ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

Spatial trends in the nitrogen budget of the African agro-food system over the past five decades

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
8 September 2019

REVISED
26 November 2019

ACCEPTED FOR PUBLICATION
29 November 2019

PUBLISHED
20 December 2019

LETTER

Spatial trends in the nitrogen budget of the African agro-food system over the past five decades

Ahmed S Elrys[1,2,3], **Mohamed K Abdel-Fattah**[2], **Sajjad Raza**[1,3], **Zhujun Chen**[1,3] **and Jianbin Zhou**[1,3]

[1] College of Natural Resources and Environment, Northwest A&F University, Yangling, 712100, Shaanxi, People's Republic of China
[2] Soil Science Department, Faculty of Agriculture, Zagazig University, 44511 Zagazig, Egypt
[3] Key Laboratory of Plant Nutrition and the Agri-Environment in Northwest China, Ministry of Agriculture, Yangling 712100, Shaanxi, People's Republic of China

E-mail: jbzhou@nwsuaf.edu.cn

Keywords: nitrogen (N) budget, N use efficiency (NUE), N loss, human diet, Africa

Abstract

Low nitrogen (N) fertilization is a dominant cause of malnutrition in Africa, but the spatial and temporal variability of N cycling patterns in Africa remain unclear. This study is the first to perform a detailed analysis of the N cycling patterns of 52 African countries from 1961 to 2016. We calculated the N use efficiency (NUE) in crop production, country-specific N fertilization trends, and the impacts of N fertilization on human protein demand and the environment. Over the past five decades, total N input to African croplands increased from 20 to 35 kg N ha^{-1} yr^{-1}, while the application of synthetic N fertilizers (SNF) increased from 4.0 to 15 kg N ha^{-1} yr^{-1}. N contributions from animal manure and biological N fixation remained lower than 10 kg N ha^{-1} yr^{-1} and 20 kg N ha^{-1} yr^{-1}, respectively. The total N crop production increased from 15 to 22 kg N ha^{-1} yr^{-1} from 1961 to 2016. Total N surplus in Africa increased from 5 to 13 kg N ha^{-1} yr^{-1}, while estimated gaseous losses increased from 4.0 to 11 kg N ha^{-1} yr^{-1}. However, NUE declined from 74% to 63% during the past five decades, and protein consumption increased from 2.99 to 3.78 kg N $capita^{-1}$ yr^{-1}. These results suggest that Africa suffers from extremely low N input and that N loss is increasing in agricultural land. We recommend the implementation of an effective N management strategy incorporating the use of locally available organic material along with the balanced application of SNF. Such measures will require effective policy development and cooperation between all stakeholders.

Acronyms and abbreviations

N	Nitrogen
Mg	megagram (1 Mg $= 10^6$ g)
Gg	gigagram (1 Gg $= 10^9$ g)
SNF	synthetic N fertilizer
ANM	animal N manure
BNF	biological N fixation
AND	atmospheric N deposition
NUE	N use efficiency

1. Introduction

The world is facing a crisis in global food security, as approximately 8.15×10^8 people worldwide are currently undernourished (FAO 2017a). Global food demand has significantly increased over the past 50 years due to rapid population growth and dietary shifts towards meat and dairy consumption (Lassaletta *et al* 2016). Africa has the highest proportion of malnourished people (18% of the population) in the world (Ciceri and Allanore 2019). Low agriculture production in Africa is a result of poverty, pervasive conflicts, poor government performance, unstable climate, land degradation, and poor soil fertility (Sasson 2012, FAO 2017b). Africa's population is expected to reach 2.5×10^9 by 2050, which will account for approximately 58% of the world's population growth (Worldometers 2018).

Africa imports approximately 40% of its food, despite its large cropland area and its high proportion of younger workers (FAOSTAT 2018, Ciceri and Allanore 2019). Low domestic food production in Africa is a result of lower fertilizer application (Li *et al* 2013). On average, most African countries use <7.0 kg nutrients ha^{-1} yr^{-1} (Hickman *et al* 2015). The amount of nutrients absorbed by crops is greater than the amount of fertilizers applied, which causes soil nutrient mining and subsequent soil degradation (Chianu *et al* 2012). Moreover, less than 1% of farmers in most African countries apply fertilizers (Nkonya *et al* 2011).

Most African countries failed to achieve the 6-fold increase in fertilizer use (at a rate of 50 kg ha^{-1} yr^{-1}) by 2015 (Masso *et al* 2017) as recommended by The Alliance for a Green Revolution in Africa (AGRA) (Toenniessen *et al* 2008). In Africa, fertilizers are predominantly used to supply N (approximately 90% of fertilizers used). A small number of fertilizers also supply phosphorus (P) and potassium (K), while micronutrients are rarely applied (Sutton *et al* 2013). The imbalance in nutrient application to African soils is the dominant cause for low crop productivity relative to the rest of the world (Masso *et al* 2017). Limited financial capacity, high input costs, poor economic returns, poor awareness, and insufficient extension services are key factors that affect the adoption of synthetic fertilizer use (Akudugu *et al* 2012). Accordingly, increasing the use of synthetic fertilizers in African agriculture is a necessary step towards sustainable development by improving soil fertility and food security (van Ittersum *et al* 2016).

Effective policies towards the improvement of African agriculture are limited by poor data collection and management. This study therefore aimed to determine the agricultural N cycle of 52 African countries to improve our understanding of the limitations towards sustainable N management in Africa. Several studies have calculated the N budget (balancing all inputs and outputs) and its influence on the environment at the global scale. These studies include fairly general calculations of the African N budget without considering local influences. To our knowledge, this is the first study that attempts to estimate the country-specific total amount of the various N inputs into African agricultural land, including AND, ANM, BNF, and SNF. We also assessed the country-specific NUE in crop production as well as its impact on human protein demand and the environment. We analysed the African N cycling patterns and the efficiency of crop N use from 1961 to 2016 in 52 African countries to determine the variability in trends from country to country, and to identify impacts on the human protein demand and the environment. Based on our results, we discuss potential measures for effective management of the African N budget that support crop production and protect the environment.

2. Methods and assumptions

Africa represents 14% of the world's population and is the second-largest continent in terms of both area (30.2×10^6 km^2) and population (1.22×10^9 people) (Worldatlas 2018, Worldometers 2018). Africa extends across the subtropical and tropical belts from the Mediterranean Sea (37 °N) to the Cape of Good Hope (35 °S) (FAO 1993). Africa's climate is spatially variable and includes equatorial, tropical wet and dry, tropical monsoon, semi-desert (semi-arid), desert (hyper-arid and arid), and subtropical highland climates (Beck *et al* 2018). Africa is the warmest continent on Earth, with dry lands and deserts accounting for approximately 60% of the total land area (Worldatlas 2018). The average annual temperature in Africa is 25.7 °C, and the average annual rainfall is <1000 mm yr^{-1} (Worldatlas 2018). Rainfall tends to decrease with distance from the equator and is negligible in the Sahara (north of latitude 16 °N), eastern Somalia, and in southwestern countries such as Namibia and South Africa. Rainfall is highest on the eastern seaboard of Madagascar, the highland regions in eastern Africa, large areas of the Congo Basin and central Africa, and coastal countries of western Africa, including Liberia, Sierra Leone, and Guinea (Worldatlas 2018). The southern and central parts of Africa are covered by dense rainforests and savanna plains, while the northern half is primarily desert or arid land. (Worldatlas 2018).

Africa is the largest untapped land reserve in the world, where only <10% of the 162×10^6 ha of fertile land is currently used for agriculture (ARD 2009). Africa has a large variety of soil types. Over 60% of African soil are hot, arid, or immature soil assemblages: Arenosols (22%), Leptosols (17%), Cambisols (11%), Calcisols (6%), Regosols (2%) and Solonchaks/Solonetz (2%) (Jones *et al* 2013). Tropical or subtropical soils account for ~20%: Ferralsols (10%), Plinthosols (5%), Lixisols (4%) and Nitisols (2%) (Dewitte *et al* 2013). A significant area (6%) of the African land mass is occupied by a further 16 soil groups that each cover an area of <1% (Jones *et al* 2013). The soils range from stony, shallow, and infertile to deeply weathered and recycled soil that supports considerable quantities of biomass (Jones *et al* 2013). African soils suffer from poor fertility as they are very old and lack volcanic renewal. The mismanagement of soil resources in the continent has promoted vegetation loss, salinization, and soil erosion (Dewitte *et al* 2013).

The agro-food system in Africa has changed significantly over the last five decades (table 1). Africa experienced a significant increase in total population (268%) and a decrease in rural population (−26%) (table 1), and the total agricultural and arable land area increased by 8.71% and 51.6%, respectively. Moreover, the yield of almost all crops had increased (except fibre crops and oil crops), particularly for cereals (table 1). The continent had experienced a 30% increase in total protein consumption, with animal protein accounting for 31% of the increase during the last 56 years (table 1). A large increase in the number of animals has been recorded in recent years, with

Table 1. Agricultural intensification in Africa during 1961–2016 (FAOSTAT 2018).

Variables		1961–1965	2011–2016	(%)
Population	Population (10^9)	0.31	1.14	268
	Rural population %	81	60	−25.9
Agriculture surface (10^6 ha)	Agricultural area	1045	1136	8.71
	Arable land	157	238	51.6
	Cropland	173	225	30.1
Production (kg ha^{-1} yr^{-1})	Cereals	864	1570	81.7
	Citrus fruit	6850	10 950	59.9
	Coarse grain	810	1343	65.8
	Fibre crops	304	198	−34.9
	Fruits	5892	8739	48.3
	Oil crops (oil equivalent)	235	166	−29.4
	Pulses	498	743	49.2
	Roots and tubers	5846	8529	45.9
	Vegetables	6637	8583	29.3
Livestock (10^6 heads)	Asses	10.8	19.7	82.4
	Buffaloes	1.56	3.86	147
	Camels	9.37	25.0	167
	Cattle	128	315	146
	Chickens	294	1778	505
	Goats	97	376	288
	Horses	3.52	6.29	78.7
	Pigs	6.00	34.0	467
	Rabbits and hares	2.84	16.0	463
	Sheep	137	343	150
	Turkeys	1.34	26.1	1848
Diet	Protein supply quantity (g cap^{-1} d^{-1})	53.3	69.1	29.6
	Animal protein supply quantity (g cap^{-1} d^{-1})	10.7	16.1	50.5
	Proportion animal protein (%)	20	23	15.0
	Food supply quantity (kg cap^{-1} d^{-1})	1.20	2.30	91.7

particularly high increases in the number of turkeys, chickens, goats, cattle, sheep, and buffalo (table 1).

2.1. Nitrogen budget and NUE

We calculated the cultivated area per year for each African country over the past 56 years (1961–2016) by combining the area of all cropland in each country using the FAO database (Elrys *et al* 2019a). We calculated the total annual N uptake by crop production using the annual yield of each crop harvested and its N content (Lassaletta *et al* 2014). The total N input to cropland includes the combined inputs of SNF, ANM, AND, and BNF. We used data on SNF consumption during the past five decades from the IFASTAT (IFA 2018) and FAOSTAT (FAOSTAT 2018) databases. However, the IFA and FAOSTAT data does not distinguish between cropland and grassland, and therefore only includes the total amount of agricultural N used annually for each country. SNF is not added to grasslands in Africa, and therefore we did not subtract the ratio of grassland SNF from the data (Heffer *et al* 2013). AND input was calculated based on regional estimates of AND rates on agricultural land (Dentener *et al* 2006) multiplied by the total crop area for each country (FAOSTAT 2018). We used ANM input data over the past five decades from the FAOSTAT database (FAOSTAT 2018). Manure application in Africa is mostly added to cropland and is seldom applied to grasslands (Suttie *et al* 2005). We therefore assumed grassland ANM application to be negligible in this study. The quantity of BNF was calculated based on the yield-based method using the following equation (Lassaletta *et al* 2014):

$$\text{N Fixed} = \%\text{Ndfa} \times \frac{Y}{\text{NHI}} \times \text{BGN}, \qquad (1)$$

where % Ndfa is the percentage of N uptake derived from N fixation, Y is yield (expressed in kg N ha^{-1} yr^{-1}), NHI is the N harvest index (defined as the ratio of the harvested material to the total above-ground N production), and BGN is a multiplicative factor indicating total N_2 fixation, which includes below-ground contributions associated with roots, nodules and rhizo-deposition via exudates and decaying root cells and hyphae. These parameters were collected from Lassaletta *et al* (2014). We used a constant rate of BNF for forage products, rice paddies and sugarcane (Herridge *et al* 2008).

Following the application of SNF and ANM, we calculated the loss of N in soils by NH_3 volatilization using regional emission factors (table 2) reported in Bouwman *et al* (2002). NH_3 volatilization emission

Table 2. Emissions factors used for the estimation of NH_3, NO and N_2O emissions.

Gaseous N emissions		Synthetic N	Manure N	Reference
NH_3	Upland crops	0.19	0.36	Bouwman et al (2002)
	Wetland rice	0.21	0.33	
NO		1.40	0.13	FAO (2001)
N_2O		3.40	4.56	FAO (2001)

factors varied with cropland type (upland crops, wetland rice) and N source (SNF, ANM), which were multiplied by the annual input of SNF and ANM. We also estimated NO and N_2O emissions using the emission factors (table 2) of developing countries (FAO 2001). The total protein consumption (kg N cap^{-1} yr^{-1}) was calculated using data on the daily intake of protein (derived from crops, livestock, and fish) per capita (FAOSTAT 2018) and its N content (Lassaletta *et al* 2014). We calculated the NUE and N surplus using equations (2) and (3), respectively (Raza *et al* 2018):

$$\mathrm{NUE}(\%) = \frac{\text{Total N crop production(N removed from the field)}}{\text{Total N Input}} \times 100 \quad (2)$$

$$\text{N surplus} = \text{Total N Input} - \text{Total N crop production}. \quad (3)$$

African countries were divided into four groups based on N input (total N input, SNF, BNF, ANM), N crop production, and N losses (N surplus, estimated gaseous losses) (expressed as kg N ha^{-1} yr^{-1}): (i) low (<10), (ii) moderate (10–20), (iii) high (20–50), and (iv) very high (>50). The countries were also divided into four groups based on human diet (kg N cap^{-1} yr^{-1}): (i) low (<2), (ii) moderate (2–4), (iii) high (4–6), and (iv) very high (>6); and three groups based on NUE (%): (i) low (<60), (ii) moderate (60–70), and (iii) high (>70).

Figures were prepared using SigmaPlot 12.5 (Systat Software Inc., San Jose, CA, USA), and maps were created using ArcMap 10.2.1.

3. Results

3.1. Sources of N input

The total N input to croplands in Africa increased from 2160 Gg N yr^{-1} (20 kg N ha^{-1} yr^{-1}) in 1961–1965 to 8626 Gg N yr^{-1} (35 kg N ha^{-1} yr^{-1}) in 2011–2016 (figure 1). Over the past five decades, SNF showed the highest increase compared to all other N inputs from 4.0 kg N ha^{-1} to 15 kg N ha^{-1}. BNF increased from 7.0 kg N ha^{-1} yr^{-1} (1961–1965) to 10 kg N ha^{-1} yr^{-1} (2011–2016). The highest increase in BNF was observed in North Africa from 4.0 kg N ha^{-1} (1961–1965) to 16 kg N ha^{-1} (2011–2016). In contrast, the rate of BNF decreased in western Africa (−12%) and southern Africa (−48%) (figure 2).

During 1961–1965, the total N input in Botswana, Egypt, Guinea-Bissau, Gambia, Mauritius, and Reunion was >50 kg N ha^{-1} yr^{-1} (figure 2). However, N input in most African countries were moderate to high (figure 2). N input values in Djibouti, Egypt, Libya, Mauritius, Reunion, Seychelles, Senegal, South Africa, and Zambia were categorized as very high in 2011–2016, with total values ranging from 54 kg N ha^{-1} yr^{-1} in Senegal to 330 kg N ha^{-1} yr^{-1} in Egypt. The remaining countries were categorized as moderate to high (figure 2). SNF input in most African countries was low or moderate during 1961–1965, but input in South Africa, Botswana, and Zimbabwe was categorized as high, and input in Egypt, Mauritius, and Reunion was categorized as very high (figure 2). During 2011–2016, Egypt, Botswana, Mauritius, South Africa, and Zambia were categorized as very high, while the remaining countries ranged between low to high (figure 2). Except for Egypt, whose BNF input was categorized as very high, BNF inputs ranged between low to moderate during 1961–2016 in all African countries (figure 2). Currently, ANM application in most African countries is still <10 kg N ha^{-1} yr^{-1} (figure 2).

3.2. Agronomic performance

Total N in crop production in Africa increased from 15 to 22 kg N ha^{-1} yr^{-1} from 1961 to 2016 (figure 3). The highest total N crop production was observed in North Africa (27 kg N ha^{-1} yr^{-1}) during 1961–1965, while the highest N crop production was observed in southern Africa (52 kg N ha^{-1} yr^{-1}, figure 4) during 2011–2016. N crop production in all African countries was low to moderate during 1961–1965, except for that in Egypt, which was very high. Production in most countries was moderate to high during 2011–2016, except for in Egypt and South Africa, where it was very high (figure 2).

NUE in Africa decreased from 74% during 1961–1965 to 63% during 2011–2016 (figure 3). The highest decline in NUE occurred in North Africa from 110% to 50% during the last five decades (figure 4). We observed high variability in NUE between the different African regions (figure 5). N mining occurred in Algeria, Egypt, Morocco, Tunisia, Burundi, Rwanda, and Lesotho during 1961–1965 and is still occurring in Burundi, Ethiopia, and Rwanda. Currently, 16 countries have NUEs of >70% (figure 5). The NUEs of Comoros, the Democratic Republic of the Congo, Guinea, Malawi, Morocco, and South Africa ranged between 60%–70%, while the NUEs in the remaining countries were <60% (figure 5).

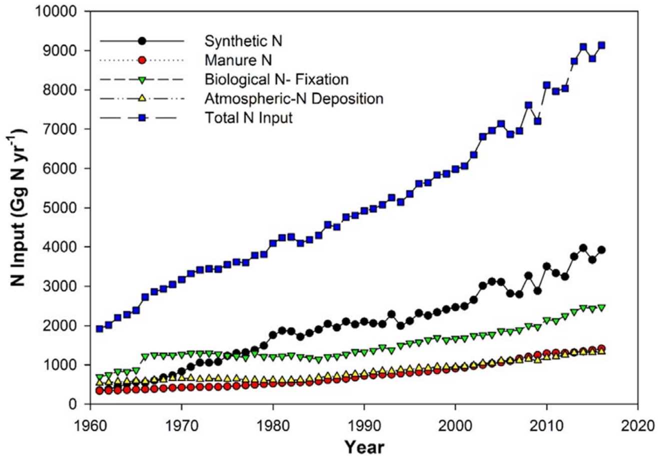

Figure 1. Historical changes in N input to crops from different sources in croplands of Africa.

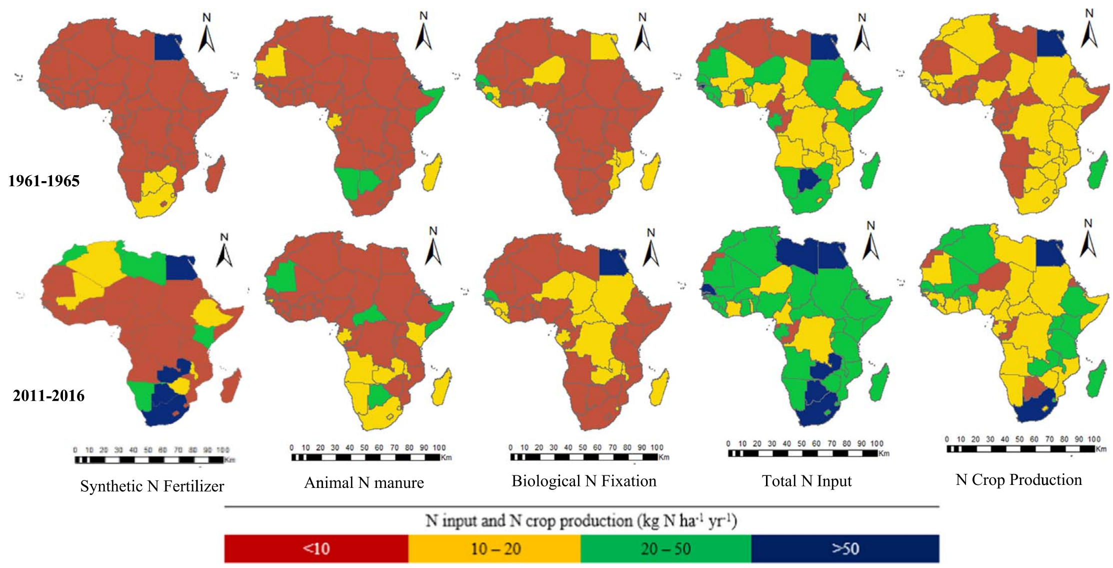

Figure 2. Historical changes in the budget of the N input to croplands from different sources and N crop production of African countries.

3.3. Environmental N loss

The total N surplus in Africa increased from 554 Gg N yr^{-1} (5 kg N ha^{-1} yr^{-1}) in 1961–1965 to 3151 Gg N yr^{-1} (13 kg N ha^{-1} yr^{-1}) in 2011–2016 (figure 3). We observed the highest rates of N surplus in South Africa throughout the entire study period. N surplus increased significantly in North Africa from −2.3 kg N ha^{-1} yr^{-1} (N mining) in 1961–1965 to 38 kg N ha^{-1} yr^{-1} in 2011–2016 (figure 2). The highest rates of N surplus were observed in Mauritius (117 kg N ha^{-1} yr^{-1}) and Reunion (111 kg N ha^{-1} yr^{-1}) from 1961–1965 and in Egypt (181 kg N ha^{-1} yr^{-1}), Botswana (172 kg N ha^{-1} yr^{-1}), and Mauritius (156 kg N ha^{-1} yr^{-1}) in 2011–2016 (figure 3).

Estimated gaseous losses (NH_3–N, N_2O–N, NO–N) from African croplands increased from 281 Gg N yr^{-1} (4 kg N ha^{-1} yr^{-1}) during 1961–1965 to 1823 Gg N yr^{-1} (11 kg N ha^{-1} yr^{-1}) during 2011–2016 (figure 3). Estimated gaseous losses in most African countries were low in 1961–2016 (figure 2). Gaseous losses in Namibia, Somalia, Kenya, Libya, and Morocco from 2011 to 2016 were moderate, while losses in Botswana, Mauritius, Seychelles, South Africa, and Zambia were high. Egypt alone was categorized as very high with regards to gaseous losses during 2011–2016 (figure 2).

3.4. Human diet

During the past five decades, protein consumption in Africa increased from 2.99 to 3.78 kg N cap^{-1} yr^{-1}, with an increase in the fraction of consumed animal proteins (including fish) from 25.3% to 27.4%. The highest increase in protein consumption occurred in North Africa from 3.1 to 5.7 kg N cap^{-1} yr^{-1} (figure 6). Protein consumption in most African countries was moderate during 1961–1965 (figure 5). From

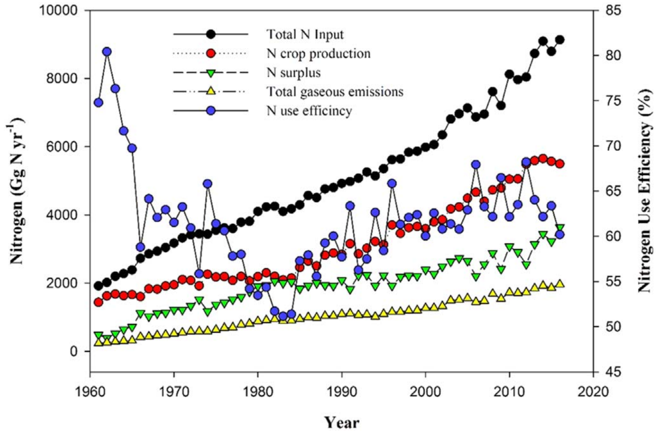

Figure 3. Historical changes in the total N input, NUE, N uptake by crops, and N surplus in Africa.

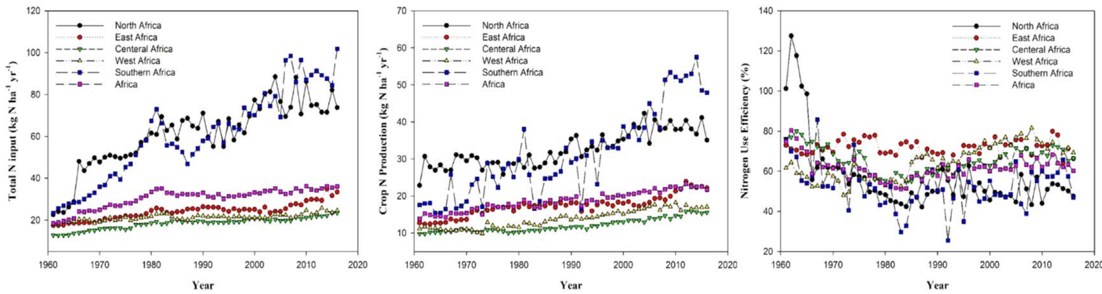

Figure 4. Historical changes in the total N input, crop N production and N use efficiency in different regions of Africa.

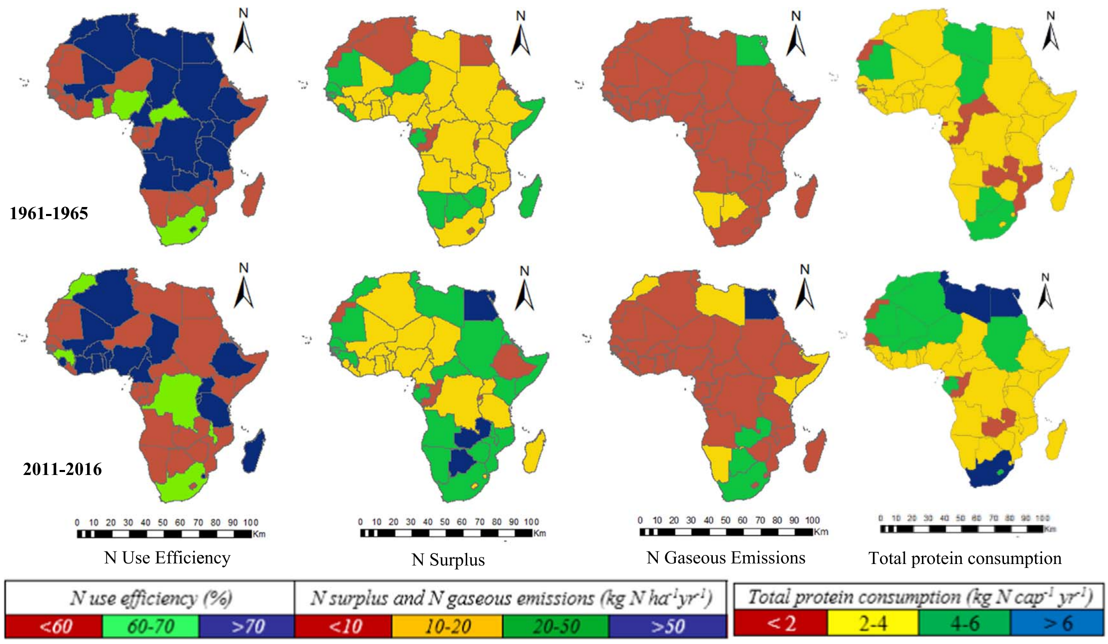

Figure 5. Historical changes in N use efficiency, N surplus, N gaseous emissions and total protein consumption of African countries.

2011–2016, protein consumption in Egypt, Libya, Tunisia, and South Africa was very high while the remaining countries were moderate to high. The largest absolute increase in animal protein consumption was observed in Angola, Benin, Cabo Verde, Egypt, Malawi, and Tunisia (figure 6).

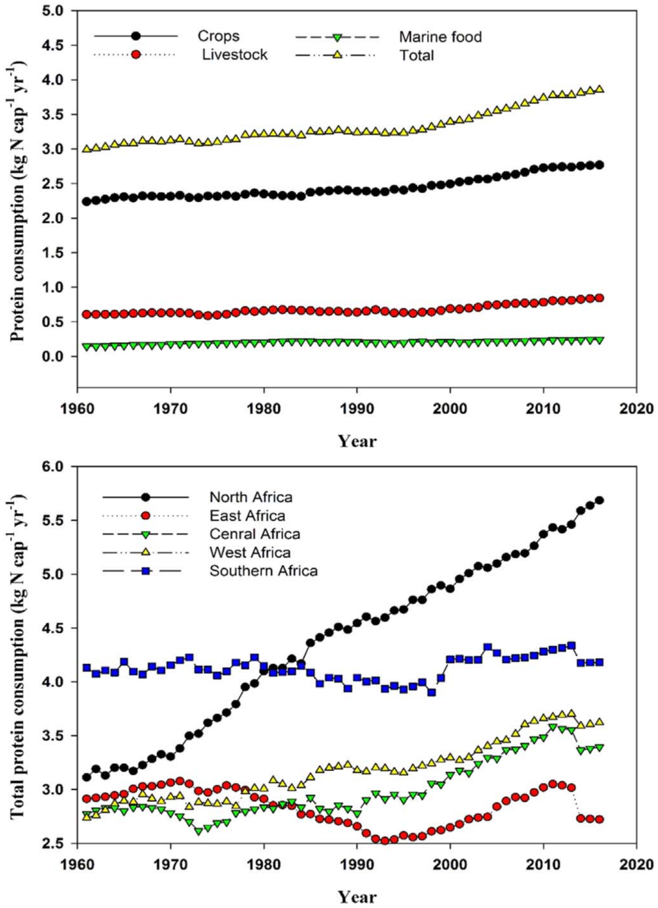

Figure 6. Protein consumption per capita from different food sources in different regions of Africa during 1961–2016.

4. Discussion

4.1. Status of the N budget and NUE in Africa

Africa is one of the poorest regions on Earth in terms of soil fertility, economy, and living standards (Ciceri and Allanore 2019). Our results infer low fertilizer use in African croplands over the past five decades (figures 1 and 2). SNF inputs increased by only 11 kg N ha^{-1} yr^{-1} (figure 1). The SNF estimates of this study are close to the values estimated by Lassaletta *et al* (2014). Reduced availability of SNF to small farmers in Africa is a result of limited market opportunities, higher transportation costs, and poor economic conditions for African farmers (Masso *et al* 2017). Moreover, the results of 369 samples showed that urea being sold in the fertilizer market in Uganda contained 31% N on average compared to 46% N in the global markets (Bold *et al* 2015).

N inputs from other fertilizer sources such as ANM and BNF are also typically low in African agriculture. Further, organic N fertilizers in Africa are not always available in sufficient amounts to increase crop production (Vanlauwe and Giller 2006), as the application of ANM and BNF in most African countries is still $<$10 kg N ha^{-1} yr^{-1} (figure 2). Quality issues also affect the use of BNF and ANM. For example, approximately 40% of $>$22 evaluated rhizobial inoculants in Ethiopia, Kenya, and Nigeria were free of active ingredients and did not perform their required role (Jefwa *et al* 2014). Animal manure in African agriculture only contributes a small percentage of N to the soil due to poor manure management and the application of low quality animal feed (Diogo *et al* 2013). The lack of interest from African policy makers and farmers on issues regarding organic N inputs (Ciceri and Allanore 2019) has resulted in poor buying capacity and reduced availability of high quality fertilizers.

N crop production only showed a minor increase from 15 to 22 kg N ha^{-1} yr^{-1} over the past five decades due to low N input in Africa (figure 3). Estimates of total crop N production in this study were in the range of values reported by Lassaletta *et al* (2014). Poor crop yield in Africa is a result of imbalanced nutrient application of predominantly N (90% of applied fertilizers) and limited use of P, K, and micronutrients (Sutton *et al* 2013). Furthermore, the observed decrease in NUE in Africa from 74% during 1961–1965 to 63% during 2011–2016 (figure 3) is likely due to failed agronomic practices, such as improper N fertilizer recommendations and poor yield due to low N fertilizer use (Masso *et al* 2017). As a result, N surplus in Africa increased from 25% to 37% of the total N input during the past five decades (figure 3). Stoorvogel and Smaling (1990) estimated N losses from cropland to be

31, 68, 112, and 27 kg ha^{-1} yr^{-1} in Zimbabwe, Malawi, Kenya and Tanzania, respectively. Further, N losses of up to 91 kg N ha^{-1} has been attributed to leaching in Niger (Brouwer and Powell 1998). Estimated gaseous losses increased from 13% to 21% of the total N input over the last five decades. N gas emissions in Africa is a significant contributor to the global greenhouse gas budget (Thompson *et al* 2014), and the small increase in the application of SNF and ANM (figure 1) in African agriculture has increased estimated N gas emissions from 2.3 to 7.7 kg N ha^{-1} yr^{-1} (figure 3) (Bouwman *et al* 2013).

N is the main component of amino acids and proteins (Masso *et al* 2017), and thus lower agricultural N application leads to lower protein content in crops (Selles and Zentner 1998). The average African per capita protein consumption (3.78 kg N cap^{-1} yr^{-1}) is still below the healthy recommendation of 4.0 kg N cap^{-1} yr^{-1} (figure 6), with 40% the total of protein consumption contributed from animal sources (1.6 kg N cap^{-1} yr^{-1}) (Billen *et al* 2015, Lassaletta *et al* 2016). Undernourishment in Africa (about 18% of the total population) can thus be linked to poor protein content in food (Masso *et al* 2017). This is particularly prevalent in eastern Africa (figure 6), where an estimated one-third of the population is undernourished (Food Security Information Network 2018). It is therefore necessary to increase the use of N fertilizers in Africa to improve crop production, grain quality, and malnutrition.

4.2. Spatial trends of the N budget and NUE in Africa

The degree of agricultural intensification differs significantly between African countries. In some countries such as Botswana, Egypt, Mauritius, South Africa, and Zambia, excessive N fertilizer use has led to large N surpluses (figures 2 and 5) and subsequent environmental problems (Lassaletta *et al* 2014). In contrast, most other African countries use insufficient amounts of N fertilizer, which leads to soil N depletion (Lassaletta *et al* 2016). We observed high SNF inputs in Botswana, Egypt, Mauritius, South Africa, and Zambia, ranging from 63 kg N ha^{-1} yr^{-1} in Zambia to 241 kg N ha^{-1} yr^{-1} in Egypt (figure 2). Farmers are typically wealthier in these countries, and N fertilizers are generally more affordable due to government subsidies (Ciceri and Allanore 2019). High N application in these countries are predominantly due to increasing cropland area, low soil fertility, and the high N demand of cereals (Masso *et al* 2017, Elrys *et al* 2019a). In particular, 37% of the total SNF use in Africa occurs in Egypt (Elrys *et al* 2019a).

We only observed high N crop production in Egypt and South Africa, despite the high SNF application rates in the five countries. Low production in Botswana, Mauritius, and Zambia can be attributed to the sharp decrease in NUE (6.5%, 14%, and 39%, respectively) caused by poor soil fertility and failed agricultural practices (Chianu *et al* 2012). Moreover, the rise of N fertilizer use in these five countries has inevitably increased N losses and decreased NUE (figure 5). N surplus had increased by 342%, 33%, 317% and 1203% in Botswana, Mauritius, South Africa, and Zambia, respectively, due to the significant decline in NUE (figure 5). Furthermore, fertilizer recommendations for particular crops in these countries are not updated accordingly (Masso *et al* 2017). Most farmers in these countries apply excess fertilizers, as they believe that higher fertilizer application results in higher growth (Kassam and Dhehibi 2016). As a result, N surplus has increased significantly in Egypt from −7.0 kg N ha^{-1} yr^{-1} (N mining) to 181 kg N ha^{-1} yr^{-1} during the last five decades (figure 2) due the prominent decline in NUE from 102% to 45% (figure 4). This decrease can be attributed to excessive N application and a shift from a dependence on soil N mining to external N input (Elrys *et al* 2019a). Further, highest estimated gaseous emissions were recorded in Botswana, Egypt, Mauritius, South Africa, and Zambia reaching 48, 138, 43, 25, and 46 kg N ha^{-1} yr^{-1}, respectively, during 2011–2016. Accelerated N losses from soils in these countries are due to high SNF application rates and a lack of education among farmers (Moawad *et al* 1984). The situation in these countries, particularly in Egypt, is an example of Africa's potential future if N fertilization rates continue to rise.

However, total N inputs in most African countries are still less than 50 kg N ha^{-1} yr^{-1} (figure 2), while SNF, ANM, and BNF inputs have not exceeded 20 kg N ha^{-1} yr^{-1}. This observed reduction in N application has resulted in low N crop production, ranging from 5.5 kg N ha^{-1} yr^{-1} in São Tomé and Príncipe to 34 kg N ha^{-1} yr^{-1} in Ethiopia during 2011–2016. Farmers cannot afford to buy high-quality fertilizers, as the gross domestic products per capita of most African countries are some of the lowest in the world (Shiferaw *et al* 2014). In addition, subsidies towards fertilizer use are rare due to poor economic conditions (Masso *et al* 2017). In most African countries, the significant decline in the quantity and quality of N input (figures 1 and 2) has led to N depletion and land degradation (Masso *et al* 2017). Depleted soil fertility has resulted in reduced crop yields in Africa at a rate of 1.0 Mg ha^{-1} yr^{-1} since the 1960s (Masso *et al* 2017). N mining was prevalent in Algeria, Egypt, Morocco, Tunisia, Burundi, Rwanda, and Lesotho during 1961–1965, and is still prevalent in Burundi, Ethiopia, and Rwanda. Currently, NUEs in Algeria, Tanzania, Uganda, Cameroon, Benin, and Togo are >90% (figure 4). These countries will therefore likely suffer from N depletion in the near future if N application rates remain low. Soil N depletion in Africa from overgrazing and/or leaching, removal of crop residues from fields, volatilization, and erosion has been found to exceed N input through SNF, AND, BNF, and ANM (Kiboi *et al* 2019). Soil mining is also the cheapest source of fertilizer in Africa (Masso *et al* 2017).

Further, there are no incentives for farmers to care for and protect agricultural land, as farmers do not own land in Africa due to land tenure agreements (Henao and Baanante 2006).

Most African countries suffer from poor agricultural production potential, and N losses therefore still occur due to inefficient N use, despite the high availability of N for plant uptake (Masso *et al* 2017). NUE has noticeably reduced in most African countries over the past five decades (figures 3 and 5). Only 10%–20% of the N applied through fertilizers is assimilated or recovered in crops under farming practices in Africa (Chianu *et al* 2012). This ineffective use of fertilizers discourages poorer farmers from investing in quality fertilizers (Woomer *et al* 2008). The increase in SNF application from 3.01 to 7.40 kg N ha^{-1} yr^{-1} in countries with relatively low SNF inputs (i.e. most African countries) led to an increase in N surplus from 7.96 to 12.9 kg N ha^{-1} yr^{-1}. In response, estimated gaseous emissions increased from 2.74 to 6.33 kg N ha^{-1} yr^{-1}. On less responsive soils where other constraints are limiting, fertilizer application alone results in low NUE and crop yields due to the absence of other corrective measures (Zingore *et al* 2007). For example, figure 3 shows a sudden decrease in NUE during 1981–1985, followed by an increase thereafter. This abrupt change in NUE is due to the increase in SNF rates adopted by several African countries in response to external or government subsidies (Masso *et al* 2017). However, these subsidies were short-lived due to the poor economy and political instability in these countries, resulting in a reduction in SNF application (Chianu *et al* 2012). In addition, imbalanced fertilization was rife during this period, as farmers had insufficient experience of fertilizer use (Elrys *et al* 2019a). Therefore, low NUE remains a significant agricultural challenge for Africa, particularly under increased N fertilizer application in future.

4.3. Global comparisons

A large gap exists between the crop yields of Africa and rest of the world. Africa's agricultural land yields only 24% of its potential, while best farming practices from around the world produces up to three times as much (AU and NEPAD/NPCA 2006). Grain yields in Africa average approximately a third of those in East Asia. This can be attributed to differences in soil quality and low fertilizer application in Africa (Lassaletta *et al* 2014). The global SNF consumption increased from 9603 to 76 716 Gg N yr^{-1} over the last five decades (IFA 2018). Of the total 67 113 Gg N yr^{-1} increase in SNF consumption between 1961 and 2016, 59% occurred in Asia, 25.5% in the Americas, 15% in Europe, 3.8% in Africa, and 2.5% in Oceania (IFA 2018). Further, Africa accounted for only 3.7% of the world's SNF consumption in 2016 (IFA 2018).

In contrast to most African countries, a significant increase in N fertilizer application occurred in other developing countries, such as China, India, Pakistan, Bangladesh, and Sri Lanka (IFA 2018). However, this considerable shift in the N budget has negatively impacted the environment, despite the resulting increases in grain yield (Elrys *et al* 2019a). There is thus an urgent need to improve management practices to minimize harmful environmental impacts from excessive fertilizer application (Raza *et al* 2018). Several developing countries also excessively apply SNF though there has been recent improvement. Fertilizer use in developed countries peaked in 1980 (Edmonds *et al* 2009). For instance, the excessive use of SNF during 1970–1980 in the United Kingdom resulted in serious environmental problems such nitrous oxide (N_2O) emission, eutrophication and soil acidification (EPA 2017), and drastic changes in agricultural policies after 1980 resulted in higher cereal yields and improved nutrient management—particularly for N (EPA 2017).

The world suffers from high rates of N losses from croplands (Lassaletta *et al* 2014), with the Middle East, Europe, the USA, India, China, and Central America experiencing N losses at a rate of ~50 kg N ha^{-1} yr^{-1}. On average, N losses remain below 25 kg N ha^{-1} yr^{-1} in most of Africa, Australia, and the former Soviet Union countries (Lassaletta *et al* 2014). Huge environmental N losses from excessive N use in a number of developing countries (e.g. China, Pakistan, Egypt) (Li *et al* 2017, Raza *et al* 2018, Elrys *et al* 2019a) have resulted in soil acidification (Guo *et al* 2010), water pollution, and increased N_2O emissions to the atmosphere (Lassaletta *et al* 2014). Furthermore, NUE declined from 65%, 58%, and 71% in the 1960s to present-day values of 25%, 23%, and 44% in China, Pakistan, and Egypt, respectively (Zhang *et al* 2015, Raza *et al* 2018, Elrys *et al* 2019a). Therefore, high N losses should be considered in Africa if SNF application becomes high in future.

4.4. Implications and practical recommendations

We observed significant changes in the N cycle of a number of African countries during the last five decades, but there was no significant change in the total African N budget (figure 7). However, it is necessary to increase soil N input and promote NUE in African agriculture to improve crop production and minimize impacts on human health and the environment (Yuan and Peng 2017, Elrys *et al* 2019a). Such progress requires effective management practices at all levels.

4.4.1. Increasing N input

It is widely agreed that increasing SNF input can improve agricultural production. However, a number of countries have suffered environmental degradation in response to high SNF application. It is therefore necessary to implement alternative solutions that are

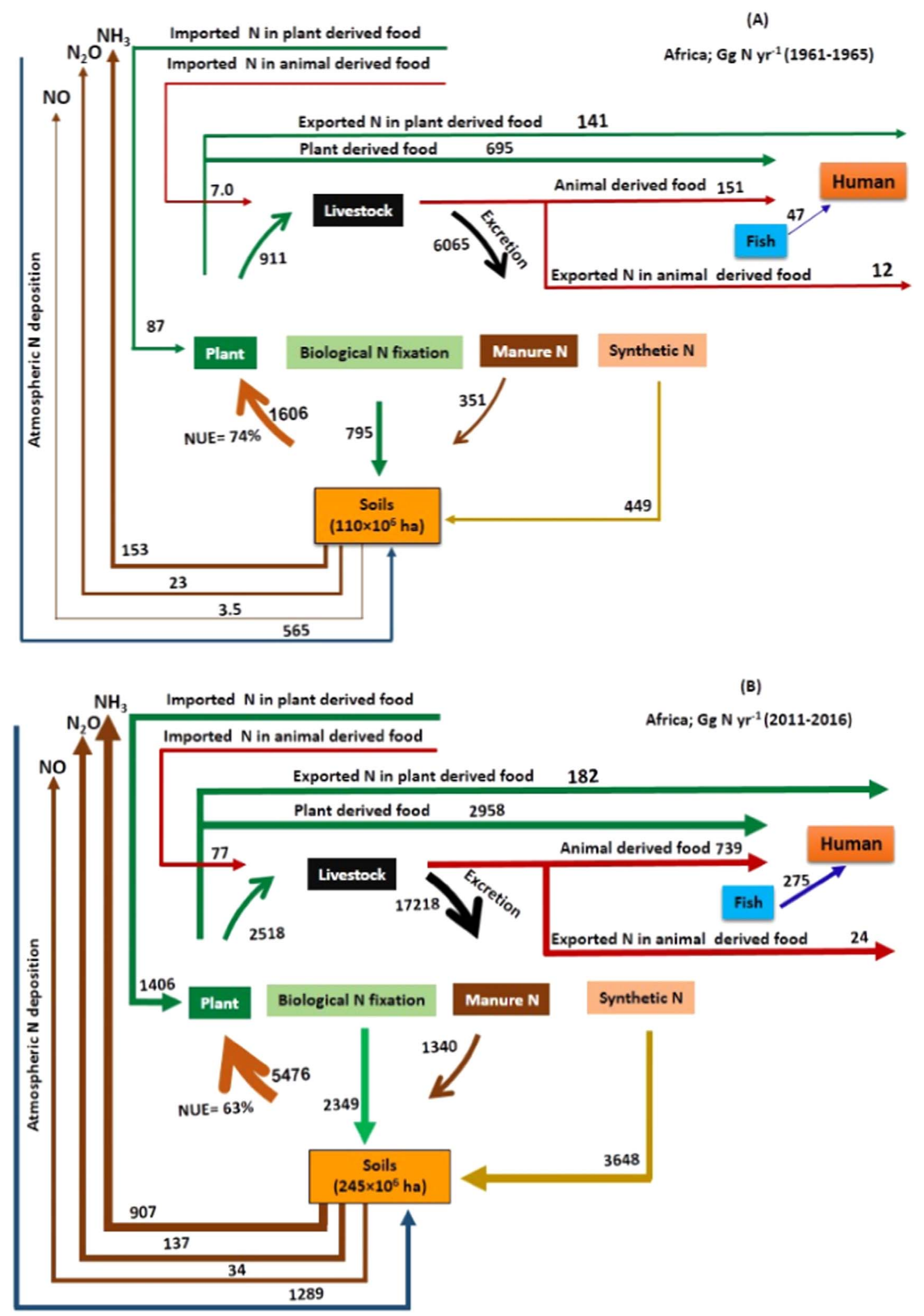

Figure 7. Major changes in N flux in the African agro-food system during the past five decades.

cheap, sustainable, and environmentally friendly—such as no-till or zero-till farming—to increase organic matter, conserve soil and nutrients, and promote plant growth (Chianu *et al* 2012). SNF and organic N inputs (e.g. ANM, BNF, crop residues) play complementary roles in agroecosystems. With regards to Africa, the primary advantages of organic N fertilizers (even of low quality) over SNFs are their local availability and reduced cost (Masso *et al* 2017). Moreover, the cultivation of high-protein N-fixing legumes such as pigeon pea, grass pea and soya beans can add 412, 80 and 59 kg N ha^{-1}, respectively, to the soil in one season, and are thus considered suitable green alternatives for growth under African conditions (Maskey *et al* 2001). Legumes can either be planted next to grain crops or alternated between seasons (Maskey *et al* 2001).

Regardless, Africa cannot solve its soil problems without the use of SNF; fertilizer subsidies are therefore necessary in Africa. An effective N management strategy should be implemented, which incorporates locally available organic material along with the judicious and balanced use of SNF (Masso *et al* 2017). Increasing the application of SNF will not improve yields unless effective agronomic practices are followed, such as growing high-yielding crop varieties that are well-adapted to local conditions and recycling of available organic matter (Roobroeck *et al* 2015). Further, fertilizer recommendations should be revised to account for balanced crop nutrition (Masso *et al* 2017). The balanced use of fertilizers should be incorporated into soil fertility management strategies, including organic applications to complement synthetic fertilizer use.

4.4.2. Reducing N loss

A number of modern fertilizer techniques have been used to reduce N loss and increase NUE in Africa, including the use of controlled fertilizers, nitrification inhibitors, and water-soluble fertilizers in irrigation water (Elrys *et al* 2019a, 2019b). Further, the principles of effective use of N input should be adopted, which includes using the appropriate source of N fertilizer that is applied at the appropriate rate, at the appropriate time, and at the appropriate place (Yuan and Peng 2017). In China, three strategies are widely applied in agriculture to enhance the NUE of irrigated rice: (1) real-time N management, (2) three-control technology (controlling N fertilizer, controlling unproductive tillers, controlling pests), and (3) site-specific N management (Yuan and Peng 2017). Furthermore, as variability in NUE exists between different crops genotypes, selective breeding of particular crop varieties with improved NUE can help to minimize the need for SNF application (Yu *et al* 2015). Such technologies are necessary for the sustainable development of African agriculture, particularly if the use of SNF becomes more prevalent.

Farmers and policy makers need a simple but robust indicator to demonstrate progress toward reducing N losses. McLellan *et al* (2018) suggested that the N surplus indicator can be used to track the sustainability of a production environment. N surplus is a robust measure of N losses that is easily to calculate and its temporal and spatial change over time can be tracked (McLellan *et al* 2018) as done in our study. N surplus provides farmers with a means of demonstrating to an increasingly concerned public that they are succeeding in reducing N losses while also improving the overall sustainability of their farming operation (McLellan *et al* 2018). N surplus targets can be established for a specific production environment to set upper levels of sustainable production. This was done recently by Sela *et al* (2019) where they calculated regional N surplus targets for different production environments in the US Midwest—accounting for the different soil types, climate and yield potential in each environment. Farmers can then use these targets to improve their N management. Perhaps in the future, realistic state-specific N surplus targets could be calculated for African states, and can aid in increasing productivity in a more sustainable way. Our study is a good first step towards understanding N surplus trends for African countries.

4.4.3. Designing and strengthening policies

African governments need to build strong institutions to create an environment in which smallholders can intensify their production systems (Camara and Heinemann 2006). This can be done through the adoption, implementation, and enforcement of policies regarding access to output markets, land tenure, water, input supplies, and physical and human capital (Richards *et al* 2016). For example, when farmers' ownership of agricultural land is made clear and guaranteed through property rights with competitive prices for agricultural land, farmers will become sensitive to the loss of the productive capacity of the land (Henao and Baanante 2006). Governments can reduce fertilizer costs while promoting the expansion of private-sector fertilizer supply networks by organizing the consolidation of important fertilizer orders (regional procurement to capture economies of scale) and by investing in transportation infrastructure (Camara and Heinemann 2006). In addition, government needs to coordinate their policies on organic N input management. It is necessary to organize sensitization programs to inform policy makers and other actors of the benefits of organic N input management, giving them a better chance to create a favourable environment for adoption of these practices, combined with adequate control and enforcement of such policies (Ndambi *et al* 2019). Therefore, such policies would set fertilizer consumption, production, and marketing in the wider context of agricultural production systems and poverty reduction.

4.5. Sources of uncertainty

The establishment of long-term agricultural budgets incorporates several generalizations and presumptions (Lassaletta *et al* 2014). These presumptions are accompanied by unavoidable uncertainties and restrictions. N transformation within the soil as well as its uptake by crops is a complex process, which depends on several factors and varies greatly even within the same locality. Unlike developed countries, Africa lack literatures and specialized systems which regularly monitor changes in N losses. Consequently, we had to rely on some factors for calculation of N budget for whole Africa. For example, using of specified factors for crops N uptake, AND and BNF as well as emission factors for gaseous losses, could be a source of uncertainties in our estimated results. The estimation of N uptake by crops was based on fixed global nutrient contents (Lassaletta *et al* 2014). However, N consumption by crops can vary locally according to their genetic potential, management practices and local environmental conditions (Lassaletta *et al* 2014), but taking these variations into account is unfortunately unaffordable at these time and spatial scales. This study estimated the gaseous N losses following territorial emission factors (FAO 2001, Bouwman *et al* 2002), which are relatively dated and may produce intermediate values for developing countries. Our African estimates of N gaseous emissions (10 kg N ha^{-1} yr^{-1} in 2014) are consistent with estimates by Galy-Lacaux and Delon (2014) (7–11 kg N ha^{-1} yr^{-1} in 2014). However, a lot of uncertainties still remain, as N gaseous losses are highly variable even within the same field. There is need to establish long-term experimentations in different regions of Africa to accurately estimate N transformation within the soil at a gradient of N fertilization levels. This will provide basis for accurate regional modelling of N budget and its losses.

Also, the AND input was calculated based on regional estimates of AND rates on agricultural lands multiplied by the total crop area for each country. Accurate estimation of AND in Africa require establishment of AND monitoring sites in different regions of Africa. Our estimation of BNF on the basis of legumes area could also bring differences in the final result (Lassaletta *et al* 2014). For example, soybean yield varies widely in different regions of Africa, therefore, BNF estimation based on its area could produce inaccurate results. Using a specific regional value of Ndfa instead of a fixed value for each country can also bring uncertainties. Moreover, due to the lack of data, we did not consider N losses in the form of NO_3^-–N leaching from African soils or N inputs by irrigation in the N budget. Although there could be some differences in the data used in this study, anyhow it still provides comprehensive evaluation of African N budget. Further analysis and more experimental research would be still necessary for reducing uncertainties. Finally, our estimates of N inputs are comparable with estimates from other sources. Thus, the results of this study reliably highlight the issue of low N fertilization in most African countries, and we suggest effective measures to manage Africa's N budget in a way that supports crop production and environmental protection.

5. Conclusions

African total N input and total N crop production increased from 20 and 15 kg N ha^{-1} during 1961–1965 to 35 and 22 kg N ha^{-1} during 2011–2016, respectively. BNF was the dominant source of N input to croplands during 1961–1965. We observed an increase in the contribution of SNF and a synchronous decrease in the contribution of BNF during 2011–2016. Over the last five decades, NUE in Africa decreased from 74% to 63% and N surplus increased from 25% to 37% of the total N input. Gaseous emissions of N were 13% of the total N input during 1961–1965, and increased to 21% during 2011–2016. The low use of N in soil results in crops with low in protein. African average per capita protein consumption is still below the healthy recommendation (4.0 kg N cap^{-1} yr^{-1}). Our findings suggest that Africa still faces the challenge of low N in food production, excessive N loss in the environment, and a lack of effective policies and awareness. To address these issues, African governments must adopt effective N management strategies that incorporate locally available organic material and promote the judicious use of SNF. Modern fertilizer techniques (controlled release fertilizers, nitrification inhibitors, etc) have been shown to decrease N losses and increase NUE. African governments must also adopt new and effective policies to reduce fertilizer prices and increase their availability in the market. In addition, government should coordinate their policies with regards to organic input management.

Acknowledgments

This work was supported by the National Key R&D Program of China (2017YFD0200106), the National Natural Science Foundation of China (41671295), and the 111 Project (No. B12007).

Data availability statements

Any data that support the findings of this study are included within the article.

References

Akudugu M A, Guo E and Dadzie S K 2012 Adoption of modern agricultural production technologies by farm households in Ghana: what factors influence their decisions? *J. Biol., Agric. Healthcare* **2** 1–13

ARD 2009 *Awakening Africa's Sleeping Giant: Prospects for Commercial Agriculture in the Guinea Savannah Zone and Beyond* ed M Morris, H P Binswanger-Mkhize and D Byerlee (Washington, DC: World Bank Publications)

AU, NEPAD/NPCA 2006 *The Abuja Declaration on Fertilizers for an African Green Revolution: Status of Implementation at Regional and National Levels* (Addis Ababa and Midrand: Policy Brief African Union and NEPAD Planning and Coordinating Agency)

Beck H E, Zimmermann N E, McVicar T R, Vergopolan N, Berg A and Wood E F 2018 Present and future Köppen-Geiger climate classification maps at 1 km resolution *Sci. Data* **5** 180214

Billen G, Lassaletta L and Garnier J 2015 A vast range of opportunities for feeding the world in 2050: trade-off between diet, N contamination and international trade *Environ. Res. Lett.* **10** 025001

Bold T, Kaizzi K C, Svensson J and Yanagizawa-Drott D 2015 *Low Quality, Low Returns, Low Adoption: Evidence from the Market for Fertilizers and Hybrid Seed in Uganda Policy Brief International Growth Centre London* Working Paper Series RWP15-033 HKS Faculty Research

Bouwman A F, Boumans L J M and Batjes N H 2002 Emissions of N_2O and NO from fertilized fields: summary of available measurement data *Glob. Biogeochem. Cycle* **16** 6-1–13
Bouwman L, Goldewijk K K, Van Der Hoek K W, Beusen A H W, Van Vuuren D P, Willems J, Rufino M C and Stehfest E 2013 Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period *Proc. Natl Acad. Sci.* **110** 20882–7
Brouwer J and Powell J M 1998 Increasing nutrient use efficiency in West-African agriculture: the impact of micro-topography on nutrient leaching from cattle and sheep manure *Agric. Ecosyst. Environ.* **71** 229–39
Camara O and Heinemann E 2006 *Overview of the Fertilizer Situation in Africa: Background Paper Prepared for the African Fertilizer Summit June 9-13, Abuja, Nigeria* International Fertilizer Development Center (IFDC) and International Fund for Agricultural Development (IFAD)
Chianu J N, Chianu J N and Mairura F 2012 Mineral fertilizers in the farming systems of sub-Saharan Africa: a review *Agron. Sustain. Dev.* **32** 545–56
Ciceri D and Allanore A 2019 Local fertilizers to achieve food self-sufficiency in Africa *Sci. Total Environ.* **648** 669–80
Dentener F *et al* 2006 Nitrogen and sulfur deposition on regional and global scales: a multimodel evaluation *Glob. Biogeochem. Cycles* **20** GB4003
Dewitte O *et al* 2013 Harmonisation of the soil map of Africa at the continental scale *Geoderma* **211–212** 138–53
Diogo R V C, Schlecht E, Buerkert A, Rufino M C and van Wijk M T 2013 Increasing nutrient use efficiency through improved feeding and manure management in urban and peri-urban livestock units of a West African city: a scenario analysis *Agric. Syst.* **114** 64–72
Edmonds D E *et al* 2009 Cereal nitrogen use efficiency in Sub Saharan Africa *J. Plant Nutri.* **32** 2107–22
Elrys A S, Raza S, Abdo A I, Liu Z, Chen Z and Zhou J 2019a Budgeting nitrogen flows and the food nitrogen footprint of Egypt during the past half century: challenges and opportunities *Environ. Int.* **130** 104895
Elrys A S, Desoky E-S M, Abo El-Maati M F, Elnahal A S, Abdo A I, Raza S and Zhou J 2019b Can secondary metabolites extracted from Moringa seeds suppress ammonia oxidizers to increase nitrogen use efficiency and reduce nitrate contamination in potato tubers? *Ecotoxicol. Environ. Saf.* **185** 109689
EPA 2017 *Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2000* (Washington, DC: Office of Atmospheric Programs US)
FAO 1993 *Soil Tillage in Africa: Needs and Challenges* (FAO SOILS BULLETIN) p 69
FAO 2001 *Global Estimates of Gaseous Emissions of NH_3, NO and N_2O from Agricultural Land* (Rome: Food and Agriculture Organization of the United Nations)
FAO 2017a *The State of Food Security and Nutrition in the World 2017. Building Resilience for Peace and Food Security* (Rome: FAO)
FAO 2017b *Africa Regional Overview of Food Security and Nutrition. The Challenges of Building Resilience to Shocks and Stresses* (Accra: FAO)
FAOSTAT 2018 *Statistics Division* (Rome: Food and Agriculture Organization of the United Nations) (www.fao.org/faostat/en/#data)
Food Security Information Network 2018 *Global Report on Food Crises, 2018* World Food Programme, Rome
Galy-Lacaux C and Delon C 2014 Nitrogen emission and deposition budget in West and Central Africa *Environ. Res. Lett.* **9** 125002
Guo J H, Liu X J, Zhang Y, Shen J L, Han W X, Zhang W F, Christie P, Goulding K W, Vitousek P M and Zhang F S 2010 Significant acidification in major Chinese croplands *Science* **327** 1008–10
Heffer P, Gruère A and Roberts T 2013 *Assessment of Fertilizer Use by Crop at the Global Level International Fertilizer Association (IFA) and International Plant Nutrition Institute (IPNI)* Report International Fertilizer Industry Association (IFA) Paris, France
Henao J and Baanante C 2006 *Agricultural Production and Soil Nutrient Mining in Africa Implications for Resource Conservation and Policy Development* Report International Center for Soil Fertility and Agricultural Development
Herridge D F, Peoples M B and Boddey R M 2008 Global inputs of biological nitrogen fixation in agricultural systems *Plant Soil* **311** 1–18
Hickman J E, Tully K L, Groffman P M, Diru W and Palm C A 2015 A potential tipping point in tropical agriculture: avoiding rapid increases in nitrous oxide fluxes from agricultural intensification in Kenya *J. Geophys. Res. Biogeosci.* **120** 938–51
IFA 2018 Nitrogen statistics from 1961–2015 IFADATA Statistics (ifadata.fertilizer.org/ucSearch.aspx)
Jefwa J M *et al* 2014 Do commercial biological and chemical products increase crop yields and economic returns under smallholder farmers' conditions? *Challenges and Opportunities for Agricultural Intensification of Humid Highland Systems of Sub-Saharan Africa* ed B Vanlauwe *et al* (Cham: Springer International Publishing) pp 81–96
Jones A *et al* 2013 *Soil Atlas of Africa European Commission* (Luxembourg: Publications Office of the European Union) p 176
Kassam S N and Dhehibi B 2016 *Mechanization to Drive A Process for Fertilizer Subsidy Reform in Egypt* ERF Policy Brief No. 22 ERF
Kiboi M N, Ngetich F K and Mugendi D N 2019 Nitrogen budgets and flows in African smallholder farming systems *AIMS Agric. Food* **4** 429–46
Lassaletta L, Billen G, Garnier J, Bouwman L, Velazquez E, Mueller N D and Gerber J S 2016 Nitrogen use in the global food system: past trends and future trajectories of agronomic performance, pollution, trade, and dietary demand *Environ. Res. Lett.* **11** 095007
Lassaletta L, Billen G, Grizzetti B, Anglade J and Garnier J 2014 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland *Environ. Res. Lett.* **9** 105011
Li Q Q, Cui X Q, Liu X J, Roelcke M, Pasda G, Zerulla W, Wissemeier A H, Chen X P, Goulding K and Zhang F S 2017 A new urease-inhibiting formulation decreases ammonia volatilization and improves maize nitrogen utilization in North China Plain *Sci. Rep.* **7** 43853
Li X, Tang L, Xu X, Qi G and Wang H 2013 What can Africa learn from China's experience in agricultural development? *IDS Bull.* **44** 4
Maskey S, Bhattarai S, Peoples M and Herridge D 2001 On-farm measurements of nitrogen fixation by winter and summer legumes in the Hill and Terai regions of Nepal *Field Crops Res.* **70** 209–21
Masso C, Baijukya F, Ebanyat P, Bouaziz S, Wendt J, Bekunda M and Vanlauwe B 2017 Dilemma of nitrogen management for future food security in sub-Saharan Africa—a review *Soil Res.* **6** 425
McLellan E, Cassman K G, Woodbury P, Sela S, Tonitto C, Eagle A, Marjerison R and van Es H M 2018 The nitrogen balancing act: tracking the environmental performance of food production *BioScience* **68** 194–203
Moawad H, Mahmoud S A Z, Badr El-Din S M S, Gamal R F and Enany M H 1984 Transformations and effects of urea derivatives in soil *Z. Pflanzenernaehr. Bodenk.* **147** 785–92
Ndambi O A, Pelster D E, Owino J O, de Buisonjé F and Vellinga T 2019 Manure management practices and policies in sub-Saharan Africa: implications on manure quality as a fertilizer *Front. Sustain. Food Syst.* **3** 29
Nkonya E, Place F, Pender J, Mwanjololo M, Okhimamhe A, Kato E, Crespo S, Ndjeunga J and Traore S 2011 Climate risk management through sustainable land management in sub-Saharan Africa *IFPRI Discussion Paper (Washington DC)* (https://doi.org/10.1007/978-3-319-61194-5_19)
Raza S, Zhou J, Aziz T, Afzal M R, Ahmed M, Javaid S and Chen Z 2018 Piling up reactive nitrogen and declining nitrogen use

efficiency in Pakistan: a challenge not challenged (1961–2013) *Environ. Res. Lett.* **13** 034012
Richards M, van Ittersum M, Mamo T, Stirling C, Vanlauwe B and Zougmoré R 2016 Fertilizers and low emission development in sub-Saharan Africa *CCAFS Policy Brief* no. 11 Copenhagen, Denmark: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)
Roobroeck D, van Asten P, Jama B, Harawa R and Vanlauwe B 2015 *Integrated Soil Fertility Management: Contributions of Framework and Practices to Climate-Smart Agriculture Climate-Smart Agriculture Practice Brief* (Copenhagen, Denmark: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS))
Sasson A 2012 Food security for Africa: an urgent global challenge *Agric. Food Secur.* **1** 2
Sela S, Woodbury P B, Marjerison R and van Es H M 2019 Towards applying N balance as a sustainability indicator for the US Corn Belt: realistic achievable targets, spatio-temporal variability and policy implications *Environ. Res. Lett.* **14** 064015
Selles F and Zentner R P 1998 *Nitrogen Management for Yield and Protein in Wheat in the Brown Soil Zone* (Swift Current: Agriculture and Agri-Food Canada)
Shiferaw B, Tesfaye K, Kassie M, Abate T, Prasanna B M and Menkir A 2014 Managing vulnerability to drought and enhancing livelihood resilience in sub-Saharan Africa: technological, institutional and policy options *Weather Clim. Extremes* **3** 67–79
Stoorvogel J J and Smaling E M A 1990 Assessment of soil nutrient depletion in sub-Saharan Africa, 1983–2000 *Rep.* 28 Win and Staring Centre Wageningen 137
Suttie J M, Reynolds S G and Batello C 2005 *Grasslands of the Worlds* (*Plant Production and Protection* Series No. 3) ed A Palmer *et al* (Rome: Food and Agriculture Organization of the United Nations)
Sutton M A *et al* 2013 *Our Nutrient World: the Challenge to Produce More Food and Energy with Less Pollution* (Edinburgh: Global Overview of Nutrient Management Centre for Ecology and Hydrology)
Thompson R L *et al* 2014 Nitrous oxide emissions 1999 to 2009 from a global atmospheric inversion *Atmos. Chem. Phys.* **14** 1801–17
Toenniessen G, Adesina A and DeVries J 2008 Building an alliance for a green revolution in Africa *Ann. N Y Acad Sci.* **1136** 233–42
Vanlauwe B and Giller K 2006 Popular myths around soil fertility management in sub-Saharan Africa *Agric. Ecosyst. Environ.* **116** 34–46
van Ittersum M K *et al* 2016 Can sub-Saharan Africa feed itself? *Proc. Natl Acad. Sci.* **113** 14964–9
Woomer P L, Bokanga M A and Odhiambo G D 2008 Striga management and the African Farmer *Outlook Agric.* **37** 245–310
Worldatlas 2018 Geography website that aids students, teachers, travelers and parents with their geography, map and travel questions 100 - 7405 Transcanadienne St. Laurent Quebec Canada H4T1Z2 (www.worldatlas.com)
Worldometers 2018 Population (www.worldometers.info/) (Accessed date: 3 September 2019)
Yu P, Li X, White P J and Li C 2015 A large and deep root system underlies high nitrogen-use efficiency in maize production *PLoS One* **10** e0126293
Yuan S and Peng S 2017 Exploring the trends in nitrogen input and nitrogen use efficiency for agricultural sustainability *Sustainability* **9** 1905
Zhang X, Davidson E A, Mauzerall D L, Searchinger T D, Dumas P and Shen Y 2015 Managing nitrogen for sustainable development *Nature* **528** 51
Zingore S, Murwira H K, Delve R J and Giller K E 2007 Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe *Agric. Ecosyst. Environ.* **119** 112–26