The effectiveness of integrated floating treatment wetlands (FTWs) and lake fountain aeration systems (LFAS) in improving the landscape ecology and water quality of a eutrophic lake in Indonesia

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Abstract. Concerns over the impacts of floating cage aquaculture (FCA) systems on ecosystem health have led to the exploration of alternative green technologies as a way of improving water quality and preventing eutrophication problems in Lake Maninjau, Indonesia. This lake has been suffering from frequent harmful algal blooms (HABs) and hypoxic conditions due to excess nutrient and organic inputs from FCA. These have caused mass fish kills and decreased the local fish population. The main goal of this study was to assess the effectiveness of using integrated floating treatment wetlands (FTWs) and a lake fountain aeration system (LFAS) to improve lake water quality and enhance ecological conservation. The FTWs, which resembled artificial islands (AFIs) and covered an area of 23.75 m², were planted with Echinodorus palaefolius. An LFAS was installed at the front of the FTWs. The impacts of the FTWs were evaluated from July to December 2018, while those of the LFAS was evaluated from October to November 2018. Lower nutrient and chlorophyll-a concentrations were observed within and around the FTWs and LFAS. Also, the LFAS increased the dissolved oxygen concentrations in the water to more than 100% at night. The results suggested that FTWs and LFAS could be used to prevent eutrophication and lake hypoxia. The plants in the FTWs grew much faster in the parts that were facing the waves, with their higher plant biomass suggesting that more nutrients had been removed from the lake. Also, the FTWs and LFAS, which resembled floating gardens, help to make the lake landscape more attractive and increase its amenity value. The improved water quality and habitat provision provided by these systems has attracted more local fish and other wildlife to the FTWs. The overall improvement in lake water quality and ecosystem health has the potential to ensure better provision of essential lake ecosystem services.

1. Introduction
Concerns over the impacts of floating cage aquaculture (FCA) systems on ecosystem health have led to the exploration of alternative green technologies as a way of improving water quality and preventing eutrophication problems in Lake Maninjau, Indonesia. This lake has been suffering from frequent harmful algal blooms (HABs) and hypoxic conditions due to excess nutrient and organic inputs from FCA. These have caused mass fish kills that have aggravated the lousy state of the lake.
[1,2,3]. The lake has been in a eutrophic state for more than a decade [3,4]. The consequences of this lake contamination include the loss of ecosystem services, especially to recreation or tourism and water supply, and a decrease in local fish production.

Worldwide, the green technologies that are being applied to remediate contaminated waterbodies are floating treatment wetlands (FTWs) with integral aeration systems. The pollutant removal capacity of FTWs has been evaluated in closed methods, such as microcosms, or open systems such as urban waters, rivers and small lakes [5,6,7,8]. Many of these studies have shown that FTWs are effective, low cost and low maintenance tools for removing excess levels of nutrients (nitrogen and phosphorus) from water bodies [8,9,10,11]. Recently, cutting edge green technologies, which comprise constructed floating wetlands or artificial floating islands with integral aeration systems, i.e., ‘green energy landscape fountains’ (GLF), have been developed by Chang et al. [12,13], who also evaluated a solar-powered artificial floating island (SAFI) equipped with aerators in terms of its ability to improve the landscape ecology and water quality of a small lake [14]. Both GLF and SAFI were able to purify the water, create habitat, beautify the landscape, shade the water surface, and reduce the risk of lake eutrophication by inhibiting phytoplankton growth. Fountain or aerator type aeration systems have, widely, been used to increase water flow to oxygenate the water and enhance pollutant transformation, especially of nitrogen by microbial biofilms, and uptake by plant roots [13,14,15,16].

This study is part of a continuing effort to improve the water quality of Lake Maninjau to conserve biodiversity and increase its amenity value by enhancing the landscape ecology of the lake. Few studies have examined the performance of FTWs to the remediation of such a large lake, and our previous study revealed that one of the main challenges of applying FTWs to a large lake is to keep the FTW frame remain intact during turbulent conditions [17], especially during the daytime and during the rainy season or under extreme climatic conditions. The objectives of this study were to (1) evaluate the impact of the integrated FTWs and aeration system on lake water quality, and (2) examine the benefit that FTWs can provide in terms of improving habitat for wildlife and increasing biodiversity.

2. Materials and Methods

2.1. Study site
The study was conducted at the open area around the shoreline of Lake Maninjau, a caldera lake, located at Agam District in the Western region of Sumatra, Indonesia (S 0°22’33.0”, E 100°11’35.1; Figure 1). The lake has a surface area of 9737.5ha and the maximum depth of 165m. More than 10,000 floating net cages have been reported in this area [2]. The lake suffers from eutrophic conditions characterized by harmful algal blooms (HABs), elevated nutrient concentrations, and frequent mass fish kills due to hypoxic conditions that have occurred almost every year over the last decade. The lake experiences high climate variability and strong wind-induced waves. The integrated treatment system was placed within an area without cage aquaculture systems, with a depth of around 6 – 8 m and at about 20 m from the shoreline. This area has been designated as a recreational area to attract tourism.

2.2. Design of Floating Treatment Wetland (FTW) systems
A floating treatment wetlands (FTWs) system was installed in the lake in June 2018 as a potential green technology for reducing the risk of eutrophication. These FTWs consisted of letters inscribing the word LIMNOLOGISTM that had been assembled from PVC pipe (15 cm Ø), to provide flotation, and fabric matting made from palm sugar fibers, which were attached to a woven vinyl rope. In combination, the FTW units covered an area of 23.75m² and were planted with Echinodorus palaeofolius. A net fence was placed underneath the FTWs to prevent fish from grazing the plant roots. The assembled FTWs were placed inside a square metal frame (4m x 15.5m), which was attached to buoyant plastic drums that provided protection against waves (Figure 2). A lake fountain aeration system (LFAS) was installed at the front of the FTWs in September 2018. The LFAS consisted of 5x1hp submersible pumps that channeled water towards a 2.5cm nozzle that sprayed water into the air (figure 3). Power was provided from an electricity generating station. The pumps were controlled by a
timer that switched them on and off at four hourly intervals. Monitoring of the effects of the FTWs on water quality began in early July 2018, one month after the FTWs had been installed and the plants had developed roots.

2.3. Sampling and lake water analysis
Direct water quality measurements and water sampling were conducted within the FTWs (‘FTW-inside’), on the outside close to the FTWs (FTW-outside), and on the lake surface within 10m of the FTWs (‘FTW-lake’) and on the LFAS area (‘aerator’) (Figure 4). The FTWs were monitored for about six months, whereas LFAS performance was observed for two months. Water was collected from at least 20cm below the surface. Physicochemical parameters measured included pH, temperature, conductivity, and dissolved oxygen (DO) concentration. A water quality meter (Horiba U-10) was used to measure pH and conductivity, while a DO meter (YSI 6000) was used to measure temperature and DO levels in water. Total Nitrogen (TN), Total Phosphorus (TP) and chlorophyll-a levels in the water samples and C, N, P and K levels in the plant tissues were analyzed using spectrophotometric methods. Total suspended solids (TSS) concentrations were determined using a gravimetric method. The samples were prepared by spectrophotometric methods and measured using Shimadzu UV 2100 spectrophotometer. All laboratory analyses were performed according to APHA standard methods [18]. A portable HACH DR-3900 spectrophotometer was used to measure nitrate ($NO_3$) and orthophosphate ($PO_4$) concentrations.

2.4. Plant growth and biodiversity survey
Plant growth was monitored by measuring the lengths of randomly selected shoots, root lengths and plant biomass (dry weight). In July and August, biomass estimation (dry weight) was conducted on the above-ground parts of the plants (shoots), only, with at least three plants being harvested, and then air-dried and oven-dried (50°C) until a constant weight was obtained. Wild flora and fauna were observed visually, photographed and documented.

2.5. Data analysis
Mean, and standard deviation were calculated for plant shoot and root length. Contaminant removal efficiency (RE) was measured by determining the difference between the contaminant concentration in the FTWs and that in the lake, following the formula:

$$RE\ (%) = \frac{(C_{lake} - C_{FTWs})}{C_{lake}} \times 100$$
Figure 1. Map of Lake Maninjau (left and upper right) (Source: GIS Laboratory RC for Limnology LIPI); location of the study site (lower right) (Google Earth Pro, 2018).

Figure 2. Floating treatment wetlands (FTWs).
3. Results and Discussion

3.1. Climatic conditions

The highest rainfall over the study period was recorded in October and November 2018 (figure 5). The lake experienced hypereutrophic conditions, including HABs, during April and May. However, during the period when the FTWs were set on the lake, the water was clear and with no indication of algal bloom. The algae had either subsided and sunk to the lake bottom, or they had been washed out of the lake outlet.
3.2. Water temperature, pH, DO and conductivity

Temporal profiles of water temperature, pH, DO, and conductivity are shown in Figure 6a-d. Water temperatures inside and close to the FTWs ranged from 28 °C to 29 °C, which was slightly cooler than the lake water temperatures (28 °C to 30 °C) (figure 6a). The highest water temperature in the lake of around 30°C was recorded in August 2018. The FTWs shaded some of the lake surface, decreasing the water temperature around these systems [6,12,13,14,17].

The pH levels in the lake were slightly lower than in the FTWs except in July 2018, when the pH level was lower and in October when it was somewhat higher (figure 6b). The pH ranged from 8 to 9, indicating alkaline conditions; this is normal for eutrophic waters [1,6,11,20]. A high pH > 8 indicates high photosynthetic activity by phytoplankton and plant assimilation processes [13, 21], which is consistent with the time of sampling, i.e. during the day.

Similar to pH, the DO levels in the lake water were slightly lower than in the FTWs. DO level reached 10mg/L during the first two months of monitoring (figure 6c). This may be attributed to higher photosynthetic activity by phytoplankton and a contribution from the plant roots in the early period of growth [9,13,22]. In contrast, urban waters have higher DO levels after treatment by FTWs [6,12,20]. The study area was in the open space of the lake, which is always affected by moderate to strong wave drifts [17].

Electrical conductivity (EC) levels in the lake and within the FTWs followed similar temporal changes (figure 6d). Higher EC levels usually indicate a high concentration of ions in the water. EC levels ranged from 0.68 to 0.113 mS/cm, but the cause of the lower ECs in December 2018 was unclear. The values recorded were within the range expected for eutrophic waters [1,6,11,13,17]. The study was undertaken in an open area with no cage aquaculture and where the lake receives runoff from the mountain through a small inlet channel. During the rainy season, November to December 2018, the water flow from this channel was quite large, so dilution may also have caused the lower EC recorded in the lake water. Throughout the monitoring period, the lake water in the study area was usually cleaner than in other areas, especially those with high cage aquaculture activities.

![Figure 6](image_url)
3.3. TN, TP, Chlorophyll-\(\alpha\), and TSS

Temporal variation in concentrations of total nitrogen (TN), total phosphorus (TP), chlorophyll-\(\alpha\), and total suspended solids (TSS) in the lake water and FTWs are shown in Figure 7a-d. TN concentrations in the FTWs varied over time and were consistently lower than those in the lake, except for September 2018 (figure 7a). TP concentration was high in April 2018, as was chlorophyll-\(\alpha\) (figures 7b,c). This coincided with the lake being highly eutrophic and HABs occurring. Chlorophyll-\(\alpha\) concentrations in Lake Maninjau can reach 75 - 100 mg/L during hypereutrophic conditions [1,3,4]. Both TP and chlorophyll-\(\alpha\) levels decreased over time with TP being below the level of detection limit (0.01 mg/L) from October to December 2018. Concerning chlorophyll-\(\alpha\), concentrations in the lake were slightly higher than those in the FTWs in December 2015. These results indicated that phosphorus was the limiting factor for phytoplankton productivity and controlled the chlorophyll-\(\alpha\) concentration [1,23,24].

The temporal pattern of TN, TP and chlorophyll-\(\alpha\) concentrations in April and July 2018 supports the finding that chlorophyll-\(\alpha\) levels are determined by TP concentrations (Figure 8). Some discrepancies between chlorophyll-\(\alpha\) in the FTWs and the lake may be attributable to a decrease in the phytoplankton population in the FTWs. Our other study of the phytoplankton community indicates a lower abundance of phytoplankton in the FTWs and an associated shift in the dominant species (unpublished). Variations in nutrient and chlorophyll-\(\alpha\) concentrations during this FTWs field study were consistent with the results from previous studies [6,11,16,17,20]. Nitrate concentrations ranged from 0 to 0.01 mg/L and phosphate concentrations from 0 to 0.01 mg/L. However, in general, both were below the limit of detection.

TSS concentrations were relatively low and fluctuated throughout the observation. Although in April, the lake was in a highly eutrophic condition, levels of suspended solids were relatively small (figure 7d). Only in August and December 2018 were the TSS concentrations in the lake slightly higher than those in the FTWs. It may be because the turbulent lake water and high wind-driven currents sometimes washes away the solids and the chlorophyll-\(\alpha\). It was observed that the HABs were drifting from one place to another. The TSS concentrations measured in this study were similar to those from our previous FTW studies [17].

![Figure 7](image-url)
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Figure 8. Temporal pattern of (a) TN, (b) TP and (c) chlorophyll-a (CHL) in the lake water

3.4. TN, TP, Chlorophyll-a and TSS removal efficiency

Percentage removal efficiency (RE) was calculated, based on differences in values inside and outside of the FTWs, for concentrations of TN, TP, chlorophyll-a and TSS (figure 9a-c). TN concentration inside the FTWs was much higher than those outside the FTWs giving the negative RE of TN in September. The RE for TN reached as high as 50% in November 2018 (figure 9a). Deficient TP concentrations in the lake water contributed to the negative REs for TP (figure 9b). The RE values for TN and TP for this study were small in comparison to those from our previous study [17]. The RE values for chlorophyll-a were substantially higher in July and December 2018 than at other times of the year (figure 9c), and slightly higher than the RE values for chlorophyll-a from our previous FTW studies [17]. These earlier studies were smaller in size, used different combinations of vegetation and were located in the area where cage aquaculture is undertaken, which is less affected by waves. The current study also gave low RE values for TSS (figure 9d), probably caused by the more turbulent water in this area, which may be responsible for washing solids away from the plant roots. However, the performance of this FTWs study, using *Echinodorus palaefolius*, was as effective as that of many other field scale FTW trials. Besides a vegetation effect, the aeration incorporated into the integrated system may explain the results in this study, which were similar to those from the previous studies [6,8,11,14,16,17].
Figure 9. Removal efficiency for (a) TN, (b) TP, (c) chlorophyll-a and (d) TSS concentrations in the lake water and the FTWs.

3.5. LFAS performance

In addition to conducting measurements and collecting water samples each month during the period over which the LFAS was being operated, its performance was evaluated by measuring changes in DO, temperature, pH and EC levels in the water column, over the area that the LFAS encompassed with the aeration system switched on and switched off (figure 10a,b). The water temperature in the area over which the LFAS operated was as high as that of lake water (figure 10a). Water circulation did not affect the water temperature, and the DO, pH, and EC values were also consistent with those of the lake water. Measurements were conducted during the day time when the phytoplankton was photosynthetically active. On sunny days, DO levels in the water and pH tended to be higher than on cloudy or rainy days, or during the night when only respiration processes take place [25].

TN, TP, chlorophyll-a, and TSS concentrations in the LFAS area are presented in Figure 11a,b. TP level remained low, but still above the limit of detection and TN increased slightly. Although TSS increased slightly, its concentration remained low. Chlorophyll-a decreased slightly over the two months. Water circulation, or disturbance, caused by the fountain during daytime, is likely to have increased the aerobic microbial activity that transforms organic pollutants and nitrogen. Transformation of ammonia to nitrate by bacteria (nitrification) is a process that requires high oxygen levels in the water, with remediation of ammonium consistently increasing with higher levels of aeration [15,16,26]. Aerobic conditions may also increase N and P ion uptake by plant roots. A previous study showed that N ion uptake was higher in the non-aerated than in the aerated systems [16], but plant uptake was higher in the aerated than the non-aerated systems. It suggests that integrated FTW and aeration systems could be used to increase nutrient uptake by the plants in the FTWs.
Figure 12 shows the spatial variation in DO levels around the area encompassed by the LFAS. When the LFAS system was switched off, during daytime, the area with a low DO level was more significant than when the LFAS was turned on. The low DO level area became more restricted and the higher DO level area expanded when the LFAS was turned on (figure 12). Overall, the DO concentration increased by 14.86% in the area exposed to LFAS. In contrast, when the LFAS was switched off at night, the DO level decreased rapidly in the area covered by the LFAS, leaving only a restricted area with higher DO levels close to the fountain. When the LFAS was turned on at night, the area with higher DO levels enlarged. Higher DO levels in the area encompassed by the LFAS indicated that, even though the fountain had been switched off, oxygen molecules remained in the water column longer. The sector with high DO concentrations at night was around 99.8m² when the LFAS was switched off and about 237m² when the LFAS was switched on. There was an increase in DO level of about 137.47%, demonstrating that the LFAS could increase DO concentration in the lake water more effectively at night. This aeration could prevent oxygen depletion during critical times in the lake, such as periods of hypoxia caused by rapid uptake of oxygen caused by the respiration processes of all organisms, including phytoplankton. Also, the lake water was relatively calm and there were fewer waves at night. Most previous studies have indicated the marked effect of aeration systems, such as fountains, mechanical mixers and/or aerators, in increasing DO levels in contaminated or eutrophic water bodies or treated wastewater [12,13,14,16]. Aeration has the potential to create toxic conditions in hypoxic lakes at a spatial scale that is much larger than that encompassed by the aerator [27].

Figure 10. Temporal variation in (a) DO (mg/L), temperature, pH and (b) EC levels at the LFAS area.

Figure 11. Temporal variation in (a) TP, TN, TSS and (b) chlorophyll a levels in the LFAS area.

3.6. FTW vegetation stability and plant growth
Plants’ height and shoot numbers were recorded from July to December 2108, while root length was recorded in October 2018, only. *E. palaefolius* grew and adapted well even though the FTW raft swayed under the influence of massive waves. The average shoot length gradually increased over this
period (figure 13a), and root length reached > 50 cm. Harvesting was not performed during the monitoring period, but the aerial shoots of 2-3 plants were sampled to check the N, P, C and K content in July and August 2018; these were found to be 375 – 430; 38.7 – 66.1: 1.6 – 3.3 and 31.2 – 55.7g/kg (dry weight), respectively. The dry weight of plant biomass was 250g/m² and 450g/m² in July and August, respectively. These results indicated that the plants removed significant amounts of carbon and nutrients from the lake water, although the nutrient concentrations within the FTWs and in the lake were not substantially different. A harvesting strategy could be implemented to increase the removal efficiency of nutrients by the plants [6,11].

Figure 12. Changes in the spatial variation in DO profile during the LFAS experiment

Even though the plants adapted well to turbulent conditions, it is clear that the waves had a strong influence on plant growth and morphology, and, conceivably, on their physiology. The plants that were affected by first-order wave forces were more prominent and faster growing than the plants in the more sheltered rows behind them (figure 13b). It suggested that FTWs can attenuate the waves and reduce the speed of water flow, allowing nutrients or pollutants to be intercepted and settled by the plants and their roots. Shading by FTW plants could suppress the growth of algae, thus helping to prevent eutrophication problems; we found that the FTW could play a role in reducing the waves traveling toward the lakeshore. Figure 14 shows the differences observed in plant morphology. The plants in the front line, close to the LFAS, grew faster. It is possible that improvements in water circulation as a result of the fountain, and the waves, might also trigger better uptake of nutrients, or other ions, by the plant roots. Another possible explanation is that aeration may enhance the transformation of microbial nutrients or complex organic-based carbon, to ions making them more readily available for plant uptake [14,16,17].

The plants in this study had smaller, thicker, and less green-colored leaves than those from our microcosm study, where the FTW plants were grown in cells with still water and in a shady area (unpublished). Another important finding was that the plants were flowering earlier, improving the lake environment aesthetically and increasing biodiversity by attracting insects. The impact of the
waves could also be seen from the roots’ appearance, with those in the FTWs being clean and slightly white while those in the mesocosms were more brown. These observations support our conclusion on the removal efficiency of suspended solids, which was small or even negative at times. The solids attached to the roots seem to be washed away by the waves and remain in the water around the FTWs.

Figure 13. Growth characteristics of *Echinodorus palaefolius* (mean ± standard deviation) (a) and shoot length (b) about their position in the FTW rafts. The plants were transplanted in June and acclimated for around one month prior to the start of the experiment.

Figure 14. Growth of *Echinodorus palaefolius* as a result of waves and aeration.

3.7. Ecological survey
Another benefit of FTWs is habitat provision for living organisms [14,17]. The plants and the FTW raft seemed to attract wildlife and local aquatic biota. Among the fauna documented within the FTWs were aquatic insects, spiders and crickets, butterflies, black beetles, and several types of dragonflies and snails. Small clams, shrimps, insect larvae and freshwater lobsters were found attached to the plant roots. Many small, endemic local fish were found inside and around the FTWs in the area that was affected less by the waves. This local fish is consumed by the people and has high economic value. More than 60 good-sized of tilapia and black flower horn (15 – 20 cm) were captured inside the net fence that was placed underneath the FTW. Common grass carp were captured within the protective fence of FTWs that were installed in a eutrophic pond and lake [9,17]. FTWs show great potential for improving habitat provision [6,12,13,14,17]. The presence of FTWs might increase the populations of local fish and small clams. These small clams live among the pebbles on the lake bottom, within the euphotic zone, and the FTWs may provide food and shelter for them; this requires further investigation. A few wild plant species were observed to be thriving on the uncovered parts of the FTW mat, but in a minimal area, the presence of these ‘weeds’ was not considered to be inhibiting the growth of the FTW plants. Previous field studies have also found weeds thriving on the FTW mats,
especially when the target plants are growing slowly and are less dense; the ‘weeds’ also contribute to nutrient removal from the lake water [5,15,17,19]. It is important to make sure that the plant canopy covers the whole mat to prevent weeds, for example by using black fabric on the mat between the FTW plants. The FTWs added new habitat to the lake that was able to support economically important aquatic biota. Different trophic levels inhabited and frequently visited, the FTWs, clearly increasing the biodiversity of wild flora and small fauna [9,12,13,14, 17].

3.8. Implication for increasing provision of lake ecosystem service

Building FTWs that resemble artificial floating islands (AFI) may provide a sustainable and economical treatment for improving the water quality and landscape ecology of this sizeable eutrophic lake. Like AFI, designing a large scale FTW for deployment in a giant lake has to take into account the factors that affect their viability, such as wave forces and secure mooring. Our design includes a square metal frame attached to a buoyant plastic drum that secures the FTW structure and provides protection against waves. Therefore, a large-scale FTW could act as barrier that reduces wave energy. Artificial islands at suitable locations in a reservoir can attenuate wave heights by approximately 10% -30% [28,29]. Our study showed that the vegetation on the FTW that received the main brunt of the wave forces had achieved higher and faster growth than the plants in the more sheltered rows. It indicated that the FTWs reduced the speed of water flow and allowed the nutrients, or the pollutants, to be intercepted and settled through the plant roots and body. The FTW plants were able to reduce the growth of phytoplankton and algae and prevent further eutrophication problems.

The improved water quality and habitat provided by this system attracted fish and other wildlife to the FTWs. The FTWs also added landscape improvements to the lake, which increased biodiversity and improved local fish production. The economically crucial local fish are small fish that prefer calm water and the presence of the FTWs increased the population of these fish in this area, with many being spotted within and around the FTWs. Fisherman have reported that more small local fish and clams have been caught in this area since the FTWs were installed, although this needs to be investigated further.

FTWs that resemble floating gardens can beautify the lake landscape and increase its amenity value. The study site has been proposed for use as a recreational area, and the presence of FTWs and LFAS has already attracted sightseers. Our other study (unpublished) indicates that the lake water around the FTWs contained less coliform bacteria than elsewhere in the lake, indicating that the treated water near the FTW area is safe for people to swim or play in.

4. Conclusion

This paper is the first report of a combined FTW and fountain aeration system being used to remediate a large eutrophic lake in a tropical region to improve its ecosystem health. Our FTW design and structure proved to be resistant to wave damage, and the raft and its plants remained intact throughout the study, demonstrating its sustainability. In general, Echinodorus palaefolius is a robust plant that can adapt well to wavy water conditions. Overall, the results showed that this integrated system could be used to improve lake water quality and reduce the risk of lake eutrophication problems occurring. FTWs with flowering plants can also beautify the landscape and provide better habitat to support ecological conservation and increase biodiversity and local fish production. The fountain aeration system is particularly beneficial because it attracts tourists. Our results provide good evidence that integrated FTWs and LFAS can improve a lake’s ecosystem health and improve ecological conservation, both of which are essential to ensuring the provision of essential ecosystem services.

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