophenema angustum* and *Staurosira construens*, decline and are replaced by planktonic diatoms such as *Cyclotella stelligera*. This shift is likely reflective of a loss of aquatic plant communities that were reported as abundant in the past but are now clearly absent or disappearing rapidly around the lake (Fig. 3).

Observations of charophyte (Characeae) presence along the lakeshore from the late 1980s to 2018 provide further evidence of changing lake conditions. Charophytes are carbonate-precipitating, macroscopic green algae that form an important floral element in the littoral zones of carbonate-rich freshwater lakes up to ∼12 m deep (35). At Lake Kutubu, Characeae beds are the main habitat for the endemic freshwater crayfish *Cherax papuanus* as well as major feeding, spawning, and nursery grounds for endemic fish (12). They likely also play a principal role in maintaining the high dissolved oxygen levels and water clarity of the epilimnion (13, 19). These algae were observed in abundance during field work in the late 1980s and described in detail in a baseline hydrological study (36) but by 2018 had all but disappeared. This observation was confirmed by local residents, who also reported the disappearance of the algae in recent years (13, 19).

There have also been changes in the turbidity of Lake Kutubu. Secchi disk depths recorded in 1988 and 1989 varied between 7.0 and 8.3 m (15), while a depth of 2.8 m was recorded in 2018 on the northwest side of the lake (6°21′17.00″S; 143°16′28.98″E) at a similar position as the previous study, indicating a decrease of about 5 m water transparency in 30 y. This decrease in transparency was observed across the whole lake and likely relates to increased algal or suspended sediment load. No change in color was evident.

Given that Lake Kutubu's Ramsar listing is based on its endemic fish species, which rely on food chains based on autochthonous algae, any change to the lake's algal communities could place the lake's ongoing Ramsar status in doubt. The loss of *Pediastrum* spp., along with increasing turbidity, the rapid decline of Characeae, and abrupt changes in diatom communities, suggests the lake's primary producers have undergone a rapid ecological reorganization in recent decades. Some of the more important changes in algal communities occurred prior to the site's Ramsar listing in 1998, which means that the baseline established at that time was that of a lake that had recently undergone a critical ecological transition and was already polluted by earlier oil exploration and development activities. Paleoecological research in other wetlands worldwide has likewise shown that Ramsar listing often came in the aftermath of major ecological changes (5). As a consequence, the ecological baselines linked to the time of listing do not represent pristine (or long-term natural baselines). It is critical to stabilize the lake's algal communities in order to preserve the globally significant endemic fish populations that rely upon them as a primary or secondary food source.

Changes in the fish fauna of Lake Kutubu have been reported over the last 30 y, and loss of algal primary producers are likely to have even greater effects on the fish community in the future. The lake is home to 22 species of fish, at least 12 of which are endemic to the lake itself (10). Most of these fish are listed on the International Union for Conservation of Nature Red List as being vulnerable or critically endangered. The pressure of increased population density, overfishing, and the introduction of invasive fish species and diseases have led to a reduction in the size and numbers of the endemic fish population (13, 19, 37–39). Carp (*Cyprinus carpio*) and tilapia (*Oreochromis niloticus*) are the two main invasive fish species that threaten the endemic fish populations. Carp were introduced to the waterways of the highlands in the 1950s (40), while tilapia were unintentionally released into Lake Kutubu sometime between 2010 and 2012 when heavy

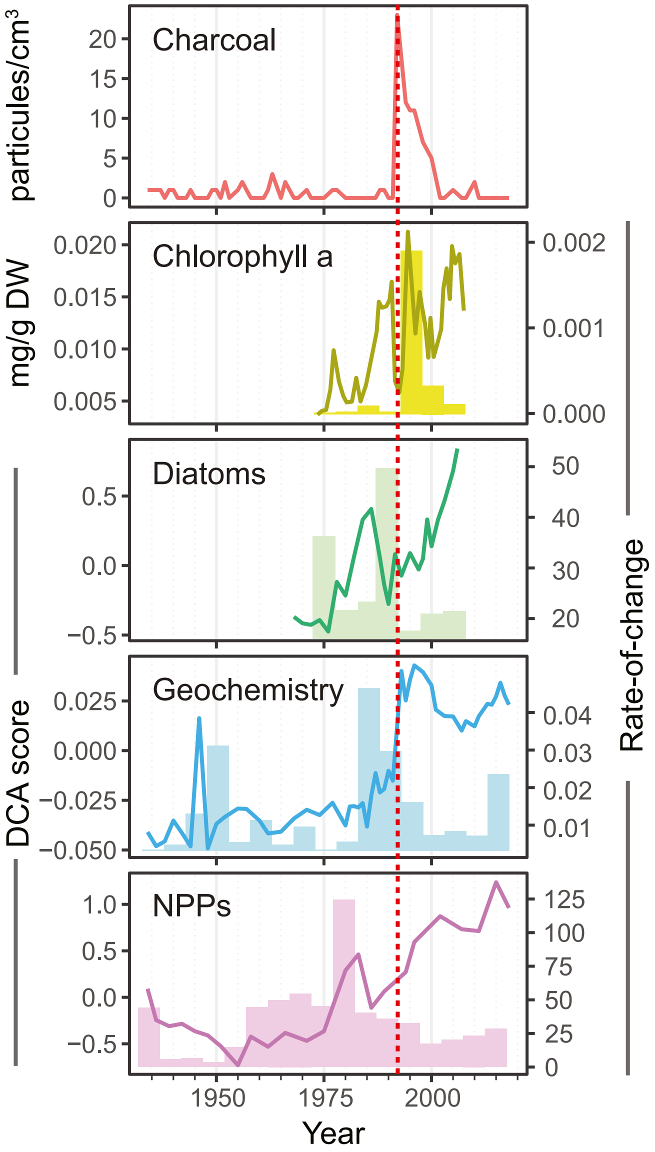

Fig. 3. Summary of recent changes in Lake Kutubu sediments. Results of the charcoal (250 μm) concentration, particles per cm^3 of sediment, for core KTB-17. Bar graphs represent rate-of-change analysis results for chlorophyll-a and diatoms from core KTB02 (34) and for geochemistry composition and algal and fungal NPPs from core KTB17. Solid line on chlorophyll-a represents milligrams per gram dry weight (mg/g DW). Solid lines on diatoms, geochemistry, and NPPs show the square-root transformed detrended correspondence analysis (DCA) score for each. The dashed red line indicates the beginning of commercial oil extraction (c. 1992).

rains flooded lakeshore aquaculture ponds. These invasive fish use the same areas as endemic fish for laying eggs (10), they increase water turbidity and destroy root vegetation, and their introduction to an area leads to a decline in native fish populations (12). In 2015, tilapia were estimated to make up 50% of the biomass of the lake (39, 41). Local residents have reported that at least three native fish species are regarded as extinct, and others are nearing a critical level (10).

Ongoing climate change is likely to exacerbate the situation at Lake Kutubu. Under global warming of ≥1.5 °C, areas of unique and threatened ecological systems of restricted geographic range with high endemism are at high to very high risk of severe impacts (42). There is also likely to be an increase in extreme rainfall events, which could lead to more complete mixing events and increased fish death at Lake Kutubu (42).

Setting Baselines for Ecological Restoration. Ongoing ecological monitoring and the development of wetland management plans are encouraged by the Ramsar Convention but remain difficult to achieve in many countries where significant economic expertise or logistical limitations exist. Our data demonstrate that even the best monitoring program would have been unable to detect the early warning signs of ecological change, which occurred prior to the lake's Ramsar listing. Comparison of the geochemical data and ecological indicators shows that the ecological indicators reacted earlier and more strongly to changes in water quality than might be inferred from the sediment geochemistry record. For instance, NPPs and diatoms showed a clear change in the 1980s, while geochemical changes in sediments are seen in the early 1990s. This suggests that even small alterations to water quality can cause dramatic ecological impacts at the level of primary producers, impacts that have flow-on effects at higher trophic levels of the food chain.

Article 3.2 of the Ramsar Convention requires countries to report on any change to wetland ecology due to development, pollution, or human interference (2). Paleoecological data can play an important role in determining whether observed changes are part of the expected dynamics of the wetland system or represent a departure from "normal" conditions (3, 6, 14). In the case of Lake Kutubu, it seems clear that there has been a recent departure from mid-20th century conditions and that this change coincides in time with the exploration and extraction of oil reserves in the catchment. Major increases in metal concentrations in the lake system have occurred over the past 5,000 y because of the deposition of nutrient-rich tephras (27). The recent increase in metal concentrations in KTB17, KTB02, and KTB10 have a different geochemical signature to the tephras, being highly enriched in Ba (*SI Appendix*, Fig. S2). While there are currently no guidelines on Ba emissions from oil and gas drilling, experiments have shown Ba to have acute ecotoxicological effects on tropical aquatic algae and crustaceans (28). The high levels of Ba input in recent decades constitute a novel pollutant to Lake Kutubu, and measures should be taken to prevent additional Ba entering the groundwater.

Multiproxy approaches to reconstructing past lake conditions are critical to revealing the full extent of ecological change in Ramsar wetlands. Our data demonstrate that a reliance on geochemical data alone would have underestimated the onset and ecological impact of recent human activity. Lake Kutubu's ecological communities began to change dramatically during the 1980s and show no sign of returning to their mid-20th century baselines. The lack of recovery is consistent with a loss of ecological resilience, and further adverse impacts might be expected if no management action is taken. More research is required to determine whether the recent critical transition in algal communities observed in Lake Kutubu is unprecedented over timescales of hundreds or thousands of years.

Baselines developed from paleoenvironmental indicators can provide much-needed data where regular monitoring is lacking, particularly prior to large-scale environmental impacts that follow the development of resource extraction projects. The economic cost of conducting post hoc paleoenvironmental research is negligible compared to the costs of regular monitoring, which are often prohibitive in developing economies. This method can be applied to other Ramsar sites to establish baselines for places that have already experienced significant anthropogenic impacts and have no independent pre-disturbance records. It can also be used to support local claims of changes to lakes, backing up local observations of water quality decline, species loss, or fish kills with scientific evidence. Such evidence has the potential to prevent environmental injustice and could lead to more equitable outcomes for local communities whose lands are host to economically important resource extraction projects. Ecological indicators (NPPs and diatoms) reacted to changes in the lake system in the 1980s, a decade earlier than geochemical indicators. While our approach does not replace ongoing ecological monitoring efforts at Ramsar sites, it does show that some indicators, like NPPs and diatoms, are more sensitive than others and are likely to provide early warning signals of ecological change. These indicators could be prioritized in circumstances in which a more comprehensive monitoring program would be impractical or uneconomical. Paleoecological approaches make the task of defining "limits of acceptable change" more achievable for Ramsar wetlands that currently lack such a baseline.

Materials and Methods

Sediment Collection. Sediments are archives of temporal ecological changes in lakes (43). Sediment cores (~1 m length) were collected from five sites (KTB02, 07, 10, 11, and 13) across Lake Kutubu using a Universal coring system with polycarbonate tubes (Aquatic Research Instruments) (Fig. 1). After retrieval, the cores were maintained in a vertical orientation and a plastic plunger used to extract sediment samples from the tube. Core sections were sliced every 1 cm using a stainless-steel spatula and ruler, and sediment sections were placed in labeled zip-lock plastic bags and transported to the Australian National University, where they were stored at 4 °C until analysis. These cores were previously analyzed to track major geochemical changes from resource extraction activities (44) and for the analyses of long-term reservoir effects and tephrochronology (27, 45).

In 2018, an additional 55 cm core, KTB17 (Fig. 1), was collected from sediments on the northwest side of the lake, in closer proximity to resource extraction activities (6°20′19.43″S, 143°16′36.62″E; Fig. 1). This core is the focus of this study because it provides a more detailed record of the impact of anthropogenic activities over the last 30 y.

In summary, cores KTB17, KTB02, and KTB10 were collected near two of the larger surface inflows at the western edge of the lake. KTB07 was collected at a water depth of ~50 m within 1 km of an inhabited island and ~3.5 km from the western margin of the lake. KTB11 and KTB13 were collected from the deepest parts of the lake (60 to 65 m water depth) ~8 km and 11.5 km, respectively, from the western margin of the lake.

^{210}Pb Dating and Chronology. All sediment cores were processed for ^{210}Pb dating at the Australian Nuclear Science and Technology Organisation. Chronologies for cores KTB02 and 10 have already been published (27, 44, 45). Core KTB17 was analyzed in 2020 by alpha particle spectrometry for the determination of polonium-210 (^{210}Po) and ^{226}Ra activities (46). The unsupported ^{210}Pb activity was calculated by subtracting the activity of ^{226}Ra from ^{210}Pb or ^{210}Po for each sample. Based on the calculated unsupported ^{210}Pb activities from each core, the CFCS model was used to determine sediment ages (47).

Geochemical Analyses. Sediment samples were analyzed for total Ba, Cd, Co, Cu, Fe, Ni, Pb, and Fe. This suite of elements was chosen based on a previous study, which found major changes with increasing anthropogenic activities (44). Geochemical analyses were performed on acid-digested and diluted (0.5 M HNO_3) samples using a 5110 synchronous vertical dual view inductively coupled plasma-optical emission spectrometer (Agilent Technologies) at the Research School of Earth Sciences ICP-MS Research Facility at the Australian National University. Details for the sediment acid digestion procedures are given in the *SI Appendix*. Typical analysis conditions are presented in *SI Appendix*, Table S2, while the utilized wavelengths for the analyses was assessed via the certified reference materials NIST- 2711a (Buffalo River sediment) and Climate Change Canada WQB-1 (Lake Ontario) (*SI Appendix*, Dataset S6).

Geochemical analyses for cores KTB02, 07, 10, 11, and 13 are published in (44).

NPP, Diatom, Chlorophyll-a, and Charcoal Analyses. Sediment samples of 2.5 mL were pretreated according to standard palynological techniques (48). These included spiking the sample with *Lycopodium* spores to calculate palynomorph concentrations, carbonate removal with 10% HCl, clay removal via settling and decantation, sieving through a 120 μm mesh to remove large particles, separation of minerogenic material with heavy liquid (specific gravity 2.0), acetolysis (9:1 mixture of $C_4H_6O_3$ to H_2SO_4), and dehydration in 100% ethanol. Residues were mounted in glycerol on glass slides. Because of poor recovery of pollen grains in the KTB17 sediments, only fungal and algal remains (NPPs) were identified at 400× magnification, using published guides (49–51).

Diatoms were prepared using a modified version of the technique outlined in Renberg (52), in which the oxidation (H_2O_2) step was repeated to destroy persistent organic matter. Diatoms were identified at 1,000× magnification, using a Zeiss Axioscope with differential interference contrast optics. Diatoms were identified with reference to a variety of sources, including refs. 53–56, and in particular the specialist PNG diatom morphology publications (57, 58). A minimum of 400 valves per sample were counted in each sample.

We inferred trends in sediment chlorophyll-a concentrations (which includes its isomers and main diagenetic products) using visible reflectance spectroscopy following the methods outlined in ref. 59 and based on updated calibrations by ref. 32. Chlorophyll-a inferred values track primary productivity in lakes, typically increasing with periods of eutrophication (32).

Charcoal particles are an indicator of fire occurrence, with macroscopic particles considered mainly indicative of catchment-scale fires and microscopic particles representing broader-scale burning patterns (60). Microscopic charcoal was quantified alongside NPPs by counting opaque black particles 10 to 120 μm in size. Contiguous macroscopic charcoal samples were sieved at two size fractions (125 to 250 and >250 μm) from a known volume of sediment and particles identified using a binocular microscope.

Aquatic Vegetation and Water Quality Assessments. Secchi disk measurements were made with a disk 20 cm in diameter painted in black and white quadrants. At the same time, the dominant species contributing to Lake Kutubu's aquatic vegetation were recorded. The ecological changes were compared by the same author (S.H.) between regular field trips from 1988 to 2018.

Numerical Analyses. A square-root transformed detrended correspondence analysis was performed using R's "vegan" package (61) on the KTB17 sediment geochemistry, NPPs, and the diatom counts. A rate-of-change analysis was performed on the chlorophyll-a and diatom data from core KTB02 and on the sediment geochemistry and paleoecological (NPP) data from KTB17 to pinpoint phases of rapid ecological turnover in the lake environment. Samples were binned into regular time intervals of 5 y and square chord distances calculated between adjacent bins, following the approach of Connor et al. (62).

To identify critical ecological transitions in the algal, fungal, and charcoal records, a tipping-point analysis was conducted in R using the method validated for paleoecological data by ref. 63. These "critical transitions" or "tipping points" are periods of change when the ecosystem shifted from one state to another after an event rather than returning to the previous state. The likelihood of a critical transition is assessed using Kendall's tau and *P* values (63). R code for this analysis can be found in ref. 63.

Data Availability. All study data are included in the article and/or supporting information.

ACKNOWLEDGMENTS. The Lake Kutubu Project was funded by the Department of Archaeology and Natural History at the Australian National University and the Australian Institute of Nuclear Science and Engineering Grants AINGRA08028 and AINGRA10113 obtained by S.G.H. The ^{210}Pb dating was funded through Australian Nuclear Science and Technology Institution Research Portal Proposal AP12071. Funding support was also provided by the Australian Research Council Centre of Excellence for Australian Biodiversity and Heritage (Project CE170100015). We thank Professor Hugh Davies and the University of PNG for collaborative in-country support. Thanks also to Shirley Lee (University of PNG student) for fieldwork assistance. We thank the local Foi and Fasu land owners for assistance in the field.

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