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RESEARCH ARTICLE

Spatiotemporal modeling of nutrient retention in a tropical semi-arid basin

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ABSTRACT

The Sokoto-Rima basin defines the natural and socioeconomic lifeblood of northwestern Nigeria. Its agrarian nature is an indication of significant dependence on the supply of ecosystem services from its various rivers, streams, and wetlands. However, nitrogen (N) and phosphorus (P) constitute a great portion of chemical fertilizers used to enhance crop yields and poor management of these portend great threats for water quality. The overarching objective of this study was to examine the extent of spatial variation of nutrient dynamics in the Sokoto-Rima basin between 1992 and 2015 using the nutrient delivery ratio (NDR) model of InVEST (Integrated Valuation of Ecosystem Service and Tradeoffs) software. Land use/landcover, precipitation, digital elevation, and biophysical variables were the principal datasets employed as model input. The result of the study showed that the surficial N load is almost 15-fold of P in the Sokoto-Rima basin. Over the period of study, cultivated areas and rivers were spatially detected as nutrient sources and sinks respectively. The subsurface nutrient load is dominated by P while the amount of N load is insignificant. The trend of nutrient export is linearly defined: with 0.87% and 1.7% increase in N and P export respectively during 1992-2015. N and P exports vary spatially with a north-south increase-decrease index. Critical length and threshold are highly sensitive to changes in the parameterization of the NDR model. Thus, synergistic cultivation practices such as agroforestry should be extended to existing crop cultivation complexes to curtail nutrient enrichment in the Sokoto-Rima basin and ensure environmental sustainability.

Keywords: Ecosystem services, InVEST, nutrient modeling, semi-arid, Sokoto-Rima basin, spatial variation.

1. INTRODUCTION

One of the numerous ways in which anthropogenic activities alter the natural nutrient cycling of any ecosystem is through land use/landcover changes particularly agricultural expansion [1-2]. The nutrient flow is a vital ecosystem service that controls ecosystem integrity. Any change in the pattern of land use/landcover can disrupt this natural pathway leading to distortions in ecosystem functioning and intactness [4-6]. The non-point sources of nutrient discharge from domestic and agricultural activities constitute a high proportion of human-induced distortions to the natural nutrient flow in any ecosystem [3, 7]. Within tropical systems, particularly in semi-arid areas of the world where agriculture determines the lifeblood of the local economy, this scenario persists. In such agrarian systems, rainwater flows over the landscape washing away natural soil minerals, animal manure, chemical fertilizers and wastes from domestic sources into abutting streams and rivers [8]. This causes great threat to both human health and welfare [9] as well as aquatic life in the water bodies. Further, it triggers eutrophication of the bodies and general aquatic pollution [10, 11].

Series of measures have been enumerated in literature towards amending this phenomenon. Naturally, vegetated ecosystems can remove pollutants via photosynthetic uptake, tissue storage or via nutrient-fixation mechanisms [12, 13]. Non-polluted soil and wetlands also provide suitable pollution-mitigation by stimulating nutrient storage prior to in-washing into proximate hydrological systems [13-15]. However, in the engagement of pollution control measures within agrarian milieu, nutrient loads are often assessed by estimating the proportion of specific nutrients that are present within identifiable non-point sources across the

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landscape [3-4, 8-9]. Two of the most common pollutants in virtually any landscape is nitrogen (N) and phosphorus (P) from different environmental sources [12-14]. N and P impact within cultivated systems are circularly causal. N fixation processes in plants are often boosted by P in certain semi-arid crops thereby increasing level of harvest. Studies across the global semi-arid basins suggest that N and P driven nutrient load exist in higher proportion within cultivated areas than any other land use/landcover classes [13-14]. For instance, Meng et al. [12], stated that 68% of the pollutants within the agricultural region of Fenhe River are N compounds. Hobbie et al. [16], conducted a study across the extensive terrestrial ecosystem of the Mississippi River in the Capitol Region Watershed (CRW) of the United States, and results showed that 22-80% of net N and P inputs from cultivated regions were retained in the basin while the difference was washed downstream. Further, Hahm et al. [15] asserted that semi-arid areas tend to erode nutrients more than forested regions, thus eutrophication and nutrient-filled hydrological bodies subsist downstream.

Geochemical characterisation of semi-arid water bodies such as lakes, streams and rivers have been studied showing heavy nutrient loads with little or no focus on retention capacities [3, 5, 6, 8, 10]. For instance, Adimalla and Venkatayogi [10] stressed that semi-arid soils of the Basara region of India have been polluted by nitrates and phosphates with grave consequences on water users. In addition, Meng et al. [12] asserted that sediment characteristics of agrarian landscapes of the Shanxi Province of China showed that the natural traits of the river systems. Within the context of Nigeria, studies such as [14, 17-20] suggest that the country is not invulnerable to the realities of this problem particularly to water quality and river eutrophication.

Literature has shown that the surface and groundwater quality of the Sokoto-Rima basin has been altered by series of human activities. This has been attributed to industrial effluent discharge into streams [18, 19], and soil enrichment sources [14, 18, 20, 21]. Magami and Sani [14] used the point-based sample collection method to analyse the temporal variations of N and P of Kware Lake with respect to proximate human activities and the result showed that the N and P varies directly with human-induced sedimentation of the freshwater ecosystem. Equally, Raji et al. [18] analysed physicochemical parameters of water samples of the Sokoto River to determine seasonal variations of its water quality. The result showed that the planting season distressed the aggregated physical properties of the river. Adelana et al. [20] examined surface water and groundwater characterisation of the Sokoto-Rima basin with respect to isotopic and geochemical traits, and the outcome of the study showed that low nutrient loads of the identified soil groups varies proportionately with places of intense cultivation. Abubakar and Ipinjolu [21] investigated the level of certain anions of the Argungu River using direct analysis method, and the results showed that the river low pollution status of the nutrient loads were detected in areas of less human disturbance.

In these previous studies on the Sokoto-Rima basin, not much attention has been given to the nutrient cycling and flow which are vital ecosystem services [1-2, 11]. This lacuna has also restricted the identification of key locations of nutrient sources and sinks thus making environmental management of the nutrient cycling difficult. In this study, an attempt is made to narrow these gaps spatially characterising the nutrient delivery pathway of the Sokoto-Rima basin using the Nutrient Delivery Ratio model of InVEST software. This model is generates output of N and P across the landscape via geographic information system (GIS) approach. This approach consequently provides a spatial visualization and variation of the nutrient flow of the Sokoto-Rima basin. Findings of this study can provide a scientific reference for spatiotemporal assessment of nutrient pathway for the semi-arid region of West Africa.

2. MATERIALS AND METHODS

2.1. The study area

The study was conducted in the Nigerian section of the West African transnational hydrological basin known as Sokoto-Rima basin. It is bounded in the north by Niger Republic, and in the west by Benin Republic while in the east and south by Katsina and Niger States of Nigeria. Its geographical location is defined by Latitudes 10°32'35'' N to 13°32'55'' N and Longitudes 3°30'30'' E to 8°1'15'' E and the total land area is 94,026.5 km^2 (Fig. 1). The semi-arid climate of tropical savanna of West Africa dictates the environmental condition of the study area. Precipitation (mostly rainfall) is typically seasonal, quasi-monsoonal in nature; confined to the wet season. Annual rainfall ranges between 350 mm to 895 mm in the northern and southern ends typifying a north-south rainfall increase index. Through the year, diurnal temperature averages 300 C with significant seasonal variability. Vital to nutrient flow is the hydrological network which flows westwards from the eastern highlands and ends southwards into the River Niger. The rock typology is dominated by the basement complex that is spatially restricted to the east. The sedimentary basin of the central and southern axis is activated by the hydrologic and hydraulic activities of the Sokoto and Rima Rivers with several spots of rolling hills (Fig. 1). The population of the Sokoto-Rima basin exemplifies that of an agrarian landscape with low density. According to the National Population Commission of Nigeria, the population of the study area was 6,538,666 in 1991, it increased to 10,238,090 by 2006 with a resultant annual growth rate of 3.11% [27]. The population figure is projected to rise to 15,719,183 by the year 2020 with population density of 167.18 persons per square kilometre. Small-scale and climate-dependent agriculture is the mainstay of the Sokoto-Rima basin. Major crops grown include rice, tomatoes, sorghum, maize, and millet. Others such as soybeans, cowpea and peanuts which are nutrient-fixing crops were cultivated in subsistence scale.

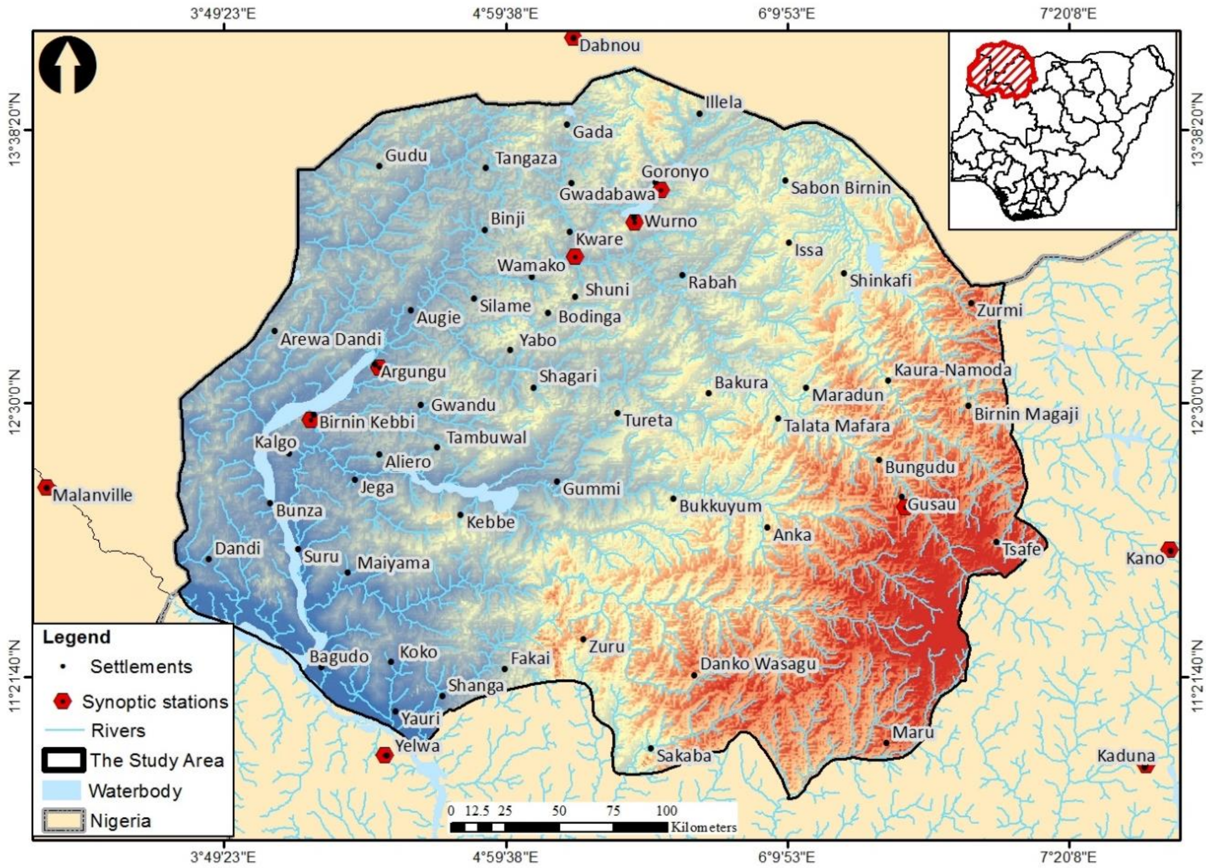

Fig 1. Geographical location of the Sokoto-Rima basin in context of northwestern part of Nigeria with the hydrological network and relief

2.2. *Data sources*

The land use/landcover data from the Climate Change Initiative (CCI) of the European Space Agency (ESA) was used as data spine for land use/landcover characterization of the study. The pre-classified data has 300 metres spatial resolution with auto-rectified benefits nullifying further image registration and rectification tasks. It has a dynamic range of 32-bit which is wide enough for detection of homogenous land use/landcover classes. It also has regional coverage thus preventing edge-matching errors and continuous phenomenal assessment; an advantage it possesses over existing remotely sensed data sources such as Landsat and Sentinel. Data for the years 1992, 2002, 2012, and 2015 were sourced based on availability at http://maps.elie.ucl.ac.be/CCI/viewer/profiles.php.

Nutrient runoff proxy data was based on mean annual rainfall which acquired from climate synoptic stations within and outside the basin to permit proximate geographic coverage. The data were acquired from Sokoto, Yelwa, Birnin Kebbi, Argungu, Gusau, Goronyo, Wurno, Kano, and Kaduna in Nigeria and Malanville in Benin Republic and Niger Dabnou in Niger. Data for the years 1992, 2002, 2012 and 2015 were to match the previously explained landuse/landcover datasets extracted for the study. Data within the Nigerian territory was acquired from the Nigerian Meteorological Agency (NIMET) of Nigeria additional datasets for Benin (Malanville) and Niger (Dabnou) were sourced from Princeton University's Climate Analytics (PCA) web-portal via https://platform.princetonclimate.com/PCA_Platform/.

Digital Elevation Model (DEM) data was extracted from the West African grid of the ALOS World 3D Digital Surface Model (DSM) version 2.2 data obtained from the digital libraries of Japan Aerospace Exploration Agency (JAXA) through https://www.eorc.jaxa.jp/. The data has a 30-metre spatial resolution and a 32-bit quantisation resolution which is sufficient for feature detection consistency.

2.3. Quantifying nutrient retention

The Nutrient Delivery Ratio (NDR) model, an integrated module of the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) software package, was employed to spatiotemporally quantify nutrient (nitrogen and phosphorus) retention. InVEST is a free and open-source software package with extensive utility for modeling and assessing diverse ecosystem services principally based on land use/landcover dynamics in conjunction with other environmental variables [1, 11]. The NDR model employs a mass-balance approach to spatially simulate the flow of N and P as influenced by the inherent natural vegetation and other nutrient constraining and stimulating factors. The outcome of the model generates raster datasets that with spatial information about nutrient loads (nutrient sources), exports, and the actual NDR for each of N and P. Data inputs into the NDR model include the prior described data on DEM, land use/landcover, and nutrient runoff.

The associated biophysical parameters are classified into tabulated data which include nutrient loads, retention efficiency, and subsurface proportion for N and P respectively (see Table 1). The software default value of 2.4 for Borselli K parameter (calibration function between hydrologic and sediment flow) was retained while threshold flow accumulation value was set at 10,000 which corresponds to 300 m data resolution. Three outputs were thus modeled from the NDR simulation.

Table 1. Land use/landcover based biophysical variables used for nutrient modeling

Land use/Landcover description	Load (N)	Efficiency (N)	Critical length (N)	Proportion subsurface (N)	Load (P)	Efficiency (P)	Critical length (P)	Proportion subsurface (P)
Cropland	89	0.5	25	0.3	3.57	0.48	15	0.01
Agroforestry	89	0.6	50	0.25	2.48	0.54	15	0
Shrubland	8	0.75	150	0.47	0.93	0.6	25	0
Grassland	8	0.75	150	0.47	0.93	0.6	30	0
Waterbody	2	0.05	10	0.66	0	0.4	15	0
Settlements	10	0.1	10	0.2	2.1	0.26	15	0
Bare surface	5	0.01	10	0.47	0.79	0.26	15	0
Woodland	2.8	0.8	300	0.47	1.4	0.67	20	0

Adapted from [3, 11, 22]

Surface NDR concentrates on the surficial traits of the basin defined by the multiplication delivery factor (downstream nutrient transportation excluding retention) and topographic position of the landscape. Mathematically, this is expressed as:

$$NDR_I = NDR_{0,I}\left(1 + exp\left(\frac{IC_i - IC_0}{k}\right)\right)^{-1} \quad (1)$$

where: IC_0 and k are calibration parameters, IC_i is topographic index computed from the DEM data, and $NDR_{0,I}$ is the ratio of retained nutrient by pixels downstream the landscape of the basin.

Subsurface NDR which is the second output is based on geographic function of distance decay or the first law of geography which states that closer events are spatially connected than distant events. The subsurface NDR relates with distance to stream and the utmost subsurface nutrient holding and it is defined in equation (2) as:

$$NDR_{subs,1} = 1 - eff_{subs}\left(1 - e^{\frac{-5.l}{l_{subs}}}\right) \quad (2)$$

where: eff_{subs} is the maximum retention efficiency traceable through the subsurface pathway in the multispectral space (retention as a function of biochemical degradation in soils), l_{subs} is the subsurface flow retention length detected at soil maximum capacity (that is the space after which it can be implicit that soil retains nutrient at its maximum capacity,), l_i is the distance from the pixel to the stream.

Nutrient export from a given multispectral location is a function of the nutrient load and the NDR, this is further explained in equation (3) as:

$$x_{expi} = load_{surf,1}\left(NDR_{surf,i} + load_{subs,i}\right)NDR_{subs,i} \quad (3)$$

At the basin level, equation (3) aggregates all the pixels within the multispectral space to give:

$$x_{exp_{tot}} = \sum_i x_{exp_i} \quad (4)$$

where: $load_{surf,1}$ is the surface load at the first pixel, and $NDR_{surf,i}$, $load_{subs,i}$ and $NDR_{subs,i}$ is surface NDR, subsurface nutrient load and subsurface NDR loads respectively while x_{expi} is the specific nutrient export, aggregate of which generates the $x_{exp_{tot}}$.

2.4. Sensitivity analysis and uncertainties of the nutrient export

As a test of model performance, sensitivity analysis, was conducted on crucial NDR model parameters particularly on critical length, threshold flow accumulation, Borselli k value, load and efficiency functions of each of the land use/landcover classes. This was performed by increasing and decreasing parameter values by 50%, precisely: Borselli k parameter varied from the default of 2.4, to 1.2 and 4.8, the critical length was varied from the default value of 90 metres to 45 metres and 180 metres while the threshold flow accumulation was varied from 10,000 (default) to 5,000 and 20,000. The load and efficiency values stated in Table 1 were adjusted ±50% for each of the land use/landcover values.

3. RESULTS AND DISCUSSION

3.1. Nature and dynamics of surface nutrient load of the Sokoto-Rima Basin

Surficial nutrient loads of the Sokoto-Rima basin as defined by the temporal distribution of N and P is displayed in Fig 2. During the period of study, N rose from 1992, peaked in 2012 and plunged slightly in 2015. This shows a linear relation with increasing mean annual load of 5,667 tonnes increasing at 9.56 tonnes per year. Over the period of assessment, surficial N load increased from 51,736 million tonnes to 513,070 million tonnes.

Spatially, Fig. 3 shows that high N loads of roughly 8.22 kg per kilometre were directly connected to headwaters of the Sokoto-Rima basin throughout the years. The outline of these major water bodies shows that they contribute the least amount of surficial N loads. The baseline year (1992) showed that tributaries of these river networks in the eastern and northern axis conduit high N loads downstream. In addition, wetlands of the southern axis which were mainly lowlands constitute the highest N loads. By 2002, areas of high N loads were observed in part of central areas with roughly 50% increase in N load while other areas remain unchanged. This observation changed slightly as notable spatial N loads were detected around wetlands close to the major rivers as well as wetlands in the east. By 2015, slight changes were detected.

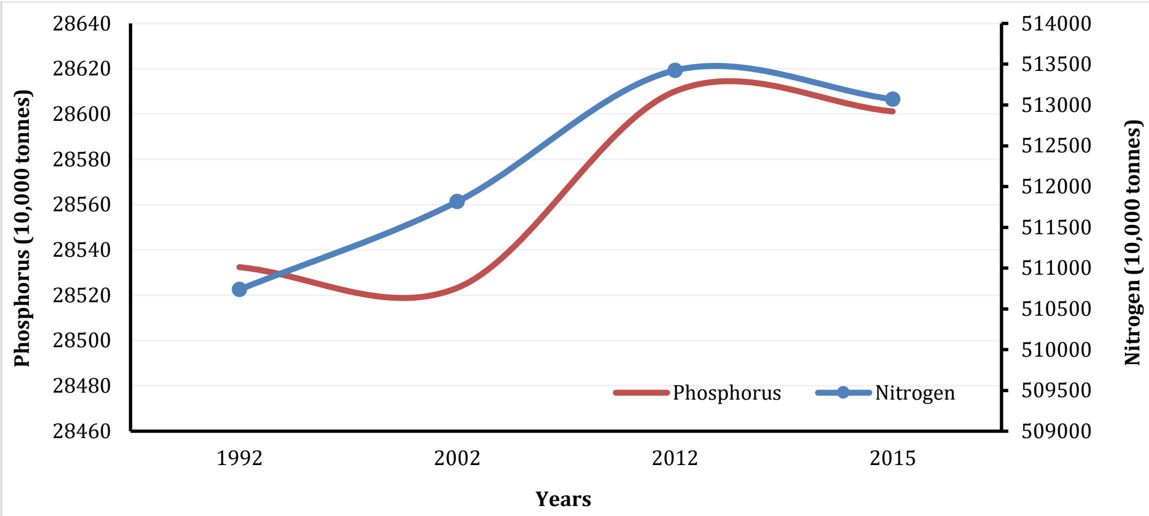

Fig 2. Temporal trend of surface loads of nitrogen and phosphorus of the Sokoto-Rima basin

Surficial P load within the Sokoto-Rima basin increased annually with a mean annual load of 26,103 tonnes per unit area, increasing at a rate of 32 tonnes for every kilometre (Fig 2). Precisely, the baseline value of 28,532 million tonnes increased to 28,601 million tonnes. Its semi-sinusoidal curve pattern showed the level of consumption and the extent of land use/landcover of the Sokoto-Rima basin, an area that is dominated by crop production.

Changes in spatial distribution of surficial P load showed a pattern that is similar to that of N where headwaters of the major streams that define the basin were detected as major sources (Fig 4). On the eastern axis where most of the rivers takes their source accounts for over 70% of the 5.86 million tonnes per km2 of P. Areas at the lowest range of P with roughly 0.89 million tonnes are directly proportional to areas of high intense crop cultivation.

These results concurred with the findings of [14, 18 and 20]. Explicitly, [14] claimed that low quantities of nitrate, nitrite, and ammonia (derivatives of N) and orthophosphates in Kware Lake was an indication of fitness of the surface water for multipurpose uses especially during the dry season. [18] stated that seasonal variation of N and P in surface water of the Sokoto River lies between 1.77 mg L^{-1} and 19.7 mg/litre which is suitable for crop cultivation. [20] indicated that the isotopic classification of the surface waters of the Sokoto-Rima basin in Group IV and V were directly proportional to rainfall input. These suggest that both N and P contribute significantly to the nature, trend and spatial dynamics of nutrient exchanges within the Sokoto-Rima basin. The results also show further the influence of land use/landcover on the spatial pathway of these nutrients particularly within a low density cultivated semi-arid ecosystem such as the Sokoto-Rima basin.

3.2. Nature and Dynamics of Subsurface Nutrient Load of the Sokoto-Rima Basin

The outcome of subsurface nutrient load returned contrasting results as spatiotemporal dynamics returned differing characterization for each of N and P. First, subsurface load of N in the Sokoto-Rima basin returned no value indicating no retention at this level. This is consistent with the deductions of [22 and 14] who affirmed that N is substantially retained at the surface as a crucial nutrient aiding crop productivity of the semi-arid zone of northern Nigeria. These have been further asserted by [8, 10] in China and India respectively where geochemical analysis of derivatives of N yielded paltry belowground outcomes.

According to [23] accumulated study of P over the centuries has shown a direct correlation with human activities and its impacts on freshwater eutrophication in China. This shows that there are latent chances of subsurface trend of P in an agrarian milieu such as the Sokoto-Rima basin. Fig 5 showed that that P load increased from 2,128.7 million tonnes in 1992 to 2,150.5 million tonnes in 2015, 0.36%

increase with a difference of 7.62 million tonnes. Despite this trend, no spatial variation of subsurface P was detected an evidence of strong surface load forcing.

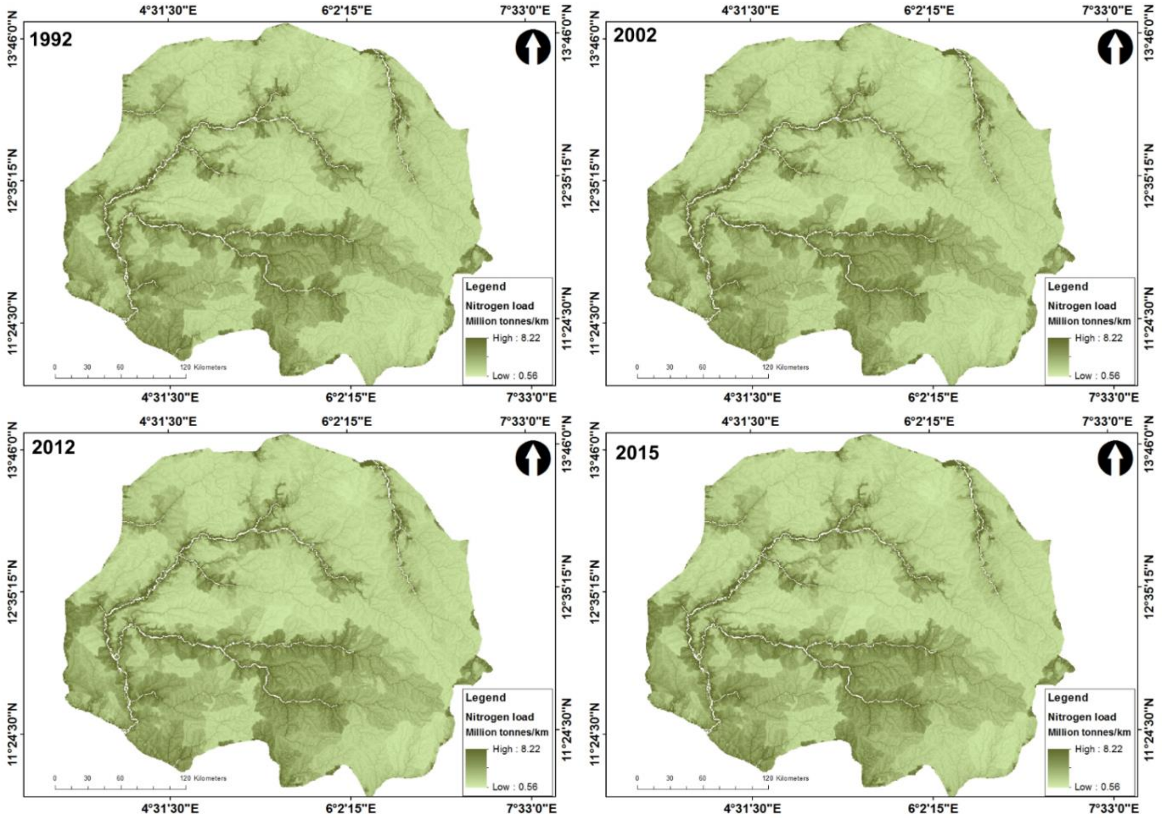

Fig 3. Spatial distribution of surficial nitrogen load in the Sokoto-Rima basin for the years 1992, 2002, 2012 and 2015

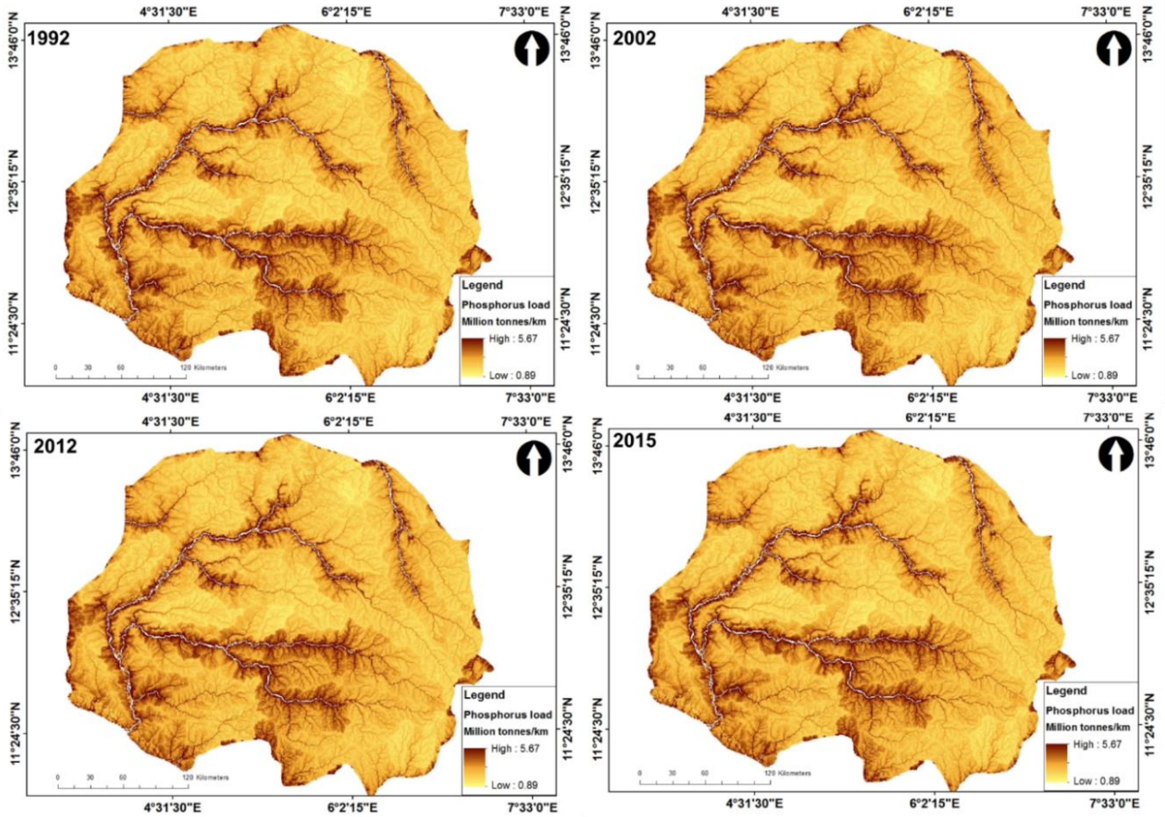

Fig 4. Spatial distribution of surficial phosphorus load in the Sokoto-Rima basin for the years 1992, 2002, 2012 and 2015

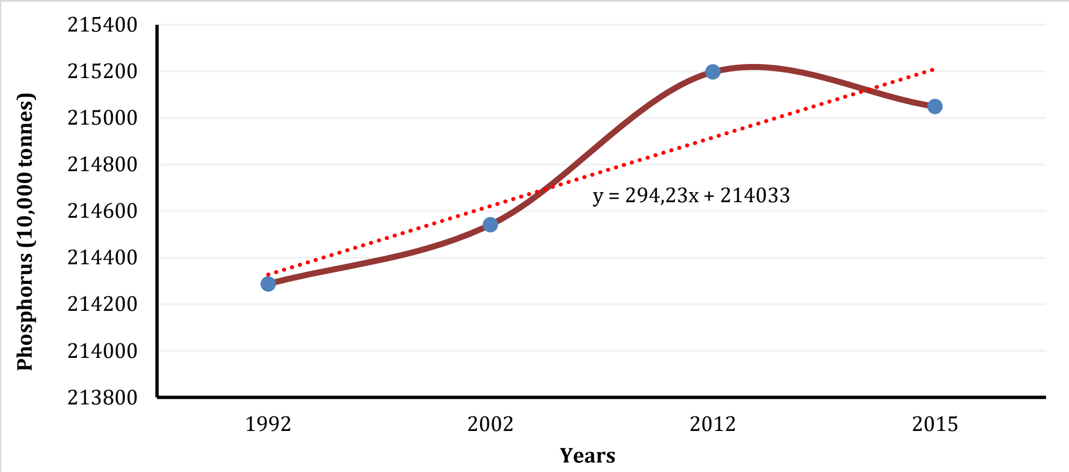

Fig 5. Trend of subsurface phosphorus load of the Sokoto-Rima basin from 1992 to 2015

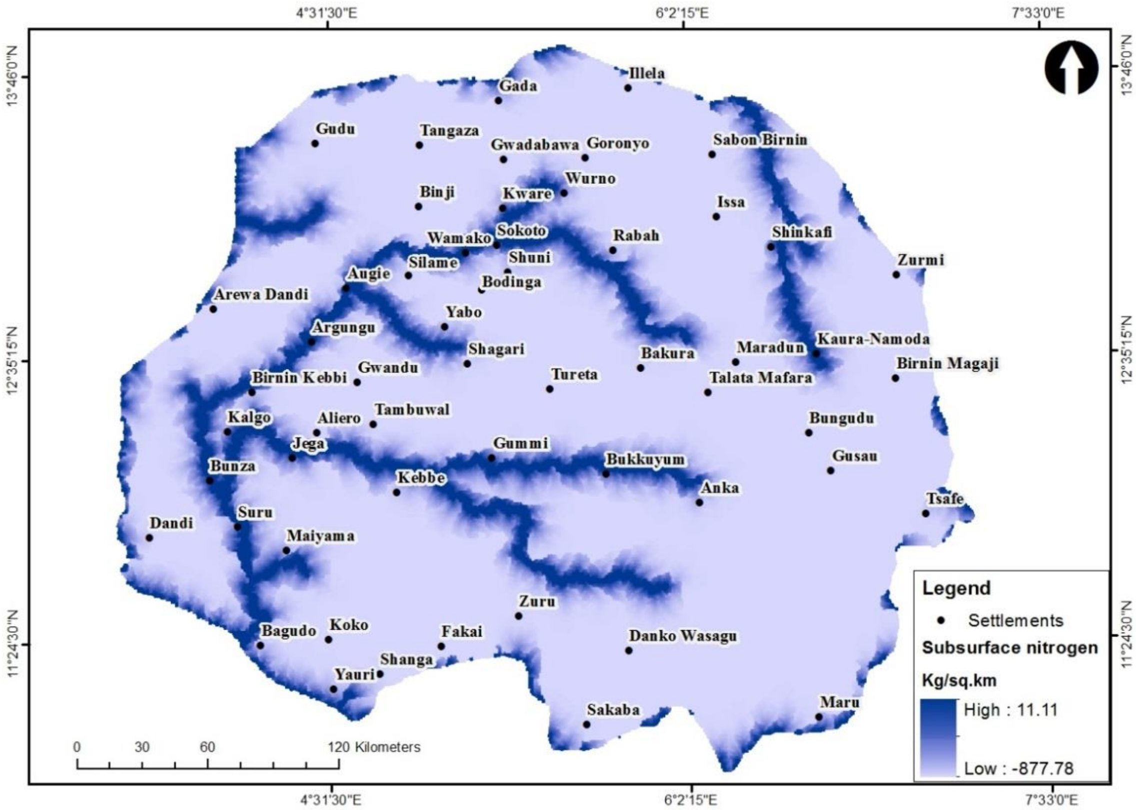

Fig 6. Spatial distribution of subsurface nitrogen loads of Sokoto-Rima basin (1992-2015)

Within the time of this study, no specific spatial variation was detected in the amount of subsurface N loads in the Sokoto-Rima basin, hence the extent of spatial distribution for the year 1992 returned the same as 2015. However, Fig 6 showed that subsurface N loads were spatially restricted to water bodies – rivers, streams and freshwater lakes, with highest values 11.11 kg km^{-2}. This was followed by the adjoining wetlands with 1.09 kg km^{-2}. Largely, subsurface N loads were unswervingly influenced by water-bearing land use/landcover classes. This is because N is a vital chemical component of aquatic ecosystems as it contributes extensively to the growth and sustenance of aquatic organisms as part of their essential feedstock, which is a vital ecosystem service [6, 12]. The deficit range of loads observed in the other areas can be attributed to high uptake of the nutrient as discerned by crop consumption rates [13, 16 22].

3.3. *Trend of nutrient export in the Sokoto-Rima Basin*

3.3.1. *Temporal dynamics of nutrient export*

It has been established that nutrient export contributed to the increasing evidence of eutrophication and sedimentation within freshwater bodies of the Sokoto-Rima basin particularly Lake Kware [14]. It was also noted that N export accounted for over 65% of the nutrient yields observed in the lake [14]. This could be directly associated with increasing intensity of economic and social activities which has resulted in adjustments of the previous natural conditions of the area. Cumulative cultivation of crops and animal husbandry around the lowlands, wetlands and upland areas have led to introduction of nutrients such as fertilizers, herbicides, pesticides, and others in the Sokoto-Rima basin [19-21].

Over the course of this study, N export outweighs P as shown in Table 2 despite the low rate of of increase. The magnitude of change showed that from 1992 to 2015, N export increase slightly by 0.87%, compared to 0.65% in 2002, and 0.92% in 2012. A similar pattern was detected for P with 1.7% increase. This observed trend could be traced to the influence of previously acknowledged human activities.

Table 2. Nitrogen and phosphorus export in 1992, 2002, 2012, and 2015

	Nutrient export ('000 ton)		Percentage change from baseline	
Year	Nitrogen	Phosphorus	Nitrogen export	Phosphorus export
1992	15,179.64	4.59	-	-
2002	15,278.19	4.62	0.65	0.74
2012	15,319.76	4.66	0.92	1.70
2015	15,311.09	4.66	0.87	1.70

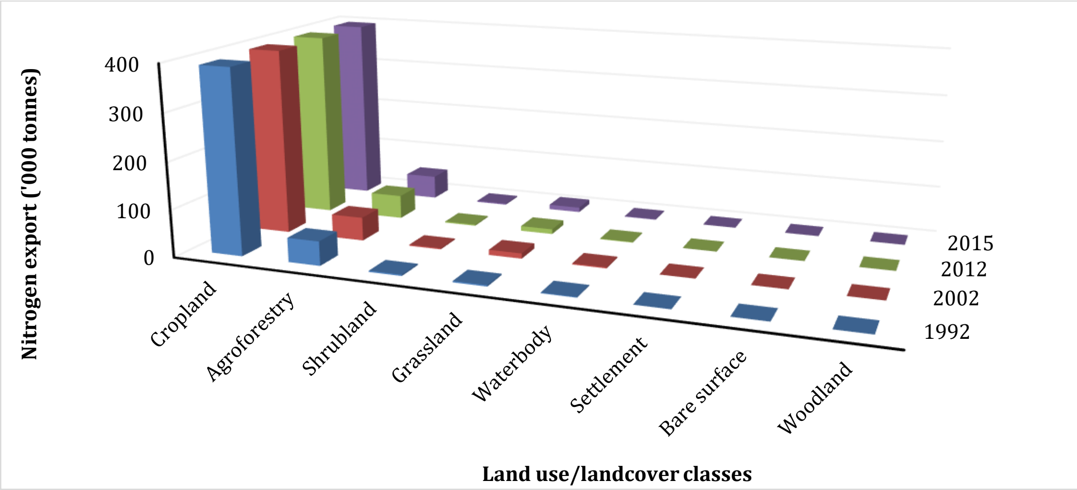

Fig 7. N export of the Sokoto-Rima across the different land use/landcover classes from 1992 to 2015

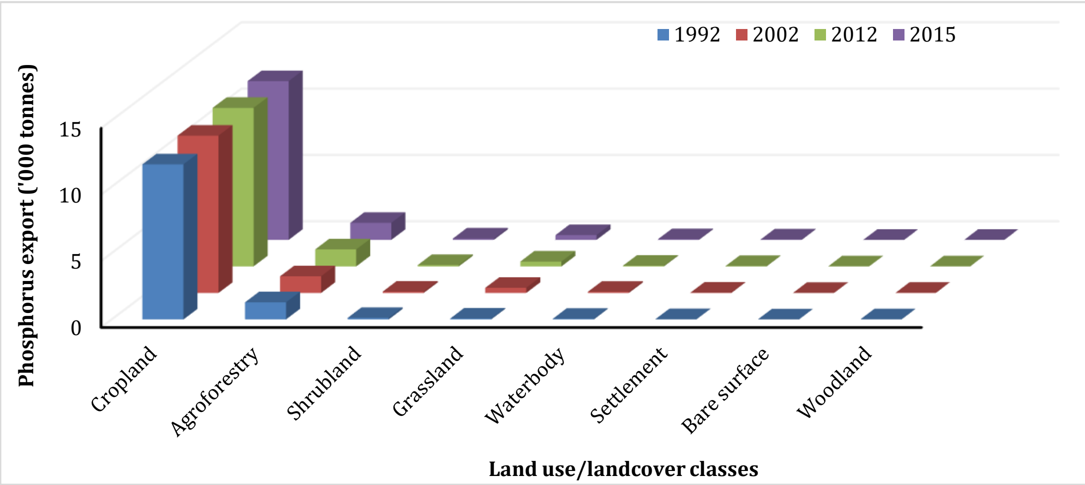

Fig 8. P export of the Sokoto-Rima across the different land use/landcover classes from 1992 to 2015

Land use/landcover influenced the proportion of N and P exported within the Sokoto-Rima basin. Fig 7 and Fig 8 show that cropland influenced nutrient export in the Sokoto-Rima basin with almost 85% of the total amount. This is immediately followed by agroforestry (which is mosaic of cropland and woodland) and grassland while bare surface contributes the least nutrient export. Infinitesimal proportion of nutrients was also exported from settlement. Roughly 90% of N export is sourced from cropland while few amounts are traceable to grassland, shrubland, woodland, and waterbody. This describes the basin N cycle in which cultivated areas determines the nature and pattern of N with respect to low tree density forested areas. [26] have shown that the trend of cropland dominated land use/landcover of the Sokoto-Rima basin will remain unchanged. By implication, this is anticipated to impede not only nutrient export and dynamics but also the attendant ecosystem services.

Fig. 8 specified that the proportion of P exported from the Sokoto-Rima basin is roughly 3-fold less than the magnitude of N. This is also directly related to the anthropogenic activities and limited P storage by the dominant land use/landcover themes [23]. Perring et al. [25] argued that available N inputs in a given terrestrial ecosystem could trigger a coupled increase in other related nutrient elements thereby boosting nutrient cycling. However, the scenario in a semi-arid environment such as the Sokoto-Rima basin where biomass response to increased N is very low, P export is high and co-related to anthropogenic forcing. This justification is proven by Fig 8 where natural land use/landcover contributes the least to P export as the landscape is dominated actively by agrarian influences.

3.3.2. Spatial variation of N and P export

The spatial context of nutrient export of the Sokoto-Rima basin over the period of this study showed dissimilar traits that explain the extent of place-based and location specific variations. In particular, spatial distribution and variation of N export as displayed in Fig 9 showed that N export is relatively unchanged within the period of study (1992-2015). Interval variation, however, depicts some explicitness. From 1992 to 2002, spatial decreases in exported N were detected around wetlands and agroforestry of the north. Spots of decreases were also detected in some parts of the east and the southern swath of the Niger plain where River Sokoto confluences with the Niger River. Local increases can be observed throughout the area with exceptions in the cultivated areas where there were no changes.

The period 2002 to 2012 had slight changes as spatial decreases in N export were detected in areas around the south and some wetland areas of the north. Substantial spatial decreases in N export within the 2012-2015 period could be related to the short space of spatial comparison. Overall, spatial differences in N exports of the Sokoto-Rima basin remain largely constant with observed declines than increases, and this is analogous to the nature of the area.

The nature of spatial variation in P export returned fluctuating values (Fig 10). Although, P export remained relatively unchanged following similar pattern as that of N. However, there were locational differences across the period of study. The observed spatial trend was such that some areas recorded P increase then decrease later. Specifically, substantial increases were detected in some parts of the north, central and south within the period 1992-2002. The pattern remained relatively unchanged for the period 2002-2012 although some spots of decreases were identified in some eastern location close to water bodies. The period 2012 to 2015 had quasi-constant P export. The aggregate spatial variation of P export showed indications of increase than decrease particularly in areas of agroforestry of the northern axis, and along wetland and extensive floodplains of the south.

3.4. Sensitivity analysis of nutrient export

The linearity function of the equations utilised in deriving the spatial relationships between nutrients and associated parameters suggests a possible degree of sensitivity. This has been justified and substantiated in Fig. 11 which showed the aggregate nutrient export varied considerably with the parameters of the Sokoto-Rima basin. The sensitivity of the nutrient export was greatest for critical length (Crit len) showing the extent of elasticity such that a ±50% adjustment triggers a corresponding 94% decline and 108.76% upsurge in nutrient export. Threshold value (Threshold) demonstrates a converse sensitivity to nutrient exports with a quasi co-equal influence in which a 50% reduction leads to increase in nutrient export while +50% increment yields a reduction up to 95.93%. Load parameters attached to each of the land use/landcover class revealed a direct level of sensitivity out of which cropland returned the highest nutrient export with +50% increment leading to 110.09%. Similar sensitivity pattern was observed for loads for agroforestry and woodland in which positive adjustment in parameter value leads to direct change in nutrient exports. It can be summed that nutrient efficiency factor across the land use/landcover spectrum largely has direct influence on change in nutrient export where cropland and woodland possess the most dynamic influences (Fig. 11).

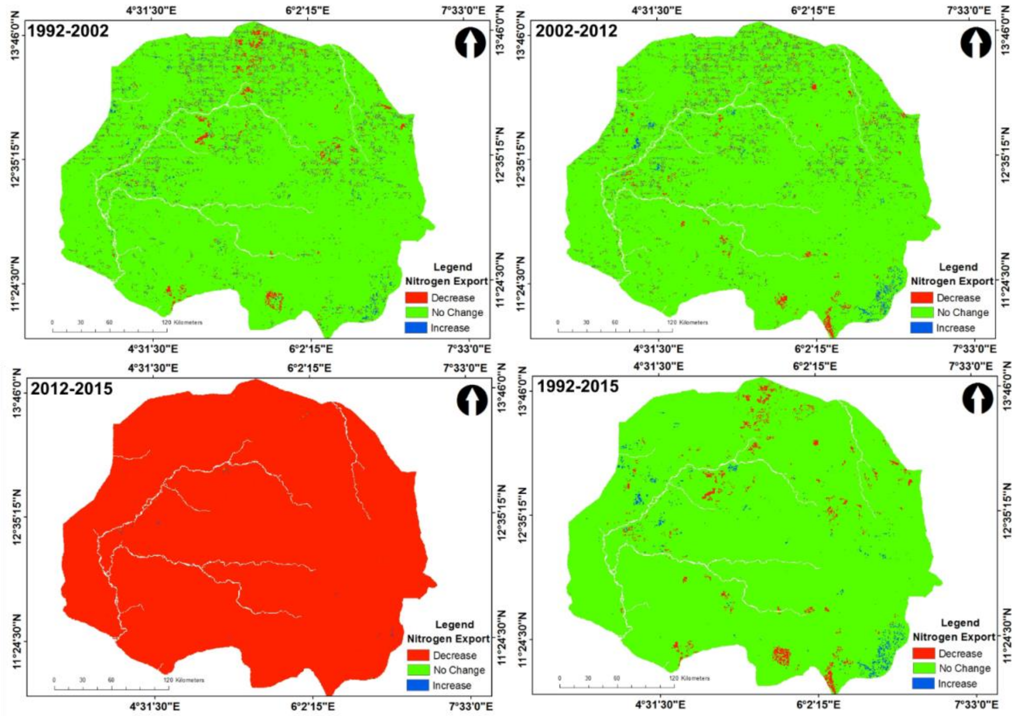

Fig 9. Spatiotemporal variation of nitrogen export in the Sokoto-Rima basin from 1992 to 2015 with specific interval differences (1992 to 2002, 2002 to 2012, 2012 to 2015 and cumulative spatial difference)

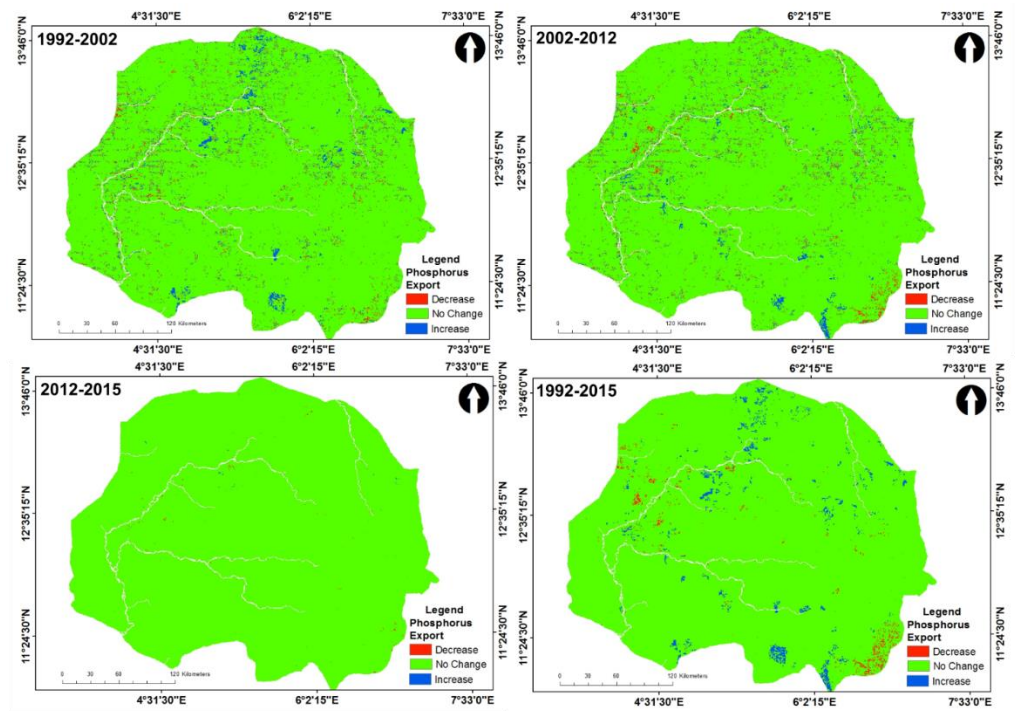

Fig 10. Spatiotemporal variation of P export in the Sokoto-Rima basin from 1992 to 2015 with specific interval differences (1992 to 2002, 2002 to 2012, 2012 to 2015 and accumulative spatial difference)

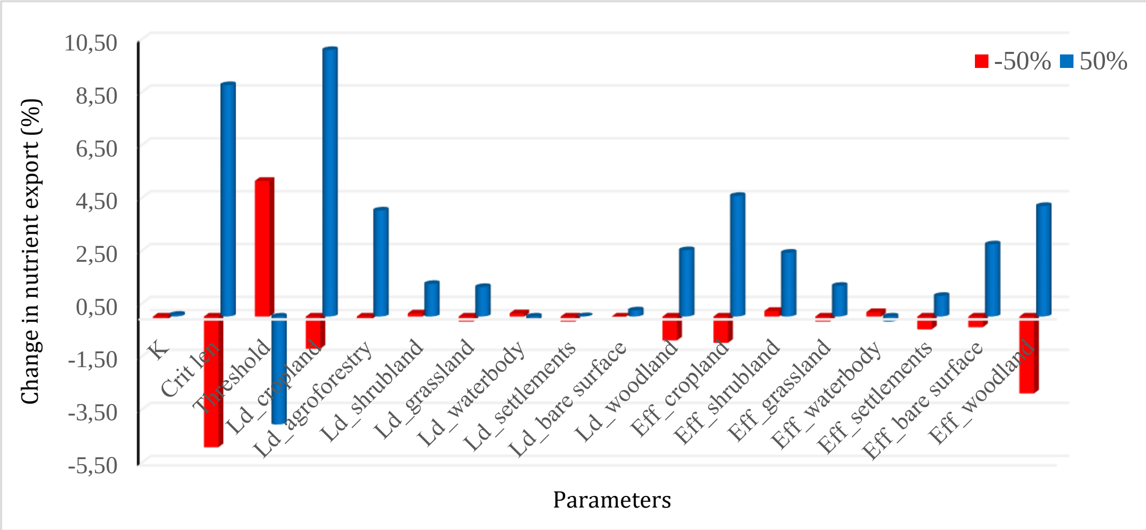

Fig 11. Sensitivity as depicted by response of the aggregate nutrient export to a ±50% change in selected input parameters for the entire Sokoto-Rima basin. K depicts Borselli factor, crit len (critical length, in Table 1), Ld and Eff stand for loads and efficiency for respective land use/landcover classes

3.5. Localized context for nutrient cycle

Nutrient cycling pathway is place-based and context-specific. It is significantly influenced by natural and anthropogenic factors. Given that the Sokoto-Rima basin is predominantly agrarian, the spatial organization of settlements is such that it is buffered by crop production complexes which stretches to wetlands and plains throughout the area. Accordingly, farmland fertilization accounts for N and P enrichment in the Sokoto-Rima basin. Related factors such as weathering of farm wastes, domestic wastes and sewage from townships and bucolic communities as well as animal droppings formed the sources of nutrients. These are usually washed into rivers and streams via surface runoffs from cultivated fields, animal production fens and the usage of animal wastes for soil enrichment. These are often washed into open water bodies leading to eutrophication problems which have been recorded in the Sokoto-Rima basin [17-20]. This scenario formed the basis of the graphical illustration of River Zamfara (Fig 12) where farmlands and buildings flanked the stream. The persistence of this scenario will lead to uncoordinated and unabated water quality issues for the entire Sokoto-Rima basin. It also calls for the consistent monitoring and improvement of existing land uses that stimulates likely cases of water pollution from domestic and land cultivation areas. The need for regulations on water environment, pollution prevention and environmental protection is therefore vital to mitigate this trend.

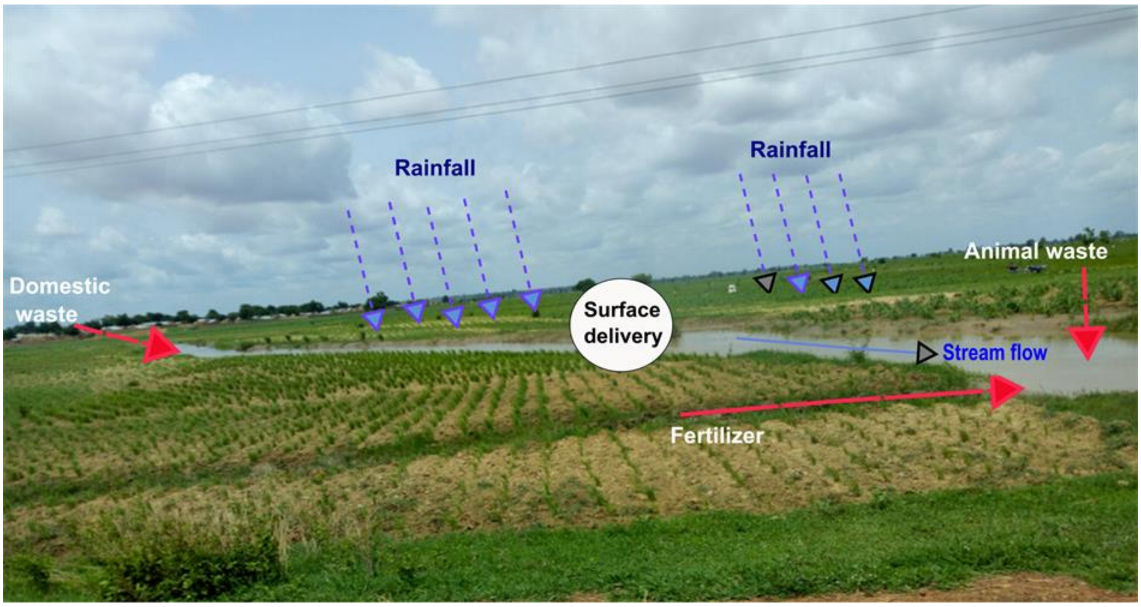

Fig 12. Pathway of nutrient flow and cycling in the along the section of River Zamfara a vital water body within the Sokoto-Rima basin. The blue arrow shows natural feature input source while the red arrow indicate the anthropogenic source of both nitrogen and phosphorus

4. CONCLUSIONS

This study has shown that amounts of surficial N outweighs P in the Sokoto-Rima basin by almost 15-fold with linear increment trend from 1992 to 2015. Also, spatial distribution showed that both nutrients were directly proportional to crop cultivation areas while water bodies particularly the major rivers were identified as sinks. As established in literature within the semi-arid regions of the world, subsurface nutrient loads of N and P loads produced different output in which N returned no trend while P returned linear increasing trend. Spatially, N loads were restricted to water bodies and P retuned no spatial characterisation and variation. Nutrient exports also showed spatiotemporal variations with large amounts of N exports were observed compared to P. Cropland and agroforestry influenced roughly 90% of the amount of nutrient exported thus establishing a firm human-nature nexus in the amount of nutrient exported.

Management of this emerging nutrient enrichment of the landscape of the Sokoto-Rima basin require a synergistic approach whereby the intensity of crop cultivation is integrated with the nutrient sink approach. For instance, agroforestry and woodland advancement schemes will aid the control of the direct influence of cropland on nutrient adjustment at the local space. This approach will engender managed nutrient cycling close to reality. Within this context, the Nigerian section of the West African Great Green Wall programme aimed at curtailing the impact of the Sahara desert encroachment, can be locally adjusted as community-based approach to enhance natural ecosystem services and by extension improve environmental resource appraisal within the Sokoto-Rima basin [20, 21].

Sensitivity analysis of the InVEST model adopted for this study revealed some level of uncertainties in the predictive abilities of the model despite its innovative theory and simplified approach. This shows that more extensive studies on model calibration processes, consideration of high-resolution land use/landcover datasets, influence of parameterization should be considered vital. Model parameterisation of the InVEST model should therefore consider inclusion of ecological and physicochemical processes that are less cumbersome for model output interpretation. Addition of material elements within a given ecosystem space such as potassium (K) will further enhance the understanding of nutrient cycling. It will also improve the spatial simulation of multiple nutrients within any ecosystem. These measures are needed within the context of emerging science of nutrient modeling in consideration of natural and anthropogenic factors and forcing.

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