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PAPER



# The contribution of roadside soil to phosphorus loading in the eutrophic Lagos Lagoon, Nigeria

**Akeem Abayomi,[ab] Malcolm Nimmo,[b] Claire Williams,[b] Kehinde O. Olayinka,[a] Bola Osuntogun,[a] Babajide Alo[a] and Paul J. Worsfold[b]**

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Roadside soils were sampled from the Lagos Lagoon catchment during the wet and dry seasons over the period 2005–2009. Lagoon sediment samples were also collected within the same period. All samples were digested with *aqua regia* to determine total phosphorus and extracted with 0.5 M sodium bicarbonate to determine the bioavailable fraction (Olsen-P). A segmented flow analyser method was used for analysis and good accuracy was demonstrated for two reference soils (SO-2 from CCMET and SRM 2711 from NIST). The Lagos Lagoon is a hypereutrophic water body (1270 ± 1170 μg P $L^{-1}$), with significant areas of anoxia and water hyacinth growth. The total phosphorus concentrations in roadside soils (16 sites; mean ± 2 S.D.) were 285 ± 279 mg $kg^{-1}$ in the wet season and 424 ± 629 mg $kg^{-1}$ in the dry season, indicating that rainwater leaching is a major source of phosphorus in the lagoon. The bioavailable fractions were 5.17 ± 3.47 mg $kg^{-1}$ (2.1 ± 1.5% of the total) in the wet season and 13.0 ± 8.7 mg $kg^{-1}$ (4.3 ± 4.5% of the total) in the dry season.

## 1. Introduction

Increasing urbanisation and agricultural activities have led to widespread discharges of nutrients, particularly phosphorus, into water bodies, including coastal waters.[1] Excessive inputs can lead to eutrophication[2,3] with consequent increases in harmful algal blooms and turbidity and expanded regions of hypoxia.[4–6] A variety of natural and anthropogenic sources input phosphorus to surface waters through different pathways and with significant temporal variability.[7] Anthropogenic inputs to receiving waters include point sources, such as wastewater discharges and industrial effluents, as well as diffuse sources, including road and track runoff, septic tank discharges and farm runoff.[8–10] The rapid urbanisation of coastal environments and the associated infrastructure, *e.g.* roads, housing and other built structures, has increased the imperviousness of catchments. This has exacerbated the mobilisation and export of phosphorus into coastal receiving waters. Aquatic ecosystems become impaired when as little as 10–15% of the catchment area is occupied by impervious surfaces.[7,11] Sources of phosphorus mobilised in urban runoff include atmospheric deposition, industrial debris, animal excreta, fertilisers, particulate emissions from vehicles (which eventually accumulate along road curbs and verges as roadside dust/soil), detergents and lubricants.[7,12]

In Lagos, as in most Nigerian towns and cities, many roads are unmetalled and roadside soil is therefore a permanent feature and a significant vector for pollutant transport to catchments, particularly during the wet season. Phosphorus can be transported in both the dissolved and particulate phases. There is usually an increase in particulate phosphorus transport with increasing erosion and runoff induced by greater rainfall

[a]Department of Chemistry, University of Lagos, Lagos, Nigeria
[b]Biogeochemistry and Environmental Analytical Chemistry Group, Biogeochemistry Research Centre, University of Plymouth, Plymouth, PL4 8AA, Devon, UK. E-mail: p.worsfold@plymouth.ac.uk

### Environmental impact

A variety of natural and anthropogenic sources input phosphorus to surface waters through different pathways and with significant temporal variability. This can lead to eutrophication and stimulate the production of harmful algal blooms. In developing countries rapid urbanisation, including extensive networks of unmetalled roads, can exacerbate the mobilisation and export of phosphorus from roadside soils into receiving waters. This study shows that Lagos metropolis is a significant source of phosphorus loading in the hypereutrophic Lagos Lagoon, particularly from sampling sites in close proximity to transport hubs. Concentrations for both total phosphorus and bioavailable phosphorus were generally higher and less variable in the dry season than the wet season, commensurate with leaching by intense periodic rain events.

 

intensity[13] and the higher the intensity of the rainfall the greater the proportion of particulate phosphorus in the total phosphorus export.[14]

About 22% of the total land mass of Lagos, situated on the southern-most tip of south western Nigeria, consists of a network of creeks, rivers and lagoons[15] and due to its equatorial location it experiences 50 to >700 mm of rainfall per month during the wet season. Most highways in the Lagos metropolis either run parallel to these numerous creeks and canals or have bridges across them and roadside soil becomes a significant potential vector for phosphorus transport to receiving waters during the rainy season. The Lagos Lagoon covers an area of >6000 km$^2$ and is the main pollutant sink for metropolitan Lagos as it receives unregulated and mostly untreated industrial and domestic effluents, sewage dumping and various other diffuse discharges. Thus, some parts of the Lagos Lagoon are highly eutrophic, with increasing levels of anoxia and other attendant effects including the proliferation of water hyacinth (*Eichhornia crassipes*).[15–17] The Lagos Lagoon is a shallow water body with a depth of 0.3–3 m[17] which facilitates phosphorus recycling from the sedimentary reservoir.[18] Due to the location of the lagoon within metropolitan Lagos there are no significant agricultural inputs of phosphorus although there may be small but unquantified inputs from more remote agrarian regions. There are likely to be inputs from industrial effluent, domestic waste and sewage as the lagoon serves as the main waste sink for Lagos but no quantitative data are available. Phosphorus export from roadside soils to the highly impacted Lagos Lagoon is likely to make a significant contribution to the total phosphorus input to the lagoon but data are sparse. Abayomi *et al.*[19] reported 2.5–18.2 mg kg$^{-1}$ of bioavailable phosphorus in roadside soil and 0.05–0.62 mg L$^{-1}$ of total phosphorus in runoff waters from the Lagos metropolis.

The aims of this study were therefore to determine the predominant sources and transport routes of total and bioavailable phosphorus from roadside soils to the receiving waters of the hypereutrophic Lagos Lagoon during contrasting wet and dry seasons over a five year period and to quantify the sedimentary phosphorus reservoir[20–22] in the lagoon over the same period. These data will facilitate more effective management of the water quality of the Lagos Lagoon by specifically targeting a lower trophic status and improved ecosystem health.

## 2. Experimental

### 2.1. Study area and sampling methods

Roadside soil and lagoon sediment samples were collected from the Lagos Lagoon catchment. The roadside soil samples were collected during each wet (May–September) and dry (December–January) season between 2005 and 2009 from three areas: (A) Mile 2-Oshodi Highway (representative of an inland road with mixed industrial and residential influences), (B) Mile 2-Wharf Highway (representative of an inland-coastal road with industrial and commercial land use) and (C) Ijora-Marina-Ahmadu Bello Road (representative of a coastal road with mainly commercial/administrative land use). Seven accessible locations in the Lagos Lagoon system receiving runoff water and roadside soil during rain events were also sampled (see Table 1 and Fig. 1). Soil and sediment samples were collected using a plastic scoop and a homemade sediment grab sampler respectively. Samples were stored in polyethylene bags previously rinsed with 2% m/v nitric acid and then Milli-Q water and air dried. Water samples were stored in similarly cleaned 2 L polyethylene bottles.

### 2.2. Procedures

Soils and sediments were air dried, sieved through a 2 mm mesh and 2 g of each sample separately weighed into 50 mL beakers and 15 mL *aqua regia* (3 : 1 v/v concentrated HCl : $HNO_3$, Sigma Aldrich, Analytical grade) was added.[23] Each beaker was covered with a watch glass and placed on a hot plate at 50 °C for 60 min and then 100 °C for 300 min. During the course of the heating, a further 10 mL of *aqua regia* was added when the volume of the mixture in the beaker was reduced to 5 mL. The resulting mixtures were cooled and transferred into acid washed (10% m/v HCl) 25 mL volumetric flasks and made up to volume with Milli-Q water. The digest solutions were then filtered through hardened ashless filters (Whatman 540) into plastic tubes pre-washed with 10% m/v HCl, followed by subsequent rinses with Milli-Q water. Acid blanks and filter blanks were analysed with each batch of digested samples. Eighty µL of each digest was made up to 25 mL with Milli-Q water.

The bio-available phosphorus fraction (Olsen P) was determined by extracting about 2.5 g of each sediment/soil sample (weighed accurately) with 40 mL of 0.5 M $NaHCO_3$.[24] Each mixture was shaken for 30 min on a reciprocating shaker and the supernatant filtered through a 0.45 µm cellulose acetate membrane. One mL of each filtrate was diluted to 25 mL with Milli-Q water to give final concentrations within the linear range of the segmented flow analyser.

The phosphorus concentration was determined in triplicate for every sample collected using a segmented flow analyser (Skalar SAN$^+$) method[25] operated in an ISO 9000:2001 accredited environment. Detection was based on the spectrophotometric molybdenum blue method.[26] Aqueous phosphorus standards in the range 20–240 µg P L$^{-1}$ were prepared daily from potassium dihydrogen phosphate (Sigma Aldrich, Analytical grade). The accuracy was determined by digesting 0.25 g ($n$ = 2) of two soil certified reference materials, SO-2 (Canada Centre for Mineral and Energy Technology) and SRM 2711 (National Institute of Standards and Technology, USA), as described above.

A one way ANOVA was applied to all datasets for each population representing each sampling site. A follow up Tukey multi-comparison test was applied in conjunction with the ANOVA to determine which sampling sites and environmental conditions (wet/dry) gave significantly different results at the 95% confidence level for total and bioavailable phosphorus.

## 3. Results and discussion

### 3.1. Method validation

The segmented flow analyser calibration graph obtained had a gradient of 14.5 counts per µg P L$^{-1}$, a 0.0 intercept and a correlation coefficient ($r$) of 0.9991. The limit of detection (blank + 3 S.D. of the blank) was 3.7 µg P L$^{-1}$. The recovery obtained for the reference materials used was 95.3% and 93.3% for SO-2 and SRM 2711 respectively. The calculated expanded

Table 1 Sampling locations for roadside soil and sediment from the Lagos Lagoon catchment

| Mile 2-Oshodi Highway | Mile 2-Wharf Highway | Ijora-Marina-Ahmadu Bello Road | Lagos Lagoon |
|---|---|---|---|
| A1 Mile 2 North | B1 Mile 2 South | C1 Ijora Olopa | L1 off Akoka (3rd Mainland Bridge) |
| A2 Itire | B2 Berger | C2 CMS | L2 off Oko-Baba |
| A3 Ijesha | B3 NPA | C3 Bonny Camp | L3 off Iddo |
| A4 Isolo | B4 Liverpool | C4 Bar Beach | L4 Ijora |
| A5 Oshodi | B5 Wharf | | L5 Leventis |
| | B6 Emergent | | L6 Cowry Creek |
| | B7 Receiving Water | | L7 Falomo |



uncertainties ($U_\Delta$; $k = 2$) were 242 and 74 mg P kg$^{-1}$ respectively. The differences between the certified values and the measured values ($\Delta_m$, Table 2) were lower than the expanded uncertainties ($U_\Delta$, Table 2)[27] which shows that there was no significant difference between the certified and measured values.

### 3.2. Total phosphorus in roadside soil

Particulate matter mobilised in runoff water accounts for the majority of phosphorus export from land to receiving waters.[28–30] In the context of water quality in the Lagos Lagoon it is therefore important to identify the sources with the greatest potential phosphorus input in order to develop targeted mitigation strategies.[31] The results obtained for total phosphorus concentrations in roadside soils from 16 locations are therefore summarised in Table 3. Generally, the concentrations measured during the wet season had higher temporal variability than those measured during the dry season. This is not surprising due to the widely variable length and intensity of rainfall events prior to and during each sampling event. Samples collected at the start of the wet season also had higher total phosphorus concentrations compared with samples collected later in the season due to flushing of the system after the dry season.[32] No samples were available for sites B6 and B7 during the dry season as these were runoff ducts and contained no soil.

The mean concentration range for total phosphorus in the different sampling locations was 73 ± 20 to 622 ± 514 mg P kg$^{-1}$ for the wet season and 170 ± 10 to 1320 ± 480 mg P kg$^{-1}$ for the dry season. These values are in the same range as those recently reported for roadside soil in Galway, Ireland[33] of 600–2400 mg kg$^{-1}$ and somewhat lower than the 3520 ± 320 mg P kg$^{-1}$ in road-deposited sediments sampled adjacent to intense traffic in Zhenjiang, China.[34] There was no significant difference between the observed concentrations for the wet and dry seasons at any of the sampling locations except for location A3, which had the highest wet season concentration for any site but also had the highest temporal variability, and locations B3, C1 and C2 for which the dry season concentrations were significantly higher, as shown in Fig. 2.

Location A3 is bordered to the west by an industrial estate (one of many in Lagos) and to the east by a densely populated neighbourhood. Traffic density at this location is around 4210 vehicles per hour with a significant percentage being heavy duty trucks, associated vehicles and commuter buses. The higher and more variable wet season concentrations at A3 are probably influenced by the higher population density surrounding this

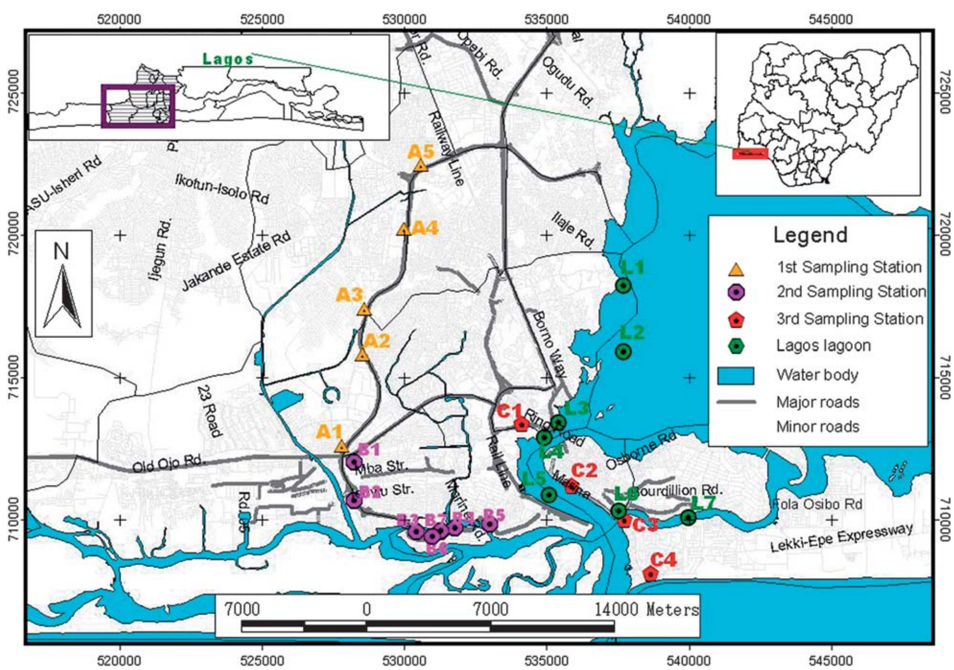


Fig. 1 Map of Lagos showing the roadside and Lagos Lagoon sampling locations.

 

**Table 2** Total phosphorus concentrations in certified reference materials using the segmented flow analyser

| | SO-2 | SRM 2711 |
|---|---|---|
| Experimental value ± 2 S.D./mg kg$^{-1}$ ($n$ = 6) | 2860 ± 332 | 802 ± 64 |
| Certified value ± 2 S.D./mg kg$^{-1}$ | 3000 ± 200 | 860 ± 70 |
| Recovery (%) | 95.3 | 93.3 |
| $\Delta_m$/mg kg$^{-1}$ | 140 | 58 |
| Expanded uncertainty $U_\Delta$/mg kg$^{-1}$ | 242 | 74 |

**Table 3** Total phosphorus concentrations (expressed as the mean ± 2 S.D.; mg kg$^{-1}$) in roadside soils from the Lagos Lagoon catchment sampled during wet and dry seasons over the period 2005–2009. $n$ = total number of analyses carried out, with the number of wet season analyses ($n$ = 6–18) given next to the sample location and $n$ = 6 for the dry season

| | Wet season | Dry season ($n$ = 6) |
|---|---|---|
| Sample location | Mean ± 2 S.D./mg kg$^{-1}$ | |
| A1 ($n$ = 18) | 196 ± 87 | 170 ± 10 |
| A2 ($n$ = 6) | 304 ± 14 | 321 ± 49 |
| A3 ($n$ = 15) | 622 ± 514 | 262 ± 10 |
| A4 ($n$ = 18) | 270 ± 180 | 266 ± 40 |
| A5 ($n$ = 18) | 342 ± 225 | 386 ± 17 |
| A (mean) | 347 ± 163 | 281 ± 80 |
| B1 ($n$ = 12) | 134 ± 46 | 302 ± 22 |
| B2 ($n$ = 12) | 208 ± 170 | 197 ± 21 |
| B3 ($n$ = 12) | 248 ± 189 | 535 ± 16 |
| B4 ($n$ = 12) | 250 ± 50 | 389 ± 92 |
| B5 ($n$ = 12) | 224 ± 170 | 329 ± 96 |
| B6 ($n$ = 12) | 226 ± 63 | — |
| B7 ($n$ = 12) | 73 ± 20 | — |
| B (mean) | 195 ± 66 | 350 ± 124 |
| C1 ($n$ = 12) | 419 ± 588 | 714 ± 181 |
| C2 ($n$ = 9) | 505 ± 214 | 1320 ± 480 |
| C3 ($n$ = 12) | 215 ± 126 | 264 ± 82 |
| C4 ($n$ = 12) | 325 ± 65 | 219 ± 117 |
| C (mean) | 393 ± 86 | 629 ± 512 |
| Overall mean | 285 ± 279 | 424 ± 629 |

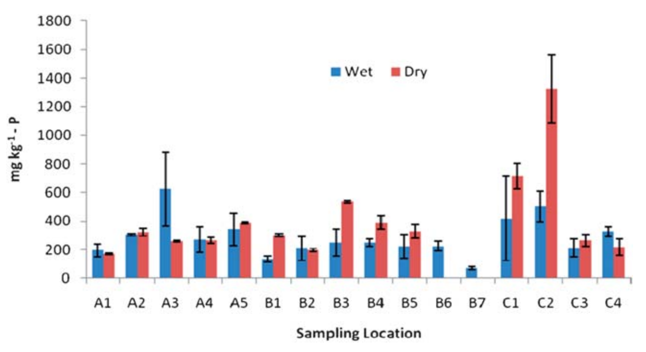


**Fig. 2** Comparative concentrations of total phosphorus (mg P kg$^{-1}$ ± 2 S.D.) in roadside soils from the Lagos Lagoon catchment for the wet and dry seasons over the period 2005–2009.

location. Location B3 is in close proximity to the port of Lagos and location C2 is the site of a major bus and ferry terminus linking mainland Lagos with the surrounding islands. Locations B3 and C2 are also major traffic hubs and this suggests a direct link between traffic density and higher total phosphorus concentrations in roadside soils, particularly during the dry season.

Further analysis of the dry season data showed that locations B3, C1 and C2 were significantly higher than the other sites. Similarly for the wet season, locations A3, C1 and C2 were significantly higher, which reinforces the view that a major source of phosphorus loading in the Lagos Lagoon is the mobilisation of roadside soil in close proximity to transport hubs. Location B7 was significantly lower due to the low organic matter content (0.29% m/m) and sandy nature of the sediment.

## 3.3. Bioavailable phosphorus in roadside soil

The results obtained for sodium bicarbonate (Olsen-P) extractable phosphorus (hereafter defined as bioavailable phosphorus) are summarised in Table 4. The concentrations for bioavailable phosphorus showed greater variability in the wet season compared with the dry season for the same reasons as those given above for total phosphorus. Another feature of the data is the consistently lower inter-site variability for the wet season data compared with the dry season, particularly for the Mile 2-Wharf Highway locations (B1–B7), suggesting a more consistent bioavailable phosphorus fraction in the solid phase that is not leached by interaction with rainwater but is leached by the standard Olsen P protocol.

The mean concentration range for bioavailable phosphorus for the different sampling locations was 2.57 ± 0.64 to 9.4 ± 5.1 mg P kg$^{-1}$ for the wet season and 4.8 ± 0.7 to 22.0 ± 0.9 mg P kg$^{-1}$ for the dry season. On a site by site basis the dry season values were consistently significantly higher than the wet season values, due to leaching of bioavailable phosphorus during intense rain events, as shown in Fig. 3. The bioavailable fraction ranged from 1.0–3.5% of total phosphorus for the wet season (with a mean of 2.1%) and 0.8–8.3% for the dry season (with a mean of 4.3%). These data are in the same range as those reported for roadside soil in Shenzhen, China[35] of 6.31 ± 0.51 mg P kg$^{-1}$ and a 3.3% bioavailable fraction using the same extraction method. A study of 32 Portuguese soils found bioavailable phosphorus concentrations in the range 2.5–116 mg P kg$^{-1}$, with a mean ± 1 S.D. of 29.4 ± 28.8 and a median of 20.2 mg P kg$^{-1}$, and a mean bioavailable fraction of 2.7%.[36] Hence the bioavailable fraction in the roadside soils is in the same range as representative Portuguese agricultural soils.

## 3.4. Phosphorus in the Lagos Lagoon

A single sampling campaign of the Lagos Lagoon water column at the seven locations (L1–L7) was undertaken in July 2009 (wet season) and the results are shown in Table 5. This limited dataset confirms that the lagoon is hypereutrophic with high spatial variability in dissolved reactive phosphorus. Lagoon sediment samples were collected from the same locations and the total phosphorus and bioavailable phosphorus concentrations are also shown in Table 5. The mean concentrations for all sites were 468 ± 387 mg P kg$^{-1}$ total phosphorus and 10.4 ± 6.2 mg P kg$^{-1}$ bioavailable phosphorus (4.0 ± 4.8% bioavailable; decreasing to 2.3 ± 1.5% if location L5 is excluded). This indicates an accumulation of total phosphorus in the lagoon sediment compared with roadside soils, *i.e.* the sediment is acting as a sink, but

**Table 4** Bioavailable phosphorus (Olsen P) concentrations (expressed as the mean ± 2 S.D.; mg kg$^{-1}$) in roadside soils from the Lagos Lagoon catchment sampled during wet and dry seasons over the period 2005–2009. $n$ = total number of analyses carried out, with the number of wet season analyses ($n$ = 6–18) given next to the sample location and $n$ = 6 for the dry season

| | Wet season | | Dry season ($n$ = 6) | |
|---|---|---|---|---|
| Sample location | Mean ± 2 S.D./mg kg$^{-1}$ | Bioavailable fraction (%) | Mean ± 2 S.D./mg kg$^{-1}$ | Bioavailable fraction (%) |
| A1 ($n$ = 18) | 3.56 ± 2.16 | 1.8 | 12.6 ± 1.1 | 7.4 |
| A2 ($n$ = 6) | 3.76 ± 0.44 | 1.2 | 17.3 ± 0.3 | 5.4 |
| A3 ($n$ = 18) | 7.94 ± 3.58 | 1.3 | 13.6 ± 2.8 | 5.2 |
| A4 ($n$ = 18) | 6.43 ± 8.04 | 2.4 | 12.8 ± 1.1 | 4.8 |
| A5 ($n$ = 18) | 4.72 ± 1.20 | 1.4 | 22.0 ± 0.9 | 5.7 |
| A (mean) | 5.28 ± 1.87 | 1.6 | 15.7 ± 4.0 | 5.7 |
| B1 ($n$ = 12) | 4.72 ± 0.76 | 3.5 | 11.7 ± 0.4 | 3.9 |
| B2 ($n$ = 12) | 4.09 ± 0.74 | 2.0 | 11.4 ± 0.3 | 5.8 |
| B3 ($n$ = 12 | 5.47 ± 2.40 | 2.2 | 16.3 ± 0.3 | 3.0 |
| B4 ($n$ = 12) | 4.18 ± 1.58 | 1.7 | 11.1 ± 0.2 | 2.9 |
| B5 ($n$ = 12) | 4.99 ± 5.70 | 2.2 | 8.3 ± 0.6 | 2.5 |
| B6 ($n$ = 12) | 5.33 ± 3.26 | 2.4 | — | — |
| B7 ($n$ = 12) | 2.57 ± 0.64 | 3.5 | — | — |
| B (mean) | 4.48 ± 0.99 | 2.5 | 11.9 ± 4.1 | 2.8 |
| C1 ($n$ = 12) | 4.60 ± 2.20 | 1.0 | 4.80 ± 0.70 | 0.7 |
| C2 ($n$ = 12) | 6.80 ± 3.50 | 2.0 | 10.7 ± 0.4 | 0.8 |
| C3 ($n$ = 12) | 4.20 ± 2.70 | 1.5 | 10.9 ± 0.5 | 4.1 |
| C4 ($n$ = 12) | 9.40 ± 5.10 | 2.9 | 18.2 ± 0.1 | 8.3 |
| C (mean) | 6.25 ± 2.39 | 1.9 | 9.73 ± 5.71 | 3.5 |
| Overall mean | 5.17 ± 3.47 | 2.1 ± 1.5 | 13.0 ± 8.7 | 4.3 ± 4.5 |

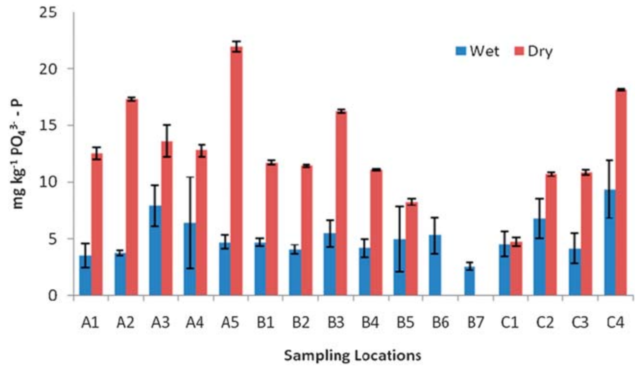


**Fig. 3** Comparative concentrations of bioavailable phosphorus (Olsen P; mg P kg$^{-1}$ ± 2 S.D) in roadside soils from the Lagos Lagoon catchment for the wet and dry seasons over the period 2005–2009.

a lower percentage of bioavailable phosphorus, commensurate with biological uptake.

Location L3 had the highest total and bioavailable phosphorus concentrations of 1204 ± 172 and 20.9 ± 0.62 mg P kg$^{-1}$ respectively, with the total phosphorus concentration significantly different from all other sites, which was due to its proximity to a large sewage discharge point and the major saw mill for Lagos (Oko-Baba). Pulp and paper industries can discharge high loads of phosphorus in their wastewaters; for example a Finnish paper mill discharged 162 tonnes of phosphorus in 2005.[37] The total phosphorus concentration at this location was comparable with the range reported for surface sediments of the eutrophic Tamar Estuary in SW England of 806–1580 mg P kg$^{-1}$.[22] The lowest total phosphorus concentration (65.9 ± 31.8 mg P kg$^{-1}$) and the highest bioavailable phosphorus fraction (14.4%) were observed at L5, which also had the lowest organic matter content (1.14%) and was a much sandier sediment (60 μm to 2 mm particle size range) than the other lagoon locations, which were

**Table 5** Total phosphorus and bioavailable phosphorus (Olsen P) concentrations (expressed as the mean ± 2 S.D.; mg kg$^{-1}$) in sediments from the Lagos Lagoon sampled over the period 2005–2009 and water column dissolved reactive phosphorus (DRP) concentrations collected in a single sampling campaign in 2009

| | Total P ($n$ = 6) | Bioavailable P ($n$ = 6) | | |
|---|---|---|---|---|
| Sample location | Mean ± 2 S.D./mg kg$^{-1}$ | | Bioavailable P (%) | Water column DRP/mg P L$^{-1}$ |
| L1 | 327 ± 15 | 4.65 ± 0.76 | 1.4 | 0.91 |
| L2 | 619 ± 33 | 7.45 ± 0.26 | 1.2 | 1.26 |
| L3 | 1200 ± 170 | 20.9 ± 0.6 | 1.7 | 3.83 |
| L4 | 254 ± 101 | 4.52 ± 0.52 | 1.8 | 0.68 |
| L5 | 65.9 ± 31.8 | 9.48 ± 0.84 | 14.4 | 0.62 |
| L6 | 175 ± 96 | 8.90 ± 0.78 | 5.1 | 0.45 |
| L7 | 637 ± 4 | 17.0 ± 0.28 | 2.7 | 1.15 |
| L (mean) | 468 ± 387 | 10.4 ± 6.2 | 4.0 ± 4.8 | 1270 ± 1170 |

 

predominantly clay (<2 μm). Location L5 is also more remote from direct exposure to roadside runoff and other anthropogenic inputs than locations L6 and L7 which are adjacent to the Ijora-Marina-Ahmadu Bello Road.

## 4. Conclusions

The phosphorus concentrations in roadside soils from a spatially resolved sampling campaign support the conclusion that mobilisation of soils in close proximity to transport hubs is a major source of phosphorus loading in the hypereutrophic Lagos Lagoon. Concentrations for both total phosphorus and bioavailable phosphorus were generally higher and less variable in the dry season than the wet season, commensurate with leaching by intense periodic rain events. The results also show a small but consistent fraction of bioavailable phosphorus that is extracted by the bicarbonate leach but is resistant to leaching by rainwater.

The sampling scheme was designed to investigate a number of contrasting locations and the results suggest that future campaigns should target locations adjacent to key transport hubs and point source discharges such as sewage discharges. There should also be a focus on higher temporal resolution sampling during the wet season and the simultaneous collection of water samples (to measure both total and dissolved reactive phosphorus) and flow data to enable flux and load calculations.

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## References

1 D. F. Boesch, E. Burreson, W. Dennison, E. Houde, M. Kemp, V. Kennedy, R. Newell, K. Paynter, R. Orth and R. Ulanowicz, *Science*, 2001, **293**, 1589.
2 R. E. Turner and N. N. Rabalais, *Nature*, 1994, **368**, 619.
3 A. J. Lyddy-Meaney, P. S. Ellis, P. J. Worsfold, E. V. C. Butler and I. D. McKelvie, *Talanta*, 2002, **58**, 1043.
4 N. N. Rabalais, R. E. Turner, D. Justić, Q. Dortch, W. J. Wiseman and B. K. Sen Gupta, *Estuaries*, 1996, **19**, 386.
5 H. W. Paerl, L. M. Valdes, B. L. Peierls, J. E. Adolf and L. W. Harding, Jr, *Limnol. Oceanogr.*, 2006, **51**, 448.
6 B. Alo, B. Orgu and A. Abayomi, *Eur. J. Sci. Res.*, 2010, **40**, 279.
7 P. J. A. Withers and H. P. Jarvie, *Sci. Total Environ.*, 2008, **400**, 379.
8 P. Haygarth, B. L. Turner, A. Fraser, S. C. Jarvis, T. Harrod, D. Nash, D. Halliwell, T. Page and J. K. Beven, *Hydrol. Earth Syst. Sci.*, 2004, **8**, 88.
9 A. C. Edwards and P. J. A. Withers, *J. Hydrol.*, 2008, **350**, 144.
10 P. Jordan, J. Arnscheidt, H. McGrogan and S. McCormick, *Hydrol. Earth Syst. Sci.*, 2007, **11**, 372.
11 L. Wang, J. Lyons, P. Kenehl, R. Bannerman and E. Emmons, *J. Am. Water Resour. Assoc.*, 2000, **36**, 1173.
12 M. J. Dunk, S. M. McMath and J. Arikans, *Water Environ. J.*, 2007, **22**, 32.
13 J. N. Quinton, J. A. Catt and T. M. Hess, *J. Environ. Qual.*, 2001, **30**, 538.
14 F. Shigaki, A. Sharpley and L. I. Prochnow, *Sci. Total Environ.*, 2007, **373**, 334.
15 M. A. Adewolu, S. L. Akintola, A. A. Jimoh, F. G. Owodehinde, O. O. Whenu and K. A. Fakoya, *Eur. J. Sci. Res.*, 2009, **34**, 337.
16 O. T. Adebayo, A. M. Balogun and O. A. Olubiyi, *Res. J. Environ. Sci.*, 2007, **1**, 196.
17 E. Ekiye and L. Zejiao, *J. Am. Sci.*, 2010, **6**, 22.
18 M. Søndergaard, J. Windolf and E. Jeppesen, *Water Res.*, 1996, **30**, 992.
19 A. A. Abayomi, K. O. Olayinka, B. Osuntogun and B. I. Alo, *J. Sci. Res. Dev.*, 2010, **10**, 51.
20 B. Boström, J. M. Andersen, S. Fleischer and M. Jansson, *Hydrobiologia*, 1988, **170**, 229.
21 R. G. Perkins and G. J. C. Underwood, *Water Res.*, 2001, **35**, 1399.
22 P. Monbet, I. D. McKelvie and P. J. Worsfold, *J. Environ. Monit.*, 2010, **12**, 296.
23 A. R. Crosland, F. J. Zhao, S. P. McGrath and P. W. Lane, *Commun. Soil Sci. Plant Anal.*, 1995, **26**, 1357.
24 S. R. Olsen, C. V. Cole, F. S. Watanabe and L. A. Dean, *USDA Circular No. 939, 1*, US Government Printing Office, Washington DC, 1954.
25 C. F. C. Gardolinski, G. Hanrahan, E. P. Achterberg, M. Gledhill, A. D. Tappin, W. A. House and P. J. Worsfold, *Water Res.*, 2001, **35**, 3670.
26 J. Murphy and J. P. Riley, *Anal. Chim. Acta*, 1962, **27**, 31.
27 T. Linsinger, Application Note 1, European Commission—Joint Research Centre Institute for Reference Materials and Measurement (IRMM), Geel, Belgium, 2005.
28 A. N. Sharpley, S. C. Chapra, R. Wedepohl, J. T. Sims, T. C. Daniel and K. R. Reddy, *J. Environ. Qual.*, 1994, **23**, 437.
29 C. L. Douglas, K. A. King and J. F. Zuzel, *J. Environ. Qual.*, 1998, **27**, 1170.
30 R. Uusitalo, M. Yli-Halla and E. Turtola, *Water Res.*, 2000, **34**, 2477.
31 G. Mitchell, *J. Environ. Manage.*, 2005, **74**, 1.
32 J. J. Sansalone and C. M. Cristina, *J. Environ. Eng.*, 2004, **130**, 1301.
33 L. Dao, L. Morrison and C. Zhang, *Sci. Total Environ.*, 2010, **408**, 1076.
34 B. Bian and W. Zhu, *Environ. Geochem. Health*, 2009, **31**, 511.
35 Z. J. Shi, Y. Lu, Z. G. Xu and S. L. Fu, *Plant, Soil Environ.*, 2008, **54**, 341.
36 M. do Carmo Horte and J. Torrent, *Nutr. Cycling Agroecosyst.*, 2007, **77**, 283.
37 F. Blomfelt, *Paperi ja Puu/Paper and Timber*, 2006, **88**, 196.