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Regional nitrogen budget of the Lake Victoria Basin, East Africa: syntheses, uncertainties and perspectives

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Abstract

Using the net anthropogenic nitrogen input (NANI) approach we estimated the N budget for the Lake Victoria Basin in East Africa. The NANI of the basin ranged from 887 to 3008 kg N km^{-2} yr^{-1} (mean: 1827 kg N km^{-2} yr^{-1}) for the period 1995–2000. The net nitrogen release at basin level is due primarily to livestock and human consumption of feed and foods, contributing between 69% and 85%. Atmospheric oxidized N deposition contributed approximately 14% to the NANI of the Lake Victoria Basin, while either synthetic N fertilizer imports or biological N fixations only contributed less than 6% to the regional NANI. Due to the low N imports of feed and food products (<20 kg N km^{-2} yr^{-1}), nitrogen release to the watershed must be derived from the mining of soil N stocks. The fraction of riverine N export to Lake Victoria accounted for 16%, which is much lower than for watersheds located in Europe and USA (25%). A significant reduction of the uncertainty of our N budget estimate for Lake Victoria Basin would be possible if better data on livestock systems and riverine N export were available. Our study indicates that at present soil N mining is the main source of nitrogen in the Lake Victoria Basin. Thus, sustainable N management requires increasing agricultural N inputs to guarantee food security and rehabilitation and protection of soils to minimize environmental costs. Moreover, to reduce N pollution of the lake, improving management of human and animal wastes needs to be carefully considered in future.

S Online supplementary data available from stacks.iop.org/ERL/9/105009/mmedia

Keywords: N budget, NANI, regional N assessment, mining of soil N stocks, Lake Victoria, Africa

1. Introduction

Reactive nitrogen (Nr), such as nitrate, nitrite and ammonium, is essential for the functions, processes and dynamics of ecosystems (Vitousek and Howarth 1991). Together with the advent of unlimited industrial nitrogen fixation at low costs by the Haber–Bosch process, anthropogenic activities have at least doubled annual global Nr inputs to ecosystems as compared with Nr inputs during pre-industrial times (Galloway *et al* 2004). Increased Nr supports the food and fuel needs of a growing human population, but it also causes numerous adverse impacts on human health and environmental sustainability, including eutrophication of aquatic ecosystems and increased N_2O emissions—a potent greenhouse and ozone-depleting gas (Vitousek *et al* 1997, Galloway *et al* 2008, Sobota *et al* 2013). However, increased Nr is not evenly distributed at spatial scales. In Africa—a region with too little Nr—the agricultural sector has not been able to produce sufficient food for the rapidly growing population and insufficient N inputs can lead to mining of soil organic N stocks (Davidson 2009). Thus, compensating for the negative impacts associated with anthropogenic Nr inputs represents an important challenge faced by land and water managers worldwide.

Better understanding of Nr inputs and sources is critical to improve the balance between their positive and negative impacts (Bouwman *et al* 2009, Hong *et al* 2011, Swaney *et al* 2012). So far, regional anthropogenic Nr assessments have been made for the European Union (Sutton *et al* 2011), North America (Sobota *et al* 2013) and China (Ti *et al* 2012). The only existing synthesis of Nr in Africa was completed for West Africa three decades ago (Robertson and Rosswall 1986). We believe that anthropogenic Nr in Africa should be included in global assessments of human-mediated Nr.

Lake Victoria in East Africa is the second largest fresh water lake in the world and the watershed is one of the most densely populated regions in Africa. The rapidly expanding population and economy within the basin (Muyodi *et al* 2010), has resulted in notable changes to the physical, chemical and biological regime of the lake over the last 50 years (Juma *et al* 2014), including enrichment of Nr (Lung′ayia *et al* 2001). Previous studies in the Lake Victoria Basin were mainly focused on either water N concentrations (Gikuma-Njuru and Hecky 2005) or estimation of loading at a relatively small scale (Lindenschmidt *et al* 1998). However, there are no studies on the regional nitrogen budget of the basin, which is critical for improving regional Nr management and balancing its negative and positive impacts.

Here, we synthesize the existing data to develop a regional Nr budget in the Lake Victoria Basin using the *net anthropogenic nitrogen input* (NANI) approach. The NANI approach is an effective method to assess human-induced Nr inputs to the landscape and to evaluate their potential impacts on riverine export from large basins (Hong *et al* 2013). The objectives of this paper are to (1) evaluate the regional Nr budget, highlighting its underlying uncertainties, and (2) identify research gaps and suggest ways to improve future estimates.

2. Methods

2.1. Characterization of Lake Victoria Basin

Lake Victoria is located in East Africa (0°30′ N ~ 3°12′ S, 31°37′ E ~ 34°53′ E; figure1), at an elevation of 1134 m above sea level. The lake has a surface area of 68 800 km^2 and is shared by Kenya, Tanzania and Uganda. The Lake Victoria Basin has a total area of 195 000 km^2, spread across five countries (Kenya, Uganda, Tanzania, Rwanda and Burundi) (LVEMP 2003). The water balance of the lake is dominated by precipitation and evaporation, with mean annual precipitation rates ranging from 886 to 2609 mm (1950–2000), while mean annual evaporation rates range from 1108 to 2045 mm (COWI 2002). Its only surface outlet is the Nile River at Jinja, Uganda.

The basin supports one of the densest and poorest rural populations in the world, with a total population of 30 million, which is increasing by more than 6% per annum. The gross annual economic product of the basin is approximately US$ 3–4 billion and contributes to one third of the combined gross domestic product of the countries in this basin (Kayombo and Jorgensen 2006). Over 70% of the population in the Lake Victoria Basin is engaged in agricultural production; primarily on small-scale, mixed farms producing a variety of products including maize, tea, coffee and livestock. Lake Victoria has experienced increased eutrophication over the last 50 years, to which elevated Nr concentrations are considered a major contributing factor (Juma *et al* 2014, Scheren *et al* 2000).

2.2. The NANI approach

The Lake Victoria Basin is divided into 23 catchments, including eight in Kenya, 12 in Tanzania and three in Uganda (LVEMP 2003). We calculated an N budget for the basin using the NANI approach described by Howarth *et al* (2006). This approach has been useful in studying N budgets for large watersheds and has been successfully applied worldwide (Howarth *et al* 2006, Hong *et al* 2011, Ti *et al* 2012, Billen *et al* 2013).

The annual riverine input of total nitrogen from the basin into the lake and outflows of total nitrogen from the lake used in this study were based on the monitoring data of the Lake Victoria Environmental Management Project I conducted during the late 1990s (Kayombo and Jorgensen 2006). Thus we calculate NANIs to the basin for the period 1995–2000. The NANI model is essentially the sum of atmospheric N deposition, fertilizer N application, agricultural N_2 fixation and net food and feed imports (table 1). It is important to note that sewage and animal wastes were not included as inputs to the region, because they do not represent newly fixed or imported nitrogen but a redistribution or recycling of nitrogen within a region (Howarth *et al* 1996). Additionally, we reviewed the literature on nitrogen flows in the Lake Victoria Basin, which included agricultural, aquatic, forestry/agroforestry and urban systems.

Atmospheric N deposition in NANI calculations includes only oxidized N (NO_x) deposition, because of the assumption that ammonia emissions from a watershed are re-deposited within the same watershed. There may be fluxes of ammonia through atmospheric transport across different watersheds, but the net ammonia/ammonium deposition due to atmospheric transport across watersheds is small relative to NO_x deposition (Boyer *et al* 2002). Total oxidized N deposition to

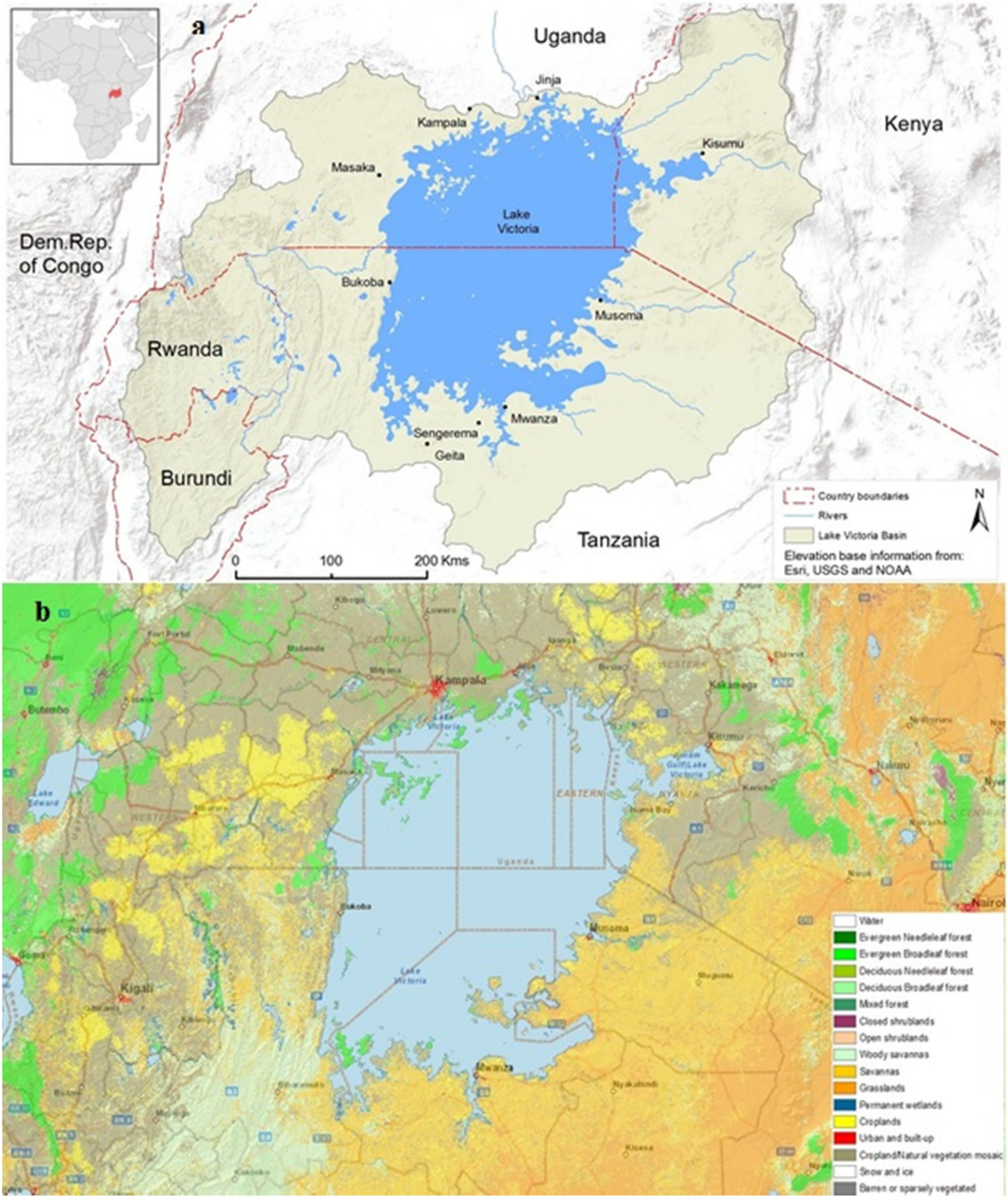

Figure 1. Location and boundaries of the Lake Victoria Basin (a), Kayombo and Jorgensen 2006) and its land use/ land cover in 2000 (b), NASA, https://earthdata.nasa.gov). The Lake Victoria Basin lies in five countries (Burundi, Kenya, Rwanda, Uganda and Tanzania) in East Africa.

Table 1. Characteristics of the Lake Victoria Basin in East Africa.

Country	Lake surface area (km^2)	Catchment area (km^2)	Population density (person km^{-2})	Proportion of rural population (%)	Proportion of cultivated land (%)
Burundi	0	13 510	285	95	51
Kenya	4113	42 460	257	92	30
Rwanda	0	21 230	323	90	45
Uganda	31 001	30 880	66	6	40
Tanzania	33 756	84 920	180	87	27

[1]Catchments in Kenya: Sio, Nzoia, Yala, Nyando, North Awach, South Awach, Sondu, Gucha-Migori; Tanzania: Mara, Grumeti, Mbalageti, E.shore stream, Simiyu, Magogo moame, Nyashishi, Issanga, S.shore stream, Biharamulo, W.shore stream, Kagera; Uganda: Bukora, Katonga, N.shore stream; Burundi and Rwanda: Kagera.

the Lake Victoria Basin was estimated using the mean value of 2.25 kg N ha^{-1} yr^{-1} (Delon *et al* 2010), which was based on observations at the stations from an atmospheric chemistry monitoring network in Africa (i.e. the IDAF network).

Nitrogen inputs from fertilizers during the period of 1995–2000 were estimated using the Global Fertilizer and Manure (V1) database (Potter *et al* 2011). The spatially explicit N fertilizer inputs were computed by fusing national-level statistics on fertilizer use with global maps of the harvested area for 175 crops. The data were compiled by Potter *et al* (2010) and are distributed in a gridded format at 0.5° resolution by the Columbia University Center for International Earth Science information Network. Agricultural N_2 fixation inputs were estimated by multiplying the crop area of legumes by the global mean rate of N_2 fixation for each crop type (Smil 1999). In the Lake Victoria Basin, the main legume crops include peanuts, soybeans and beans (e.g. snap bean). Cultivation areas of these three legume crops were taken from the world census database 'Harvested Area and Yields of 175 Crops' (M3-Crop Data) from Monfreda *et al* (2008). The gridded data are provided at a spatial resolution of 0.083°. The mean annual N_2 fixation values used were 80 kg N ha^{-1} for peanuts, 90 kg N ha^{-1} for beans and 96 kg N ha^{-1} for soybeans (Smil 1999, Boyer *et al* 2002). Green manure crops (e.g. *Tephrosia* spp., *Crotalaria* spp.) are important biological N_2 fixation species in this basin and can contribute to additional nitrogen inputs (Baijukya *et al* 2006) but due to scarcity of distribution data, it was not possible to include N_2 fixation by these species.

NANI assumes a balance of N inputs and outputs across a watershed. However, for the Lake Victoria Basin this is most likely not the case. Therefore the budgetary item 'net food and feed N import', which is calculated as the difference between (a) N consumption of humans and livestock and (b) crop and livestock N production (Hong *et al* 2013), must be interpreted differently. Since there is no evidence that there is significant food and feed import from outside the watershed through trade (Billen *et al* 2010: <20 kg N km^{-2} yr^{-1}, including crop and livestock products) this value should be interpreted as a net mining of soil N stocks within the watershed. Human N consumption was estimated by multiplying the population by N consumption per capita. On average, daily protein consumption for African people is 58 g person^{-1} (Schonfeldt and Hall 2012), resulting in an annual rate of 3.38 kg N person^{-1} yr^{-1}. Five livestock types (cattle, chickens, goats, pigs and sheep) were included into the estimation. Animal populations in the Lake Victoria Basin were derived from the data from the Gridded Livestock of the World v2.0 database (30 arcseconds resolution) (Robinson *et al* 2014). Livestock N production was estimated by multiplying the edible portion of livestock production by the corresponding nitrogen content. Beef, pork, lamb, chicken meat and eggs were included in the estimation. Livestock production was estimated by multiplying livestock production rates (kg head^{-1} yr^{-1}) by stock. The N parameters for N intake by cattle were obtained from an experimental study in East Africa (Delve *et al* 2001). The N requirements and N content of the edible portion of the other four livestock species were obtained from Hong *et al* (2011). Crop N production was estimated by multiplying mean harvests of nine main crops based on census database of 'Harvested Area and Yields' (Monfreda *et al* 2008) (i.e. maize, rice, wheat, bean, soybean, sorghum, sweet potato, banana and sugar cane) by the corresponding N content. In addition to the nine main crops, the N production of two main non-food crops (tea and coffee) in this basin was also estimated. Production data of the three legume crops were taken from a census database of Harvested Area and Yields of 175 crops (M3-Crop Data) from Monfreda *et al* (2008). The N content of sweet potato, banana and sugar cane were derived from Kwong *et al* (1987), Parikh *et al* (1994) for banana, Yeoh *et al* (1996) for sweet potato, while the values for N content of the other crops were again obtained from Hong *et al* (2011). The different spatial datasets were resampled to match a consistent spatial resolution of 0.086° or 5 arcminutes (approx. 10 km at the equator). The processing of all spatial data was done with ARCGIS 10.1.

3. Results

3.1. NANI estimates in the Lake Victoria Basin

In this study, NANI calculations for the entire Lake Victoria Basin were made by area-weighting by country. On average, NANI estimates ranged from 886.9 to 3007.5 kg N km^{-2} yr^{-1} across the five countries of the basin between 1995 and 2000 (table 2). Although high spatial variability of NANI existed, the magnitude and relative importance of individual components of NANI were somewhat consistent among the countries (figure 2). The net food and feed N imports, i.e. N inputs

Table 2. Area-weighted means of NANI and its components (kg N km^{-2} yr^{-1}) for the Lake Victoria Basin.

Budgetary item	Burundi	Kenya	Rwanda	Uganda	Tanzania	Average
Oxidized N deposition (+)	225.0	225.0	225.0	225.0	225.0	225.0
Fertilizer N application (+)	72.0	247.7	10.0	23.9	41.9	79.1
Agricultural N fixation (+)	160.7	35.9	210.1	242.5	38.6	137.5
Net food and feed imports or soil N stock mining	947.2	2543.2	1974.6	1035.2	584.0	1416.8
Human N consumption (+)	*968.4*	*908.2*	*995.0*	*655.2*	*282.0*	*761.8*
Livestock N consumption (+)	*1044.2*	*2262.5*	*1816.9*	*1502.6*	*603.4*	*1445.9*
Crop N production (−)	*981.8*	*348.8*	*706.2*	*933.0*	*185.7*	*631.1*
Livestock N production (−)	*86.7*	*278.7*	*131.1*	*189.6*	*84.9*	*153.6*
Non-food and feed N export (−)	36.7	44.3	31.5	40.5	2.6	31.1
NANI	**1368.2**	**3007.5**	**2388.2**	**1486.1**	**886.9**	**1827.4**

through the food chain to livestock and humans (soil N mining in the case of Lake Victoria) and ultimately back to the environment as organic and inorganic N in wastes, were the major inputs with average contributions ranging from 69.2% to 84.6% of total NANI in this basin. The next largest contributors were atmospheric oxidized N deposition, agricultural N_2 fixation, which averaged 12.3% (7.5–26.1%) and 7.5% (1.2–16.3%) of NANI, respectively. In contrast to other regions in the world, fertilizer N inputs were the smallest components on average accounting less than 4.3% of NANI.

3.2. N budgets of the Lake Victoria Basin

Our results show that between 1995 and 2000 annual Nr inputs to the terrestrial landscapes of the Lake Victoria Basin averaged 305.2 Gg Nr yr^{-1}, (table 3; figure 3). However, only 49.5 Gg N yr^{-1} of Nr finally went into Lake Victoria via riverine transport (Kayombo and Jorgensen 2006). This indicates that about 84% of the anthropogenic N inputs were retained in or lost (e.g., denitrification) from the basin. Annual Nr inputs for Lake Victoria averaged 152 Gg N yr^{-1}, primarily as atmospheric N deposition (102 Gg N yr^{-1}), which was two-fold higher than inputs via riverine transport. Approximately 40 Gg N yr^{-1} exited the lake through the only outflow (the River Nile at Jinja, Uganda) while 4 Gg N yr^{-1} exited through fishery export, indicating that about 107.5 Gg N yr^{-1} were retained or denitrified in the lake water columns and sediments (Kayombo and Jorgensen 2006).

4. Discussion

The NANI estimates for the basin (table 2: 886.9–3007.5 kg N km^{-2} yr^{-1}, mean: 1827.4 kg N km^{-2} yr^{-1}) fall within the range of reported values for most regions in the world (table 4). In contrast with the other regions however, where fertilizer N application often dominates NANI (Swaney *et al* 2012), the Nr inputs in the food chains of livestock and human was the largest contributor of NANI for the Lake Victoria Basin (table 2). Here, where synthetic N application rates are less than 15 kg N ha^{-1} yr^{-1} to arable land (FAO STAT), fertilizer N application contributed to only 5.1% of NANI. This confirms the statement that the Lake Victoria Basin of Africa is a region with ‘too little N’ available for sustainable agricultural production (UNEP and WHRC 2007). The insufficient agricultural N inputs can limit the ability of local agriculture to meet the basic challenge of producing enough food for the large population and contributing to economic development.

A surprising result was the overwhelming importance of net food and feed N import for NANI in the Lake Victoria Basin, because N imports as food and feed (i.e. crop and livestock products) to the Lake Victoria Basin through trade were previously estimated to be very low (<20 kg N km^{-2} yr^{-1}) (Billen *et al* 2010). This suggests that the large food and feed N imports (1198–1960 kg N km^{-2} yr^{-1}) were actually not imported from outside the basin. NANI uses food and feed N import as a proxy for N flows from sewage and animal manures (Howarth *et al* 1996, Swaney *et al* 2012) and calculates this as the difference between the N consumed in animal feed and human food and the synthetic N applied to croplands. In most other cases the assumption is that the difference between N consumed and N applied to croplands is due to food imported from other watersheds. However in the Lake Victoria Basin the human and livestock populations are typically fed by food grown on unfertilized croplands within the basin because the poor economy restricts trade from outside. Thus, we assume that what NANI considers to be N imports through food and feed are not actually imports *per se*, but rather recently mineralized N from the soil N stocks. This is confirmed by the fact that the N removed from croplands by crop harvest always exceeds fertilizer N inputs (Baijukya *et al* 2006). Similarly, Davidson (2009) demonstrated that during the period of low synthetic N fertilizer input (1860–1960), mining of soil N stocks was the main source of increasing atmospheric N_2O concentrations.

However, mining of soil N stocks has not been included in the conceptual model of NANI because so far all existing NANI estimates were made for regions with high synthetic N fertilizer applications (Howarth *et al* 2012, Hong *et al* 2013). Moreover, NANI assumes that N stocks in soil and vegetation remain stable across a given calculation period. We believe that mining of soil N stocks is a new N ‘input’ for regions with too little synthetic N fertilizer inputs (e.g., Lake Victoria Basin). Unfortunately, the rates of mining of soil N stock are still unknown and unlikely to be estimated. Nevertheless, continuous depletion of soil N stocks in the Lake Victoria

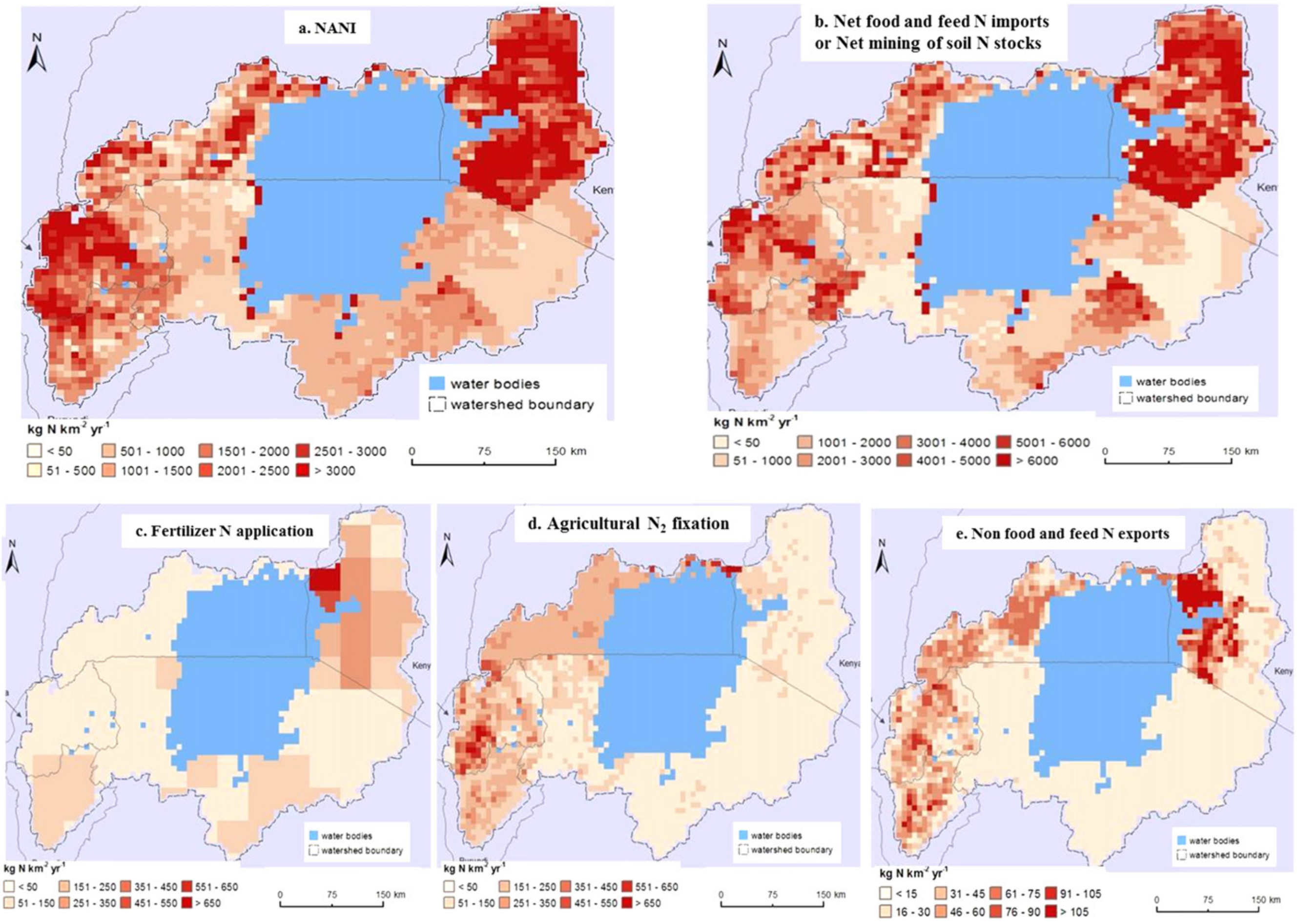

Figure 2. Area-weighted NANI ((a) kg N km^{-2} yr^{-1}), the components ((b) net food and feed N imports or net mining of soil N stocks, (c) fertilizer N applications, (d) agricultural N_2 fixation, (e) non-food and feed N exports) and their spatial variations for the Lake Victoria Basin. Note that atmospheric oxidized N deposition was not shown as it was largely uniform compared to the other components. The total oxidized N deposition to the Lake Victoria Basin was estimated using a mean value of 2.25 kg N ha^{-1} yr^{-1} (Delon *et al* 2010), which was based on observations of oxidized N depositions at the stations from the an atmospheric chemistry monitoring network in Africa (i.e. the IDAF network). Also note that due to relatively low trading imports of Nr in this region (<20 kg N km^{-2} yr^{-1}) the N inputs in the food chains of livestock and human (i.e. component of net food and feed import) are derived from mining of soil N stocks (see text).

Table 3. Composed NANI and its components (Gg N yr^{-1}) for the Lake Victoria Basin.

Budgetary item	Burundi	Kenya	Rwanda	Uganda	Tanzania	Total
Oxidized N deposition (+)	2.9	9.4	4.7	5.7	18.9	41.6
Fertilizer N application (+)	0.9	10.4	0.2	0.6	3.5	15.6
Agricultural N fixation (+)	2.1	1.5	4.4	6.2	3.2	17.4
Net food and feed imports or soil N stock mining	12.3	106.4	41.0	26.3	48.9	234.9
Human N consumption (+)	*12.6*	*38.0*	*20.6*	*16.7*	*23.6*	*111.5*
Livestock N consumption (+)	*13.6*	*94.7*	*37.7*	*38.2*	*50.5*	*234.7*
Crop N production (−)	*12.8*	*14.6*	*14.7*	*23.7*	*15.6*	*81.3*
Livestock N production (−)	*1.1*	*11.7*	*2.7*	*4.8*	*7.1*	*27.4*
Non-food and feed N export (−)	0.5	1.9	0.7	1.0	0.2	4.3
NANI	**17.8**	**125.8**	**49.5**	**37.8**	**74.3**	**305.2**

Basin has likely caused a series of serious environmental issues (e.g. soil fertility degradation) (COWI 2002, LVEMP 2003). We suggest that possible Nr management strategies regarding soil depletion should include increasing synthetic N fertilizer applications and regional biological N_2 fixation and improving both manure and soil management to prevent the continuing depletion of soil (organic) N stocks and to improve agricultural productivity at minimal environmental costs.

The current NANI estimate has a high degree of uncertainty and there is considerable room for improvement. Data for calculating NANI are usually collected at the

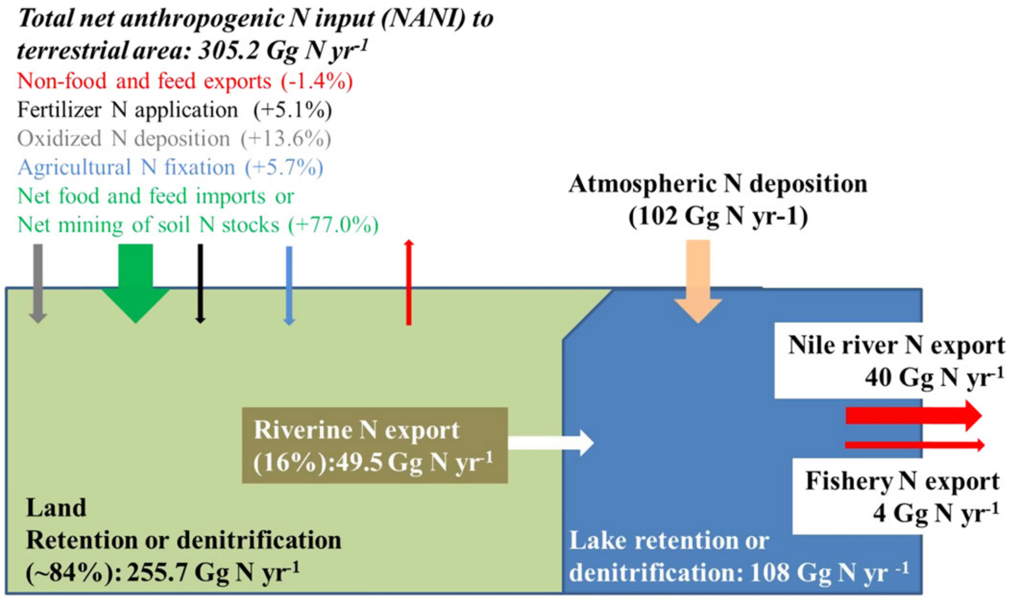

Figure 3. Estimate of regional N budget for the Lake Victoria Basin, East Africa.

Table 4. Comparison of area-weighted NANI (kg N km^{-2} yr^{-1}) and their components among the watersheds of Lake Victoria, China, Gulf of Finland (Europe), Lake Michigan (US), Mississippi watersheds (US), Hokkaido watersheds (Japan).

NANI components	China	Gulf of Finland	Lake Michigan	Mississippi watersheds	Hokkaido watersheds	Lake Victoria
Oxidized N deposition (+)	1169	320	603	174	220	225
Fertilizer N application (+)	2394	1236	1839	835	3240	79
Agricultural N fixation (+)	99	138	1355	314	1340	138
Net food and feed imports[a]	48	−232	−884	−304	4260	1417
Non-food and feed export (−)	0	0	0.01	0	2440	32
NANI	4610	1697	2912	1035	5950	1827

The data sources are: China from Ti *et al* (2012), Hokkaldo watersheds from Hayakawa *et al* (2008), Gulf of Finland from Hong *et al* (2011) and the last from Howarth *et al* (1996).

[a] Net food and feed imports for the Lake Victoria Basin means the N derived from mining of soil N stocks.

administrative unit (Howarth *et al* 2006, Han and Allan 2012, Ti *et al* 2012, Hong *et al* 2013, Han *et al* 2014), which is likely to introduce uncertainty because administrative boundaries rarely conform to watershed boundaries and the data embedded in the NANI calculations are rarely homogeneous across these administrative units (Swaney *et al* 2012, Hong *et al* 2013). Also, due to missing information, values for some parameters used in our study (e.g. crop N content, livestock N intake, N in edible portion of livestock product) were taken from previous studies outside the Lake Victoria Basin (Hong *et al* 2013). Some of these parameters are consistent across regions (e.g. crop N content) but others, related to livestock N consumption and production (e.g. livestock N intake), tend to be highly variable across regions (Hong *et al* 2011, 2013). Thus, the components of livestock N intake and production are likely to make the greatest contribution to uncertainty, since these two components were the largest contributors to NANI in this region (table 2). The key research gaps contributing to uncertainty of NANI in the Lake Victoria Basin are:

(1) General lack of agriculture-related data. This includes land-cover data and the links between land-cover and fertilizer N applications, crop types and N production, livestock populations and livestock N production/consumption.

(2) Information of biological nitrogen fixation in agricultural systems. The contribution of N_2 fixation was estimated using an area-based approach (i.e. kg N km^{-2} yr^{-1} for a given legume-crop species), while a previous study suggested yield-based modelling linked to soil N content and climate to be a more accurate approach.

(3) Spatially explicit parameters for NANI calculation. Spatially uniform parameters were used for NANI calculation in this and several previous studies. Application of fixed values for a given parameter to large regions can cause high levels of uncertainty.

(4) Monitoring data on atmospheric oxidized N deposition. Atmospheric oxidized N deposition is a major contributor of NANI while monitoring data are still scarce in this region.

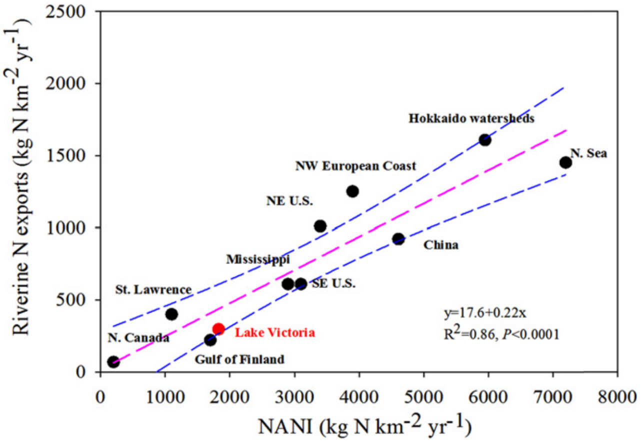

Figure 4. Comparison of the fraction of riverine N export to NANI among the Lake Victoria Basin and other watersheds in the world. The data sources are: China from Ti *et al* (2012), Hokkaldo watersheds from Hayakawa *et al* (2008), Gulf of Finland from Hong *et al* (2011) and the last from Howarth *et al* (1996).

(5) Monitoring of riverine N export to Lake Victoria, e.g. direct N exports from coastal cities and small catchments.

The proportion of NANI finally exported into Lake Victoria was about 16% (figure 3), much less than that for other regions worldwide (figure 4). In other words, approximately 84% of NANI is retained in the basin: either stored in the watershed landscapes or lost to the atmosphere by denitrification as N_2 and N_2O gases (Howarth *et al* 1996, Van Breemen *et al* 2002). The relationship between riverine N exports and NANI are complex and controlled by various factors e.g. climate conditions (Han and Allan 2008). A NANI threshold of about 1070 kg N km^{-2} yr^{-1} above which more than 25% of NANI will be exported from those watersheds by rivers has been proposed for temperate watersheds in the USA and Europe (Howarth *et al* 2012). In the Lake Victoria Basin, the NANI was much higher (mean value: 1827 kg N km^{-2} yr^{-1}) than the suggested NANI threshold for temperate watersheds, while the fraction of riverine N exports was less than the average values of those watersheds globally (figure 4). Due to the high temperature and large areas covered by riparian and wetland systems, denitrification is thought to be an important loss pathway from the Lake Victoria Basin, as in other areas (Van Breemen *et al* 2002, Han and Allan 2008). However, most N inputs to croplands in the basin are organic (i.e. manure, sewage etc), which can accumulate in organic forms in soils for a number of years (Munoz *et al* 2003). Because there is considerable transit time required to transport manure-derived Nr to the hydrosphere (Maeda *et al* 2003, Zhou *et al* 2014), we assume that the majority of non-exported NANI is retained in the soils of the Lake Victoria Basin. Unfortunately, there are no data on Nr lost through denitrification or retained in soils, wetlands and stream sediments within the basin (e.g., table S1 in the supplementary data, available at stacks.iop.org/ERL/9/105009/mmedia).

The method used in this study is something of a black box approach that relates NANI and the fraction exported to the lake through riverine N exports. Thus, it requires accurate estimates of Nr sources, fluxes and sinks in the basin. Agricultural production systems were estimated to be the major sources of Nr in the basin (table 2; table 3), and several of these terms are functionally related to each other through the organization of agriculture for a given watershed (Billen *et al* 2013). Due to the low amount of synthetic N fertilizer applied in the Lake Victoria Basin, livestock systems are the main agent of N transfer from agricultural N_2 fixation and mining of soil N stocks to arable land, primarily through the use of manure for fertilization (Rufino *et al* 2006, Davidson 2009, Billen *et al* 2013). It is certain that considerable N can be lost from agricultural soils through atmospheric and hydrological pathways. However, our literature review suggests that there are obvious knowledge gaps on atmospheric and hydrological N fluxes from agricultural systems of the Lake Victoria Basin (table S1). As indicated in table 2 and table 3, most of the food and feed N imports (soil N mining) flow to support the large human populations, in particular the large urban centres (e.g., Kampala, Kisumu). The Nr released from human excretion in urban areas cannot be easily recycled into agricultural soils but it can easily enter river systems. According to the GlobalNEWS database, global raw Nr production in 2000 for urban human excretion was 6.4 Tg N yr^{-1} although more than one third of this can be removed by wastewater treatment plants (Van Drecht *et al* 2009). In contrast with other urban areas though, urban centres in the Lake Victoria Basin contain few wastewater treatment plants and often lack effective drainage systems for collecting wastewater. Most N from human excretion is therefore likely to be released into the hydrosphere without treatment, although information on N fluxes from urban areas is not available. Thus, we recommend application of low-cost waste treatment technologies (e.g., compositing toilets: www.oursoil.org) for reducing water N pollution in this region.

Besides the major N sources of agricultural and urban systems, the drainage networks in the basin (e.g. river/stream, riparian/wetland) mainly act as Nr sinks. The N compounds are typically retained by burial in sediment and/or biotic uptake, or lost through denitrification. However, the processes and rates of retention and loss as well as the involved mechanisms are not well understood for the Lake Victoria Basin.

5. Conclusion

This is the first study to estimate an N budget for the entire Lake Victoria Basin—a region with a high population density and inadequate synthetic Nr inputs. Based on data from 1995 to 2000, the terrestrial landscapes of this basin received approximately 1827 kg N km^{-2} yr^{-1} NANI. The smallest input was fertilizer N application, while the largest is considered in NANI methodology to be net food and feed N import, however it is more likely to be from the mining of soil N stocks. This mining is likely to result in general soil degradation that could severely impact present and future agricultural productivity that is so necessary to sustain this rapidly growing population and to create conditions for economic growth. The largest source of Nr to the lake itself was atmospheric oxidized N deposition (>50%), with lake biological N_2 fixation not considered.

There are high levels of uncertainty in this estimate of N budgets for the Lake Victoria Basin, mainly due to the scarcity of data. This suggests future studies and measurements should aim (1) to develop uniform census databases (e.g., agricultural and economic data) based on hydrologic rather than administrative units and (2) to maintain and develop riverine N export measurements, as well as measurements of non-point and point source N loadings for large coastal cities with insufficient wastewater treatment plants. The immediate research priorities are to understand and quantify the N sources, sinks and fluxes in the basin as well as the involved mechanisms, in particular for agricultural (including livestock), urban and aquatic systems, and to use these data to reduce the uncertainties of NANI estimates. These efforts will not only provide an insight into strategies for improving Nr management but will also be useful for further assessing Nr budgets across this region and globally.

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