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Soil physicochemical and bacterial properties of wetland ecosystems in south-south states of Nigeria

ETUK SOLOMON JACOB *, Uchechi Ekwenye and Ome Achi

Department of Microbiology, Michael Okpara University of Agriculture, Umudike, Abia State, Nigeria.

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Abstract

Wetlands are ecologically significant ecosystems that provide critical services including biodiversity conservation, flood regulation, and groundwater recharge. However, increasing pressures from agriculture, urbanization, and oil exploration have altered their ecological balance, particularly in the Niger Delta region of Nigeria. This study evaluated the physicochemical and microbiological properties of wetland soils across three South-South states—Rivers, Bayelsa, and Akwa Ibom—to assess their ecological status and management potential. Soil samples (0–15 cm depth) were collected in August 2021 and analysed using standard culture-dependent and physicochemical procedures, complemented with metagenomic profiling. Akwa Ibom and Bayelsa soils were dominated by sand, whereas Rivers soils contained relatively higher silt fractions. Slightly acidic conditions were observed across all sites, with pH ranging from 5.56 (Bayelsa) to 6.89 (Rivers). Total nitrogen content differed significantly, increasing from Bayelsa (7.81 mg/kg) to Akwa Ibom (18.31 mg/kg) and Rivers (59.65 mg/kg). Soil pH, organic carbon, and nitrogen strongly correlated with microbial community composition. Magnesium dominated the exchangeable bases, and electrical conductivity remained low across sites. Metagenomic sequencing revealed diverse microbial assemblages, with 14 bacterial phyla detected. Core taxa common to all sites included Proteobacteria, Actinobacteria, Planctomycetes, Verrucomicrobia, Firmicutes, Nitrospirae, Acidobacteria, and Chloroflexi, which collectively dominated the soils. Site-specific phyla were also observed, such as Dictyoglomi and Spirochaetes in Akwa Ibom, and Thermotogae and Paludibacteraceae in Bayelsa. Ignavibacteriae were detected in Akwa Ibom (24.96%) and Rivers (75.04%) but absent in Bayelsa. Overall, wetland soils in the South-South region of Nigeria exhibited slightly acidic conditions, low electrical conductivity, and diverse but site-specific microbial communities dominated by Proteobacteria. These findings highlight the influence of physicochemical parameters on microbial diversity and provide baseline data essential for wetland management, restoration, and sustainable utilization.

Keywords: Wetland Soils; Microbiological Composition; Physicochemical Properties; Sustainable Agriculture

1. Introduction

Wetlands represent unique transitional ecosystems situated between terrestrial and aquatic environments, and they perform indispensable functions in sustaining ecological balance at both local and global scales. Distinguished by their structural and functional complexity, wetlands regulate hydrological cycles, support biodiversity, and contribute to the stability of global biogeochemical processes (Akinwale et al., 2024). They also deliver a broad range of ecosystem services, including flood mitigation, groundwater recharge, shoreline protection, sediment retention, climate regulation, nutrient cycling, and wastewater treatment, which are vital for both human well-being and environmental sustainability (Jisha & Puthur, 2021).

* Corresponding author: ETUK SOLOMON JACOB.

Despite these critical functions, wetlands in many African countries—particularly Niger Delta in Nigeria—are increasingly threatened by anthropogenic activities (John and Eduok, 2018). Rapid urban expansion, intensive agriculture, industrialization, and unsustainable land-use practices have introduced multiple pollutants into wetland systems. These contaminants, which include fertilizers, pesticides, petroleum hydrocarbons, landfill leachates, industrial effluents, sewage, and municipal waste, accumulate within wetland soils and waters, thereby undermining ecosystem integrity and resilience (Osinuga & Oyegoke, 2019; Isiuku & Enyoh, 2020).

The Niger Delta, which spans approximately 76,000 km^2, is one of the most extensive wetland systems in the world and hosts Africa's largest mangrove forest, covering about 11,134 km^2 (Mamat et al., 2020). Despite its ecological significance, this region has been subjected to severe environmental degradation, primarily due to recurrent crude oil spills associated with oil exploration and production. Oil contamination has imposed multiple ecological and socio-economic burdens, including the destruction of mangrove forests, loss of biodiversity, soil degradation, and declining agricultural productivity. It is estimated that 5–10% of Nigeria's mangrove ecosystems have been lost to oil pollution, with spills restricting nutrient availability, impairing soil microbial activity, and suppressing plant growth (Amaechi et al., 2022). Over time, these impacts have transformed fertile agricultural lands into wastelands, forcing communities to abandon farming and seek alternative livelihoods, thereby intensifying poverty and food insecurity in the region.

Soil forms the foundation of wetland ecosystems, consisting of minerals, organic matter, and weathered rock fragments that regulate ecosystem processes and serve as reservoirs for pollutants (Mohammeda et al., 2024). However, the introduction of contaminants alters both the physicochemical and microbiological characteristics of soils, with profound implications for soil fertility, nutrient cycling, and ecosystem productivity. Parameters such as pH, organic carbon, cation exchange capacity, and base saturation serve as indicators of soil quality, while microbial communities mediate critical biogeochemical processes that sustain ecosystem health (Akinwale et al., 2024). Therefore, evaluating the physicochemical and bacterial properties of wetland soils is fundamental for understanding ecosystem functionality and assessing the ecological consequences of pollution. The present study aims to assess the physicochemical and microbial properties of wetland soils across the South-South states of Nigeria. The study provides insights into how anthropogenic pressures, particularly crude oil contamination, influence soil quality and microbial dynamics, with implications for wetland management, restoration, and sustainable use.

2. Materials and Methods

2.1. Study Site

Wetland soils were sampled from Akwa Ibom, Bayelsa, and Rivers States in Nigeria. The study area is generally flat to gently undulating (0–3° slope) and is underlain by relatively uniform parent material. The natural vegetation comprises grasses, legumes, raffia palms, ferns, and cultivated farmlands.

2.2. Soil Sampling

Composite topsoil samples (0–15 cm) were collected in August 2021 using sterile augers. Samples were placed in clean polyethylene bags and plastic containers, transported on ice, and delivered to the University of Uyo Microbiology and Central Research Laboratories. Microbiological analyses were conducted within 24 h, while samples for physicochemical assays were air-dried and sieved through a 2 mm mesh.

2.3. Physicochemical Analysis

Physicochemical properties were determined following standard protocols (Radojevic & Bashkin, 1999; APHA, 2005). Soil pH and electrical conductivity (EC) were measured in a 1:5 soil–water suspension using calibrated electrodes. Organic carbon was analyzed by the Walkley–Black wet oxidation method and converted to organic matter. Total nitrogen was determined by the Kjeldahl method, while nitrate, nitrite, and ammonia were quantified spectrophotometrically. Major anions were assayed by titrimetric and turbidimetric methods: chloride (argentometric), sulphate (turbidimetric), and bicarbonate (acid–base titration). Exchangeable bases were extracted with 1 M ammonium acetate; Na^+ and K^+ were measured by flame photometry, and Ca^{2+} and Mg^{2+} by EDTA titration. Particle size distribution was assessed by the hydrometer method using sodium hexametaphosphate as dispersant. Total hydrocarbon content (THC) was extracted with diethyl ether, purified on silica gel, and quantified gravimetrically (Valcarcel, 2000).

2.4. DNA Extraction, Sequencing and Bioinformatics

Genomic DNA was extracted from 0.25 g of soil using the Zymo-Spin™ kit according to the manufacturer's instructions (Poly et al., 2001). DNA purity was confirmed spectrophotometrically. The V3–V4 hypervariable regions of the 16S rRNA gene were amplified using primers 341F and 785R. Amplicons were purified, adapter-ligated, indexed, and sequenced on an Illumina MiSeq platform (2 × 300 bp, MiSeq v3 kit). Raw reads were processed and taxonomically assigned using BLAST (NCBI v2.24) and CLC Genomics Workbench v7.5.1. Sequence data were used to characterize microbial community composition and diversity across sites.

3. Results and discussion

Wetlands are characterized by unique structural and functional attributes that contribute significantly to ecological stability and global biogeochemical cycles. They provide essential ecosystem services including biodiversity preservation, pollution attenuation, climate regulation, and habitat conservation (Alam et al., 2018). The ecological integrity of these ecosystems is largely determined by the physicochemical and microbial properties of their soils, which directly influence nutrient cycling, soil fertility, and human well-being (Atta-Darkwa et al., 2020).

3.1. Soil pH and Acidification Potential

The soils from Akwa Ibom, Bayelsa, and Rivers States exhibited pH values ranging between 5.56 and 6.89 (Table 1). Bayelsa wetlands recorded the lowest pH (5.56), while Akwa Ibom and Rivers soils were moderately acidic with pH values of 6.32 and 6.89, respectively. The slight acidity across all sites suggests the presence of elevated soil organic matter and potential acid sulphate conditions. Soil pH is strongly modulated by climatic factors, particularly temperature and precipitation, which drive weathering processes and soil development (Umana et al., 2017a; Sandeep et al., 2014). Acidification tendencies are also species-specific and depend on prevailing environmental conditions.

3.2. Hydrocarbon Content and Pollution Status

Total hydrocarbon content (THC) was relatively low across all sites, with values <0.01 mg/kg in Akwa Ibom and Bayelsa, and 0.69 mg/kg in Rivers State. Although Rivers soils contained the highest THC, all values remained well below the 30.0 mg/kg threshold for unpolluted soils established by the World Health Organization (WHO, 2013). These results suggest that the wetlands under study are largely unpolluted by hydrocarbon contamination.

3.3. Electrical Conductivity and Salinity

Electrical conductivity (EC) ranged from 0.046 dS m^{-1} in Bayelsa to 0.101 dS m^{-1} in Akwa Ibom. EC is a reliable indicator of soil salinity and has implications for crop suitability, microbial activity, and nutrient bioavailability (Umana et al., 2017b; Raghavendra & Vijayakumara, 2017). All observed values were significantly lower than the FAO (1974) critical threshold of 2 dS m^{-1} for salt-sensitive crops, indicating minimal risk of salinity-induced constraints on agricultural productivity.

3.4. Organic Carbon Dynamics

Total organic carbon (TOC) varied widely, with Bayelsa recording the lowest concentration (0.84%) and Rivers the highest (5.93%). The disparity likely reflects differences in hydrological regimes, where frequent flooding in Bayelsa facilitates litter washout, reducing soil carbon accumulation (Zhang et al., 2018). The relatively high organic carbon levels compared to earlier reports (Raghavendra & Vijayakumara, 2017) suggest substantial microbial activity and active decomposition of plant residues, consistent with findings by Osakwe (2014). Organic carbon not only influences soil acidity through organic acid contributions but also regulates nutrient availability by forming humus and supporting microbial-mediated nutrient turnover.

3.5. Nitrogen and Related Nutrients

Total nitrogen content ranged from 7.81 mg/kg in Bayelsa to 59.65 mg/kg in Rivers, with intermediate levels (18.31 mg/kg) observed in Akwa Ibom. Variations in nitrogen concentration may be linked to anthropogenic inputs, plant nutrient uptake, leaching, and organic matter decomposition (Hu et al., 2019). Nitrate concentrations were highest in Rivers (36.56 mg/kg), exceeding values in Akwa Ibom (10.94 mg/kg) and Bayelsa (4.89 mg/kg). Nitrite levels followed a similar pattern, with Rivers (3.11 mg/kg) showing significantly higher values than Akwa Ibom (1.14 mg/kg) and Bayelsa (0.36 mg/kg). The observed differences were statistically significant ($p < 0.05$), possibly reflecting fertilizer use, wastewater discharge, and agrochemical runoff (Uwah et al., 2009). Ammonia concentrations ranged from 2.56 mg/kg in Bayelsa to 19.98 mg/kg in Rivers. The relatively higher nitrogen fractions in Rivers suggest stronger anthropogenic influence and enhanced microbial nitrification.

3.6. Soil Salts and Ionic Composition

Salinity-inducing salts varied significantly across locations. Rivers soils contained the highest chloride (56.16 mg/kg) and sulphate (317.43 mg/kg) concentrations, whereas Bayelsa had the lowest (chloride: 19.96 mg/kg; sulphate: 86.76 mg/kg). The prevalence of sulphates and chlorides indicates saline characteristics (Reich et al., 2017), while the dominance of bicarbonates in Bayelsa soils suggests a more saline-sodic character (Uke & Haliru, 2021).

3.7. Exchangeable Cations and Soil Fertility

Total exchangeable cations were highest in Rivers (14.94 meq/100 g) and lowest in Akwa Ibom (11.32 meq/100 g). Potassium and magnesium dominated the cation pool, ranging from 3.14–4.98 meq/100 g and 4.96–6.86 meq/100 g, respectively. Potassium enrichment likely reflects soil textural properties limiting leaching, while magnesium dominance over calcium resulted in unfavorable Ca:Mg ratios (<1), which may impair soil structure and reduce calcium availability (Edem & Ndaeyo, 2009). The Mg:K ratios, however, exceeded the critical 1.2 threshold, suggesting no risk of magnesium deficiency in cropping systems (Edem & Ndaeyo, 2009).

3.8. Soil Texture

Textural analysis revealed variable compositions across sites, with Bayelsa (44.37%) and Akwa Ibom (33.57%) soils dominated by sand, while Rivers contained higher proportions of silt (41.25%). Clay fractions were relatively low across sites, ranging from 26.98% in Bayelsa to 30.42% in Akwa Ibom. These textural properties influence water retention, nutrient availability, and leaching dynamics (Umana et al., 2017a, b).

Table 1 Physiochemical properties of wetland soils in 3 South-South States

Parameter	Akwa Ibom	Bayelsa	Rivers
pH	6.32	5.56	6.89
Electrical conductivity (dsm^{-1})	0.101	0.046	0.058
TOC (%)	2.93	0.84	5.84
THC (mg/kg)	<0.01	<0.01	0.69
Total Nitrogen (mg/kg)	18.31	7.81	59.65
Nitrate (mg/kg)	10.94	4.89	36.56
Ammonia (mg/kg)	6.23	2.56	19.98
Nitrite (mg/kg)	1.14	0.36	3.11
Chloride (mg/kg)	239.92	19.96	56.16
Sulphate (mg/kg)	253.44	86.76	317.43
Bicarbonate ($CaCO_3$) (mg/kg)	62.5	62.5	125
Exchangeable Cations			
Sodium (meq/100g)	1.69	1.02	1.42
Potassium (meq/100g)	3.14	3.62	4.98
Magnesium (meq/100g)	4.96	5.11	6.86
Calcium (meq/100g)	1.53	1.78	1.68
Total	11.32	11.53	14.94
Soil Texture			
Sand (%)	33.57	44.37	23.11
Silt (%)	36.01	28.65	41.25
Clay (%)	30.42	26.98	35.64

3.9. Bacterial Community Composition Across Wetland Soils

A total of fourteen bacterial phyla were identified across the three wetland soils under investigation (Figure 1). Among these, Actinobacteria, Proteobacteria, Planctomycetes, Verrucomicrobia, Firmicutes, Nitrospirae, Acidobacteria, and Chloroflexi were consistently present across all locations, indicating their broad ecological distribution in wetland ecosystems. However, community structure showed location-specific differences. The Akwa Ibom wetland soil harboured 12 phyla, Bayelsa soil supported 11, while Rivers State soil contained 10. Unique phyla were also observed: Thermotogae and Paludibacteraceae were exclusive to Bayelsa, whereas Dictyoglomi and Spirochaetes were only detected in Akwa Ibom. In addition, Ignavibacteriae were shared between Akwa Ibom and Rivers, with relative abundances of 24.96% and 75.04%, respectively.

The majority of these belonged to Proteobacteria, followed by Actinobacteria, Acidobacteria, Firmicutes, Planctomycetes, Chloroflexi, Verrucomicrobia, Nitrospirae, and Bacteroidetes. Such distributional variability aligns with earlier findings that microbial community structures differ across wetlands depending on hydrological regime, vegetation cover, and soil physicochemical characteristics (Kavitha et al., 2016).

3.10. Dominance of Proteobacteria

In this dataset, Proteobacteria emerged as the most abundant and diverse phylum, accounting for 86,216 sequences (~60.8% of total bacterial sequences). Their predominance is consistent with previous reports in both natural and constructed wetlands (Wang et al., 2022; Wu et al., 2022). Members of this phylum are highly versatile, with rapid growth strategies and broad metabolic adaptability (Islam et al., 2020). Proteobacteria are crucial contributors to global carbon, nitrogen, and sulfur cycling, and play integral roles in wetland biogeochemistry (Iliev et al., 2019; Peralta et al., 2013). Moreover, many taxa within this group enhance plant growth by improving nutrient uptake and conferring resistance to pathogens (Trivedi et al., 2016). Their high abundance in these wetland soils suggests potential ecological benefits for soil fertility and plant productivity.

3.10.1. Actinobacteria

Actinobacteria represented 12,453 sequences (~8.8%), making them the second most dominant phylum. Their wide distribution in soils and sediments reflects their adaptability across diverse environmental conditions (Zeng et al., 2017). Actinobacteria play a central role in organic matter decomposition and have been identified as major degraders of polycyclic aromatic hydrocarbons (PAHs) in contaminated mangrove sediments (Guo et al., 2011). Although classically regarded as soil bacteria, some lineages are also prevalent in aquatic systems (Zhang et al., 2012), suggesting ecological versatility.

3.10.2. Acidobacteria

The third most abundant phylum was Acidobacteria, contributing 9,095 sequences (~6.4%). This group is globally distributed yet underrepresented in culture collections. Its abundance has been shown to correlate strongly with soil acidity, as acidic soils promote the proliferation of acidobacterial lineages (Roadcap et al., 2006). In this study, the highest relative abundance of Acidobacteria (58.13%) was observed in Bayelsa soils (pH 5.56), compared with Akwa Ibom (39.25%; pH 6.32) and Rivers (2.62%; pH 6.89). These findings are consistent with earlier reports from permafrost and wetland soils, where Acidobacteria were identified as dominant groups in moderately acidic conditions (Wilhelm et al., 2011).

3.10.3. Firmicutes

Firmicutes were the fourth most dominant phylum, comprising 8,846 sequences (~6.2%). Their ability to form endospores allows survival under harsh or fluctuating wetland environments, such as intertidal zones (Wang et al., 2012) and alkaline soils (Roadcap et al., 2006). Members of this phylum, including Clostridia and Bacilli, display wide metabolic versatility, ranging from facultative anaerobiosis to obligate anaerobiosis. Firmicutes have also been implicated in hydrocarbon degradation in oil-contaminated wetlands (John et al., 2011), highlighting their ecological and biotechnological significance.

3.10.4. Planctomycetes

Planctomycetes accounted for 7,310 sequences (~5.2%), with relative abundances of 12.70%, 12.26%, and 75.05% in Akwa Ibom, Bayelsa, and Rivers, respectively. Previously regarded as exclusively aquatic, members of this phylum are now recognized as key components of wetland soils (Prasanna et al., 2012). They are important contributors to nitrogen and carbon cycles, particularly through the activity of anaerobic ammonium-oxidizing (anammox) bacteria (Mori &

Kamagata, 2014). Additionally, certain Planctomycetes lineages have been linked with soil disease suppression and carbon cycling under fluctuating pH conditions (Niu et al., 2021).

3.10.5. Other Phyla

Chloroflexi (5.0%), Verrucomicrobia (3.7%), Nitrospirae (1.3%), and Bacteroidetes (1.3%) were also consistently detected across the study sites. Bacteroidetes, with 3,578 sequences, are widely known as anaerobic decomposers and saprophytesand are abundant in wastewater treatment and constructed wetland systems (Xiao et al., 2011; Dong & Reddy, 2010). Chloroflexi were found at varying proportions across locations, with abundance potentially linked to vegetation type, although their ecological roles remain poorly understood due to limited cultured representatives (Lucheta et al., 2013). Verrucomicrobia, though less abundant in this study compared to earlier reports (Shange et al., 2013), have been implicated in methane oxidation and nitrogen fixation (Sharp et al., 2014). Nitrospirae were enriched particularly in Bayelsa soil, likely reflecting adaptation to nitrogen-limited conditions. Members of this phylum, such as Nitrospira, are central to nitrification processes (Mhetea et al., 2020), and their relative abundance in Bayelsa may indicate an ecological strategy for nitrogen acquisition to sustain plant productivity in nutrient-deficient wetlands.

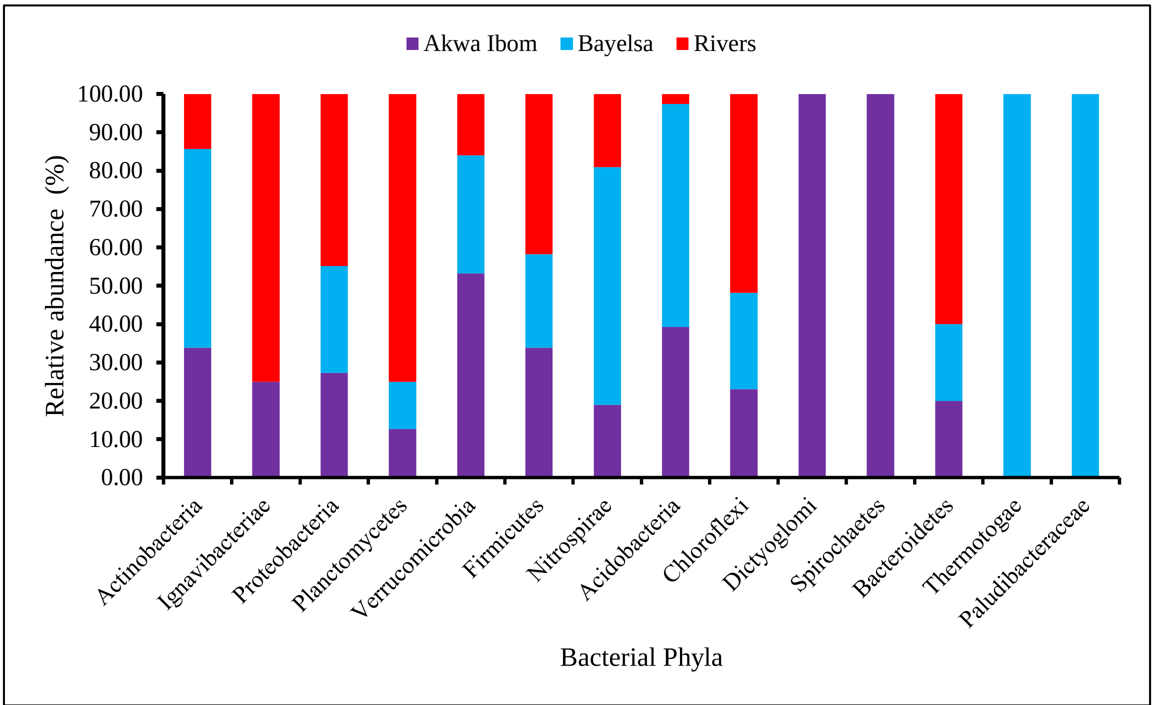

Figure 1 Relative abundance of bacterial phyla in wetland soil in Akwa Ibom, Bayelsa and Rivers States

4. Conclusion

The wetlands of South-South Nigeria exhibit distinct physicochemical and microbial properties that highlight their ecological importance and vulnerability to environmental change. Soils across Akwa Ibom, Bayelsa, and Rivers States were generally acidic, with variations in pH, organic carbon, nitrogen fractions, and exchangeable cations reflecting site-specific hydrological regimes, vegetation dynamics, and anthropogenic influences. Hydrocarbon content and electrical conductivity values were consistently low, indicating minimal contamination and negligible salinity constraints, thereby affirming the relatively unpolluted status of these ecosystems. Nonetheless, disparities in nutrient dynamics, particularly nitrogen and sulphate concentrations, underscore potential pressures from agricultural inputs and localized pollution sources. Bacterial community analyses revealed high taxonomic diversity dominated by Proteobacteria, Actinobacteria, Acidobacteria, and Firmicutes, with site-specific enrichments of specialized phyla such as Ignavibacteriae, Nitrospirae, and Planctomycetes. The predominance of functional groups involved in carbon, nitrogen, and sulphur cycling demonstrates the critical role of microbial assemblages in sustaining soil fertility and regulating biogeochemical processes. Variations in community composition were strongly linked to soil pH, organic carbon, and nutrient availability, consistent with the ecological drivers reported in other wetland ecosystems worldwide. Overall, the findings emphasize that physicochemical attributes and bacterial diversity jointly shape the ecological integrity and resilience of Nigerian wetlands. While the soils remain largely unpolluted, subtle nutrient imbalances and acidification tendencies call for proactive monitoring and management to safeguard their ecosystem services. Protecting these wetlands is vital not only for local livelihoods and agricultural productivity but also for maintaining biodiversity, climate regulation, and global biogeochemical stability.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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