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

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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 × 10⁶ km²) and population (1.22 × 10⁹ 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 × 10⁶ 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%), Calcirosols (6%), Regosols (2%) and Solonchaks/Solonetz (2%) (Jones et al. 2013). Tropical or subtropical soils account for ~20%: Ferralsols (10%), Plinthosols (3%), Lithosols (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
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 IFA (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):

\[
N_{\text{Fixed}} = \% N_{\text{dfa}} \times \frac{Y}{\text{NHI}} \times \text{BNF},
\]

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

| Variables                | 1961–1965 | 2011–2016 | (%) |
|--------------------------|-----------|-----------|-----|
| Population (10\(^6\))    | 31        | 14        | 268 |
| Rural population %       | 81        | 50        | 47  |
| 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      | 10 930    | 59.9|
| Coarse grain             | 810       | 1 343     | 65.8|
| Fibre crops              | 304       | 198       | 64.9|
| Fruits                   | 5892      | 8739      | 48.3|
| Oil crops (oil equivalent) | 235    | 166       | 29.4|
| Pulses                   | 498       | 743       | 49.2|
| Roots and tubers         | 5846      | 8 529     | 45.9|
| Vegetables               | 6637      | 8 583     | 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       | 3 15      | 146 |
| Chickens                 | 294       | 1 778     | 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 |
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$_2$O 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):

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

$$\text{N surplus} = \text{Total N Input} - \text{Total N crop production}$$

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).

| 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$_2$O              | 3.40        | 4.56     | FAO (2001) |
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\(_2\)O–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
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).
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...
tein consumption contributed from animal sources (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% of the total 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 3) 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 has 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 (N2O) 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 N2O 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
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

Figure 7. Major changes in N flux in the African agro-food system during the past five decades.
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 (Roobroek 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 NO₃⁻–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.

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Data availability statements

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

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