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RESEARCH ARTICLE

Carbon footprint of fertilizer imports to the East African Bloc and policy recommendations for decarbonization [version 1; peer review: 2 not approved]

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Abstract

Background: Almost all nitrogenous (N) fertilizers are fixed on an enormous scale using the Haber-Bosch ammonia synthesis process via a reaction of Nitrogen with hydrogen in the presence of a catalyst. This process is a leading global polluter, emitting 830 megatons of CO_2 to the atmosphere annually. On the other hand, the global transport sector emits 7.5 gigatons of CO_2 yet the fraction of emissions from freight transportation of N fertilizers from exporting countries to the East African (EA) Bloc is not known. This study examined the carbon footprint from freight transportation of N fertilizers. The findings are useful in the regions' nationally determined contributions (NDCs) as per the Paris Agreement of December 2015 regarding downsizing emissions from the transport sector.

Methods: The study area included five EA Community (EAC) countries namely, Kenya, Uganda, Tanzania, Rwanda and Burundi. Statistics of fertilizers were obtained from https://africafertilizer.org/. The carbon footprint calculator (CFC) for fertilizer production (obtained from https://www.fertilizerseurope.com/), certified by the Carbon Trust Standard, was used.

Results: Over 93% of fertilizers imported to the EA Bloc are N fertilizers, leaving a carbon footprint of 4.9 megatons CO_2-eq. Of these emissions, 1.1 megatons CO_2-eq were contributed by imports from Saudi Arabia and 0.8 megatons CO_2-eq from China. The 'dirtiest' of N fertilizers that accounted for the highest carbon footprint on the EA bloc were urea ammonium nitrate, calcium nitrate, nitrophosphates and ammonium sulphate.

Conclusions: Every metric ton of N imported results in a carbon footprint of 4.5 metric tons CO_2-eq. The Ammonia production process of exporting countries, freight distance, choice and number of N fertilizers imported are significant determinants of greenhouse gas emissions to East Africa's NDCs. To reach net-zero emissions the EA community needs to invest in new processes, circular economy and

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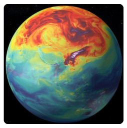
decarbonization pathways.

Keywords
Climate Change, Fertilizers, East African Community, Green House Gas emissions, Agriculture



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Introduction

In sub-Saharan Africa (SSA), smallholder farmers make up 70% of the population but productivity is significantly affected by the high cost of fertilizers. Despite policy interventions such as the "Abuja Declaration on Fertilizer for the African Green Revolution of 2006, that pledged to increase fertilizer use to 50 kg per hectare by 2015 (ADB, 2017), SSA only applies 17 kg of fertilizers per hectare of arable land compared to the global average of 135 kg/ha (FAOSTAT, 2014). In Uganda, a landlocked country, application rates are as low as 1.3 kg/ha due to high transportation costs required to bringing fertilizers into the country. However, much as fertilizers are desperately needed to increase food production in SSA, there is a growing concern of the impact of industrial nitrogenous (N) fertilizer production to global warming that has become increasingly difficult to ignore, in recent years. Almost all N fertilizers are fixed on an enormous scale using the Haber-Bosch (H-B) ammonia synthesis process" via reaction of N with hydrogen in the presence of a catalyst (Appl, 2012). This process sustains 40% of the today's global population and is considered as the most important discovery of the 20th century (Appl, 1997a; Patil, 2017). Recently, the annual amount of N fixed by the H-B process surpassed 160 million tons per year, exceeding that fixed naturally in agriculture and has doubled the number of humans supported per hectare of arable land (Erisman *et al.*, 2008). After the invention of the H-B process, the global population started growing rapidly such that by 2010, the increase in global population and the N fertilizer consumption followed a very similar trend (Canfield *et al.*, 2010). SSA still lags behind this trend as the H-B process is industrially very expensive and results in elevated retail costs of fertilizers, which are often not afforded by poor small holder farmers. In addition, the H-B process that produces 130 million tons of NH_3 per year is one of the leading environment polluters. The importance of the H-B process to sustain human lives globally and its impact on global warming makes this process arguably a necessary evil. Production of fertilizers through this process consumes approximately 1–2% of the world's total energy, and emits 830 megatons of CO_2, annually (Appl, 1997b; Cherkasov *et al.*, 2015; IEA, 2019; Tanabe & Nishibayashi, 2013). In addition to the large CO_2 emissions from the H-B process, large amounts of greenhouse gases (GHGs) are discharged in freight transportation of goods and commodities, all over the globe.

The global transport sector emits 7.5 gigatons of CO_2, making it the third largest global emitter of CO_2 emissions after the power and industry sectors Yeh *et al.* (2017). Freight transport industries are the major causes of increasing CO_2 emissions (Makan & Heyns, 2018), growing much faster than passenger transport emissions. Freight emission share in total transport CO_2 emissions increased from 35% in 2000 to 41% in 2015 (Makan & Heyns, 2018). The fraction of CO_2 emissions from freight transportation of fertilizers from countries of origin to the East African (EA) Bloc is not yet known. The entry of fertilizers into the EA Bloc is through ports of Mombasa, Kenya and Dar es Salam, Tanzania using deep sea vessels. On entry to the two East African ports, the fertilizers are transported to inland countries, Uganda, Rwanda and Burundi by road using heavy trucks through cross border trade. There lacks information on the level of CO_2 emissions by Freight transport in the distribution of fertilizers on the EA Bloc. There is available evidence that suggests that transport CO_2 emissions will need to be reduced to about 2–3 gigatons in 2050 or about 70 to 80% below 2015 levels to meet the targets set in the Paris Agreement. This study therefore investigated the amounts of N fertilizers imported by the East African Bloc on an annual basis and examined the carbon footprint from freight transportation of N fertilizers on the EA Bloc. The findings are useful in the regions' nationally determined contributions (NDCs) as per the Paris Agreement of December 2015 regarding downsizing emissions from the transport sector.

Methods

N imports to the East African Bloc

The study area was five countries in the EA Bloc, namely; Uganda, Kenya, Tanzania, Rwanda and Burundi (Figure 1). Statistics of N fertilizers coming to EA, was obtained from https://africafertilizer.org/ (2018). For Uganda and Kenya, the available data was collected in 2015, while for Tanzania, Rwanda and Burundi, the presented data was from 2017.

The carbon footprint from importation of N fertilizers to East Africa

This study focused on only N fertilizers produced through H-B ammonia synthesis and the type of fertilizers each EA country imported. The carbon footprint of each East African country was computed based on tonnage of N fertilizer imports (obtained from https://africafertilizer.org/ (2018) and the distance covered from the exporting countries from http://ports.com/sea-route/ (Ports, 2019). Data input into the calculator is shown in Table 1– Table 6. Fertilizers enter the EA bloc through ports of Mombasa (Kenya) and Dar es Salam (Tanzania) using deep sea vessels. Sea route distances from countries of origin were computed in nautical miles from a World sea ports database of sea transportation, marine and ports, sea distances and routes (Ports, 2019). Nautical miles were converted into kilometers. On entry to the two ports, the fertilizers are transported to inland countries, Uganda, Rwanda and Burundi by road using heavy diesel trucks. The distances by road were totaled in km from the two seas ports to the capital cities of Nairobi, Kampala, Kigali, Dodoma and Bujumbura.

As per the IPCC (2018), the emissions reference points for deep sea vessels is 5g CO_2/ton/km while that of trucks by road is 62 g CO_2/ton/km. Thus the Carbon footprint from transportation of N fertilizers to EA was established from a carbon footprint calculator (CFC) for fertilizer production available at http://www.calcfert.com/. The CFC is a free tool that can be accessed following free registration. This tool inputs reference values for mineral fertilizers produced globally for the year 2011. Sources of built-in data for energy includes feedstock and fuel emission factors (IPCC, 2006), feedstock and fuel supply (exploitation and transport of fuel) (GaBi, 2017), electricity generation carbon factor (IEA, 2011b), electricity energy supply (exploitation and transport of fuel) originates (GaBi, 2017), steam boiler default efficiency is 93% while for coal usage, the default efficiency is 90% (Table 1). The data is calculated in a stepwise process of production known as cradle-to-factory-gate, computing energy consumption and GHG emissions

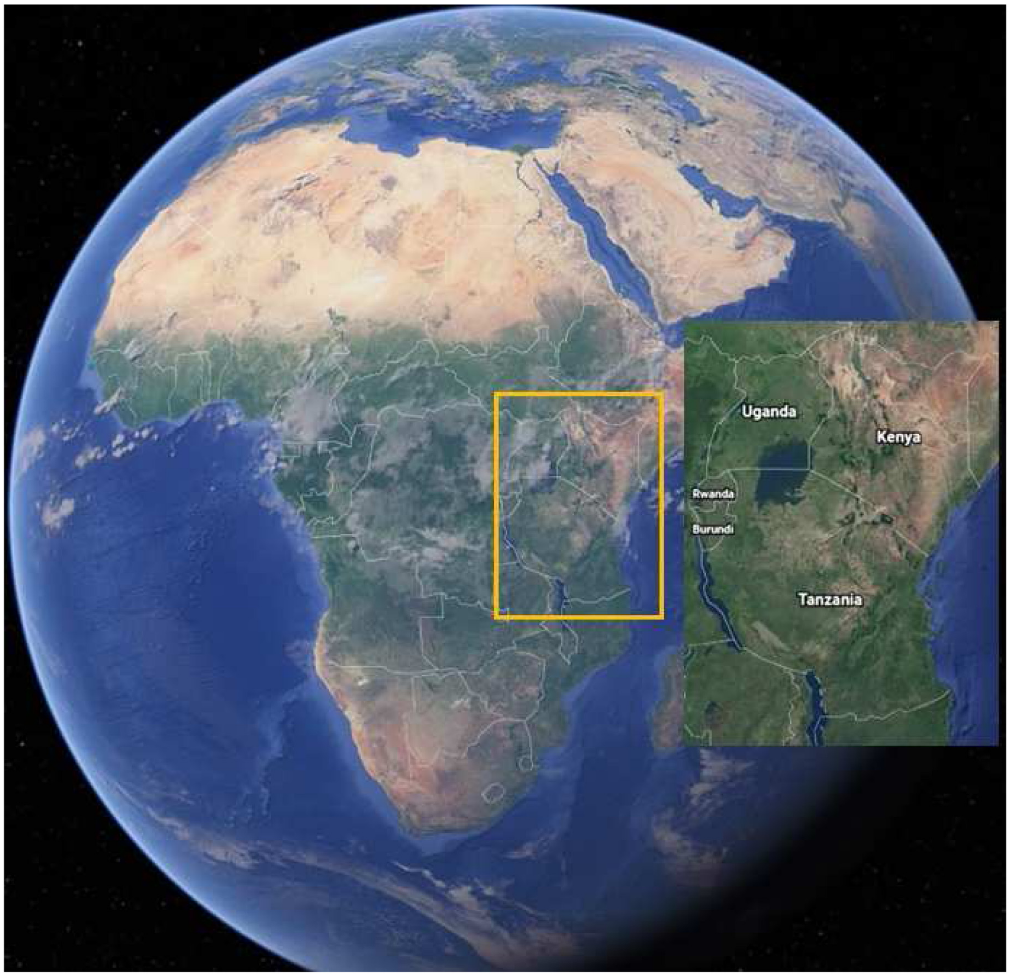

Figure 1. Map showing the study area countries in the East African Bloc (Uganda, Kenya, Tanzania, Rwanda and Burundi). Source: 'East Africa' Google Earth, 11 May 2020.

in fertilizer production. The stepwise process includes importation of raw materials, production, blends, transportation and their contributions to emissions with global warming potential (GWP), such as NO, CO_2 and CH_4 that are converted to CO_2-equivalents (CO_2-eq) (IPCC, 2007). The CFC tool has built-in default values for fertilizer-producing world regions (EU, Russia, China and US) for the reference year 2011 (Christensen *et al.*, 2014), which, in this study, were used based on the origin of fertilizers imported to the East African Bloc. A detailed stepwise guide is available as *Extended data* (Kabiri, 2020).

Statistical analysis

The output of the CFC calculator was CO_2-eq per metric ton of N (Table 8–Table 12). The total emissions were expressed as a product of the tonnage of N fertilizers from country of origin and CO_2-eq per metric ton of N as shown in the last column of Table 8–Table 12. Pearson's correlation exploration between nitrogen imports and freight distance with emissions per metric ton of nitrogen and total emissions CO_2-eq was analyzed with SPSS Version 16.0 (SPSS, 2007).

Results

Nitrogenous fertilizer imports to the EA Bloc

The results showed that on average 93% of all fertilizers imported to the East African Bloc are Nitrogenous (N) fertilizers. Specifically, 90% (Uganda), 79% (Kenya), 99% (Tanzania), 99% (Rwanda) and 96% (Burundi) of fertilizer imports are N fertilizers (Table 2–Table 6). These include ammonium nitrate (an), calcium ammonium nitrate (CAN), ammonium nitrosulphate (ANS), calcium nitrate (CN), ammonium sulphate (AS), di-ammonium phosphate (DAP), urea, urea ammonium nitrate (UAN) and nitrophosphates (NPK). The results show that together, the East African Bloc imports about 1.1 million metric tons of N fertilizers annually, with coastal countries, Kenya and Tanzania accounting for 48.5% and 37.9%, respectively. Rwanda and Burundi import 5.4% and 4.7%, respectively, while Uganda imports the least (3.5%). Uganda imports N fertilizers from 10 countries (Table 2). Of the 37,685 metric tons of N fertilizers that Uganda imports, 27% (10,076 metric tons) of them are direct imports from Kenya. These are followed by Indonesia (11%), Norway (11%) and China (10%). Kenya imports N fertilizers

Table 1. Data input into the carbon footprint calculator for fuel stock, electricity and steam boiler for production of N fertilizers from countries that export N fertilizers to the East African Bloc.

Country	Fuel stock and Fuel	Energy use	Energy supply	Electricity (Data source)	Energy use	Energy supply	Steam boiler (Data source)	Energy use	Energy supply
	Fuel source	Kg CO2/GJ	Kg CO2/GJ		Kg CO2/GJ	Kg CO2/GJ		Kg CO2/GJ	Kg CO2/GJ
Indonesia	Natural gas	56.10	7.41	South East Asia (IEA, 2011a)	192.12	64.9	gas-South East Asia	60.32	7.97
China	Natural gas	56.10	13.53	China (IEA, 2011a)	212.20	58.9	gas-China	60.32	14.55
Russia	Natural gas	56.10	11.63	CIS (Russia C. Wealth) (IEA, 2011a)	127.96	57.3	gas-CIS (Russia C. Wealth)	60.32	12.51
Ukraine	Natural gas	56.10	11.63	CIS (Russia C. Wealth) (IEA, 2011a)	127.96	57.3	gas-CIS (Russia C. Wealth)	60.32	12.51
Saudi Arabia	Natural gas	56.10	5.97	Middle East (IEA, 2011a)	176.18	49.6	gas-Middle East	60.32	5.70
UAE	Natural gas	56.10	5.97	Middle East(IEA, 2011a)	176.18	49.6	gas-Middle East	60.32	5.70
Jordan	Natural gas	56.10	5.97	Middle East(IEA, 2011a)	176.18	49.6	gas-Middle East	60.32	5.70
Morocco	Natural gas	56.10	8.73	Africa (IEA)	149.70	48.3	gas-Africa	60.32	9.38
Madagascar	Natural gas	56.10	8.73	Africa (IEA)	149.70	48.3	gas-Africa	60.32	9.38
Italy	Natural gas	56.10	11.37	EU-27 average	97.78	31.5	gas-EU	60.32	12.23
Norway	Natural gas	56.10	11.37	EU-27 average	97.78	31.5	gas-EU	60.32	12.23
Switzerland	Natural gas	56.10	11.37	EU-27 average	97.78	31.5	gas-EU	60.32	12.23
Turkey	Natural gas	56.10	11.37	EU-27 average	97.78	31.5	gas-EU	60.32	12.23
Croatia	Natural gas	56.10	11.37	EU-27 average	97.78	31.5	gas-EU	60.32	12.23
Finland	Natural gas	56.10	11.37	EU-27 average	97.78	31.5	gas-EU	60.32	12.23
Netherlands	Natural gas	56.10	11.37	EU-27 average	97.78	31.5	gas-EU	60.32	12.23
Estonia	Natural gas	56.10	11.37	EU-27 average	97.78	31.5	gas-EU	60.32	12.23
USA	Natural gas	56.10	15.27	North America (IEA, 2011a)	113.39	25.4	gas-North America	60.32	16.42

Sources (GaBi, 2017; IPCC, 2006, IEA, 2011a).

Table 2. **Uganda's annual N fertilizer imports.**

Country	N* Fertilizer imports (metric tons)	Deep sea vessels to Port of Mombasa (East Africa)		Distance from Mombasa to Kampala (Trucks), Km
		Nautical miles (nm)	Km	
Kenya	10,076			1138
China	3,585	6,981	12,740	1138
Italy	2,604	5,031	9,182	1138
Saudi Arabia	2,809	2,462	4,493	1138
Indonesia	4,077	4,325	7,893	1138
USA	3,165	9,024	16,469	1138
Russia	2,606	8,619	15,730	1138
Norway	3,966	7,763	14,167	1138
Netherlands	2,476	7,120	12,994	1138
Ukraine	2,321	4,793	8,747	1138
Total	**37,685**	**56,118**	**102,415**	

*90% of imported fertilizers are N fertilizers.

Table 3. **Kenya's annual N fertilizer imports.**

Country	N fertilizer imports (metric tons)*	Deep sea vessels to Port of Mombasa (East Africa)		Distance from Mombasa to Nairobi (Trucks), Km
		Nautical miles	Km	
China	96,828	6,981	12,740	485.7
Italy	29,430	5,031	9,182	485.7
Saudi Arabia	148,245	2,462	4,493	485.7
Russia	38,874	8,619	15,730	485.7
Norway	46,230	7,763	14,167	485.7
Switzerland	77,448	5,415	9,882	485.7
Ukraine	52,308	4,793	8,747	485.7
Turkey	16,564	4,393	8,017	485.7
Jordan	6,091	3,032	5,533	485.7
Croatia	7,500	5,010	9,143	485.7
Total	**519,518**	**53,499**	**97,636**	**4857**

* 79% of imported fertilizers are N fertilizers

from 10 countries (Table 3). Of the 519,518 metric tons of N fertilizers that Kenya imports, 29% originate from Saudi Arabia. These are followed by China (19%), Switzerland (15%) and Ukraine (10%). Tanzania imports N fertilizers from 11 countries and other unknown sources (Table 4). Of the 406,040 metric tons of N fertilizers that Tanzania imports, 19% originate from Russia. This is followed by Norway (15%), Saudi Arabia (13%) and UAE (12%). Tanzania least imports are from China (3%). Rwanda imports N fertilizers from four countries (Table 5). Of the 57,429 metric tons of N fertilizers that Rwanda imports, 50% are direct imports from Tanzania. These are followed by Morocco (19%), Saudi Arabia (15%) and Kenya (9%). Burundi does not imports N fertilizers from outside the region. Of the 50,127 metric tons of N fertilizers that Burundi imports, 93.8% come from Tanzania, followed by Kenya (6.2%) and a small fraction from Uganda (Table 6).

The carbon footprint from importation of N fertilizers to East Africa

The results revealed a highly significant positive correlation between Nitrogen imports and Freight distance with emissions per metric ton of Nitrogen and Total emissions CO_2-eq at $P<0.11$ and $P<0.001$ respectively (Table 7). In total, the East African Bloc leaves a carbon footprint of 4.9 megatons CO_2-eq from

Table 4. **Tanzania's annual N fertilizer imports.**

Country	N* Fertilizer imports (metric tons)	Deep sea vessels to Port of Dar es Salam (East Africa)		Distance from Dar es Salam to Dodoma (Trucks) Km
		Nautical miles	Km	
China	12,218	7,843	14,313	443.2
Italy	15,012	4,621	8,433	443.2
Saudi Arabia	51,900	2,652	4,840	443.2
Russia	77,507	5,148	9,395	443.2
UAE	46,973	2,901	5,294	443.2
Norway	62,795	7,783	14,204	443.2
Netherlands	17,494	7,344	13,403	443.2
Turkey	28,762	4,588	8,373	443.2
Finland	27,986	8,593	15,682	443.2
Morocco	24,000	5,746	10,486	443.2
Madagascar	22,619	835	1,524	443.2
Others**	18,774	3,871	7,169	443.2
Total	**406,040**	**61,925**	**93,938**	**5318.4**

*99% of imported fertilizers are N fertilizers.

**Source unknown.

Table 5. **Rwanda's annual N imports.**

Country	Rwanda's N** Fertilizer imports (metric tons)	Deep sea vessels to Port of Dar es Salam (East Africa)		Trucks from Dar es Salam to Kigali	Trucks from Nairobi to Kigali
		Nautical miles	Km	Km	Km
Tanzania	28,567			1442	
Kenya	5,449				1165
Morocco	10,833	5,746	10,486	1,442	
Saudi Arabia	8,724	2,652	4,840	1,442	
China	606	7,843	14,313	1,442	
Estonia	3250	3936	7184	1,442	
Total	**57,429**	**20,177**	**36,824**	7,210	1165

**99% of imported fertilizers are N fertilizers.

Table 6. **Burundi's annual N imports.**

Country	N* Fertilizer imports (metric tons)	Trucks from Dar es Salam to Bujumbura, Km	Trucks from Nairobi to Bujumbura, Km	Trucks from Kampala to Bujumbura, Km
Tanzania	47,033	1,424		
Kenya	3,088		1,389	
Uganda	6			692
Total	50,127			

* 96% of imported fertilizers are N fertilizers

Table 7. Pearson's correlation between nitrogen imports and freight distance with emissions per metric ton of nitrogen and total emissions.

		CO_2-eq/ metric tons Nitrogen	Total emissions metric tons (CO_2-eq)
Nitrogen imports	Pearson Correlation	0.036	0.914**
	Sig. (2-tailed)	0.823	0.000
	N	41	41
Freight Distance	Pearson Correlation	0.392*	0.039
	Sig. (2-tailed)	0.011	0.807
	N	41	41

*Correlation is significant at the 0.05 level (2-tailed).

**Correlation is significant at the 0.01 level (2-tailed).

fertilizer imports (Table 8–Table 12). While Uganda is accountable for 0.26 megatons CO_2-eq (Table 8), Kenya leaves the largest carbon footprint (3.4 megatons CO_2-eq), (Table 9). Tanzania is responsible for one megaton CO_2-eq (Table 10), while Rwanda (Table 11) and Burundi (Table 12) leave the lowest carbon footprints, of 0.11 and 0.09 megatons CO_2-eq N, respectively. The results further determined that specifically N fertilizers from Saudi Arabia accounted for 23% (1.1 megatons CO_2-eq) of the total carbon footprint of imports to the East African Bloc (Figure 2). This was followed by imports from China (16%), Norway (10%), Switzerland (10%) and Russia (9%). Jordan, Indonesia, USA and Estonia were below 1% and therefore the lowest contributors to the East African carbon footprint (Figure 2) (detailed numbers in Table 13).

The study also observed that Kenya and Uganda emit more for every metric ton of N fertilizer imported. Kenya left a carbon footprint of 66.33 metric tons CO2-eq and Uganda, 63.89 metric tons CO_2-eq, per metric ton of N imported. Tanzania was half that (31.13), while Rwanda and Burundi were 12.31 and 4.67 CO2-eq respectively per metric ton of N imported (Table 8–Table 12). The 'dirtiest' N fertilizers observed also varied per country. For both Uganda and Kenya, the types of N fertilizers that left the largest carbon footprint were UAN and CN. Importation of UAN to Kenya and Uganda was responsible for 21% and 18%, respectively, of each country's carbon footprint, while importation of CN to Kenya and Uganda was responsible for 19% and 14% of the carbon footprint, respectively. For Tanzania, the 'dirtiest' type of N fertilizer was NPK, leaving up to 59% of its total carbon footprint while for both Rwanda and Burundi, the dirtiest' type of N fertilizer was AS, leaving 45.5% and 42.8% of the total carbon footprint, respectively.

Discussion

The results show that over 93% of fertilizers imported to the EA Bloc are N fertilizers which come in nine types of ammonia compounds and derivatives. This is not surprising since soils in East Africa are highly weathered and leached, lacking in major nutrients specifically Nitrogen and Phosphorus (Okalebo *et al.*, 2007). The study found that the EA Bloc imports 1.1 million metric tons of N fertilizer that leave a carbon footprint of 4.9 megatons CO_2-eq, annually. This implies that for every metric ton of N imported, results in a carbon footprint of 4.5 metric tons CO_2-eq. Of these, Kenya is responsible of 70% (3.4 megatons CO_2-eq), of the total EA carbon footprint from N imports. This is explained by the observation that Kenya imports almost half (48.5%) of the total imports in the region, while Uganda imports only a fraction (3.5%). This confirms why fertilizer application rates in Uganda are low. Studies have shown that while global fertilizer prices have fallen in real terms, that trend hasn't been reflected in Uganda. For instance a 50 kg bag of fertilizer costs approximately $50, while farmers in the United States pay half this sum for an equivalent quantity of fertilizer (Schnitkey, 2015). Furthermore, Uganda being landlocked, the cost of transport is a major constraint. There is hardly domestic production of both fertilizer compounds and blends and therefore most of these nutrient inputs have to be imported and transported across great distances from Mombasa or Dar es Salaam ports. In this regard the results showed that despite the fact that Uganda imported 45% less fertilizers than Kenya, both countries left a similar footprint per metric ton of N, imported (66.33 and 63.89 CO_2-eq/metric tons N for Kenya and Uganda respectively). Tanzania, on the other hand, imports ten times more than Uganda but has a carbon footprint four-folds lower than Uganda per metric ton of N. This indicates that freight distance is a determinant of GHG emissions to NDCs of countries on the EA bloc. This was confirmed through Pearson's correlation analysis, which revealed a significant correlation ($P<0.01$) between freight distance and CO_2 emissions per metric ton of N imported on the East African Bloc. These findings are in line with observations by Yeh *et al.* (2017), who found that in the last 15 years direct CO_2 emissions from the transport sector globally have increased by 29%. Of these, 75% have come from road, 3% from rail and 22% from aviation and shipping.

This study also found that countries of origin (exporters) greatly determined total emissions of the EA Bloc. Specifically, of the total 4.9 megatons CO_2-eq of emissions from N imports on the

Table 8. Uganda's total carbon footprint of N fertilizer imports.

Country	Ammonium nitrate	Calcium ammonium nitrate	Ammonium nitrosulphate	Calcium nitrate	Ammonium Sulphate	Di-ammonium phosphate	Mono-ammonium phosphate	Urea	Urea ammonium nitrate	Nitrophosphates	Total*	Total emissions (Total **CO_2 fertilizer imports
	33.5% N	15.5% N	21% N	15.5% N	21% N, 24% S	18% N, 46% P_2O_5		46% N	30% N	15% N		
Kenya	0.64	0.74	0.33	1.27	0.66	0.17	0.17	0.15	1.73	0.56	6.42	64,688
China	0.77	0.90	0.27	1.50	0.27	0.21	0.29	0.29	2.00	0.67	7.17	25,704
Italy	0.70	0.80	0.38	1.33	0.03	0.23	0.23	0.29	1.80	0.62	6.41	16,692
Saudi Arabia	0.68	0.80	0.44	1.36	0.17	0.14	0.25	0.18	1.72	0.59	6.33	17,781
Indonesia	0.82	0.93	0.58	1.52	0.32	0.25	0.25	1.81	0.20	1.81	8.49	34,614
USA	0.79	0.91	0.51	1.39	0.08	0.28	0.28	0.25	1.86	1.86	8.21	25,985
Russia	0.75	0.89	0.43	1.49	0.19	0.28	0.26	1.84	0.25	0.70	7.08	18,450
Norway	0.73	0.83	0.41	1.36	0.06	0.26	0.26	0.17	1.73	0.65	6.46	25,620
Netherlands	0.72	0.83	0.26	1.35	0.97	0.25	0.25	0.30	1.78	0.64	7.35	18,199
Ukraine	0.72	0.86	0.46	0.86	0.15	0.24	0.24	0.21	1.81	0.67	6.22	14,437
Total	**6.68**	**7.75**	**3.74**	**12.16**	**2.24**	**2.14**	**2.48**	**5.34**	**13.15**	**8.21**	**63.89**	**262,169**

* (CO_2-eq/metric tons N)

** (CO_2-eq)

Table 9. Kenya's total carbon footprint of N fertilizer imports.

Country	Ammonium nitrate	Calcium ammonium nitrate	Ammonium nitro Sulphate	Calcium nitrate	Ammonium Sulphate	Di-ammonium phosphate	Urea	Urea ammonium nitrate	Nitrophosphates	Total*	Total emissions (total CO_2 **fertilizer imports)
	33.5% N	15.5% N	21% N	15.5% N	21% N, 24% S	18% N, 46% P_2O_5	46% N	30% N	15% N		
China	0.81	0.93	0.56	1.53	0.27	0.24	0.20	1.94	0.70	7.18	695,225
Italy	0.65	0.75	0.75	1.27	0.68	0.18	0.17	1.73	0.57	6.75	198,653
Saudi Arabia	0.72	0.83	0.31	1.39	0.65	0.17	0.11	1.69	0.62	6.49	962,110
Russia	0.74	0.85	0.30	1.41	0.14	0.23	0.24	1.83	0.65	6.39	248,405
Norway	0.69	0.79	0.37	1.32	0.67	0.22	0.22	1.76	0.61	6.65	307,430
Switzerland	0.65	0.75	0.19	1.28	0.70	0.18	0.17	1.74	0.57	6.23	482,501
Ukraine	0.70	0.81	0.25	1.36	0.73	0.19	0.16	1.79	0.61	6.6	345,233
Turkey	0.64	0.74	0.32	1.27	0.65	0.17	0.15	1.73	0.56	6.23	103,194
Jordan	0.72	0.83	0.47	1.40	0.67	0.18	0.13	1.70	0.62	6.72	40,932
Croatia	1.65	0.75	0.19	1.30	0.55	0.18	0.17	1.73	0.57	7.09	53,175
Total	**7.97**	**8.03**	**3.71**	**13.53**	**5.71**	**1.94**	**1.72**	**17.64**	**6.08**	**66.33**	**3,436,856**

* (CO_2 -eq/metric tons N), ** (CO_2-eq).

Table 10. **Tanzania's total carbon footprint of N fertilizer imports.**

	Calcium ammonium nitrate	Ammonium Sulphate	Di-ammonium phosphate	Urea	Nitrophosphates	Total*	Total emissions (total CO_2 **fertilizer imports)
Tanzania emissions	15.5% N	21% N, 24% S	18% N, 46% P_2O_5	46% N	15% N		
China	0.93	0.93	0.25	0.22	0.71	3.04	37,143
Italy	0.74	0.65	0.17	0.15	0.56	2.27	34,077
Saudi Arabia	0.83	0.64	0.17	0.11	0.62	2.37	123,003
Russia	0.80	0.73	0.19	0.16	0.61	2.49	192,992
UAE	0.81	0.60	0.16	0.10	0.61	2.28	107,098
Norway	0.78	0.79	0.21	0.21	0.60	2.59	162,639
Netherlands	0.77	0.77	0.20	0.21	0.60	2.55	44,610
Turkey	0.74	0.74	0.65	0.17	0.60	2.90	83,410
Finland	0.80	0.82	0.21	0.23	0.60	2.66	74,443
Morocco	0.83	0.80	0.20	0.17	0.63	2.63	63,120
Madagascar	0.78	0.55	0.15	1.10	0.57	3.15	71,250
Others*	0.73	0.62	0.16	0.14	0.55	2.20	41,303
Total	**9.54**	**8.64**	**2.72**	**2.97**	**7.26**	**31.13**	**1,035,088**

*(CO_2-eq/metric tons N), **(CO_2-eq).

Table 11. **Rwanda's total carbon footprint of N fertilizer imports.**

Country	Ammonium sulphate	Di-ammonium phosphate	Urea	Nitrophosphates	Total*	Total emissions (total CO_2 **fertilizer imports
Rwanda	21% N, 24% S	18% N, 46% P_2O_5	46% N	15% N		
Tanzania	0.75	0.2	0.19	0.58	1.72	49,135
Kenya	0.66	0.17	0.16	0.56	1.55	8,446
Morocco	1.10	0.17	0.31	0.59	2.17	23,508
Saudi Arabia	0.94	0.24	0.25	0.69	2.12	18,495
China	1.23	0.32	0.35	0.79	2.69	1,630
Estonia	0.92	0.24	0.27	0.63	2.06	6,695
Total	**5.6**	**1.34**	**1.53**	**3.84**	**12.31**	**107,909**

*(CO_2 -eq/metric tons N), **(CO_2-eq)

Table 12. **Burundi's total carbon footprint of N fertilizer imports.**

Country	Ammonium Sulphate	Di-ammonium phosphate	Urea	Nitrophosphates	Total*	Total emissions (total **CO_2 Fertilizer imports)
Burundi	21% N, 24% S	18% N, 46% P_2O_5	46% N	15% N		
Tanzania	0.74	0.19	0.19	0.58	1.7	79,956
Kenya	0.73	0.19	0.18	0.58	1.68	5,188
Uganda	0.53	0.14	0.09	0.53	1.29	8
Total	**2**	**0.52**	**0.46**	**1.69**	**4.67**	**85,152**

*(CO_2-eq/metric tons N), **(CO_2-eq).

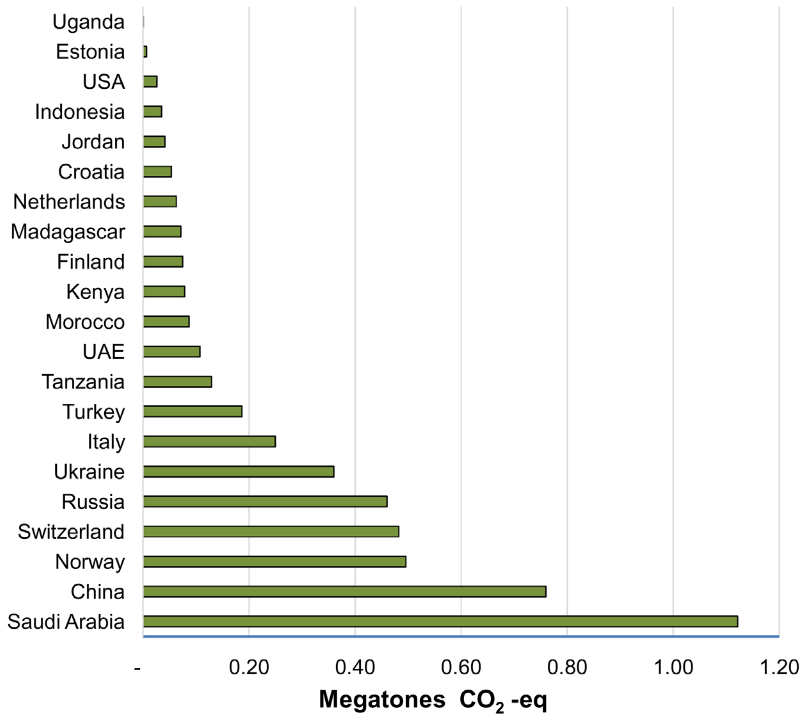

Figure 2. Contribution of emissions by countries exporting N fertilizers to East Africa.

Table 13. The contribution of CO_2 emissions by country of origin for N fertilizer imports in East Africa.

Exporter	Megatons CO_2 -eq	% emissions Contribution
Saudi Arabia	1.12	22.95
China	0.76	15.55
Norway	0.50	10.15
Switzerland	0.48	9.88
Russia	0.46	9.41
Ukraine	0.36	7.36
Italy	0.25	5.10
Turkey	0.19	3.82
Tanzania	0.13	2.64
UAE	0.11	2.19
Morocco	0.09	1.77
Kenya	0.08	1.60
Finland	0.07	1.52
Madagascar	0.07	1.46
Netherlands	0.06	1.29
Croatia	0.05	1.09
Jordan	0.04	0.84
Indonesia	0.03	0.71
USA	0.03	0.53
Estonia	0.01	0.14
Uganda	0.00	0.00

EA bloc, 1.1 megatons CO_2-eq were contributed by imports for Saudi Arabia and 0.8 megatons CO2-eq from imports from China. This is in part a result of high imports to Kenya (the highest importer on the Bloc) coming from Saudi Arabia and China, and the industrial process used by these in the production of ammonia. A considerable amount of emissions of the chemicals sector is caused by the production of ammonia. Ammonia is a key feedstock for fertilizer production and is made by catalyzing hydrogen with nitrogen. Currently, the hydrogen for ammonia production is usually based on reforming natural gas but leaves a carbon footprint of 830 megatons CO_2 yr^{-1}(IEA, 2019). China leaves the largest footprint in its N fertilizer production process as it involves coal (IFS, 2019). Some countries are looking at future hydrogen from electrolysis based on low zero-carbon energy sources (MaterialEconomics, 2019; Stork *et al.*, 2018). This implies that the EA bloc can reduce its carbon footprint of N fertilizer imports by acquiring them from economies that demonstrate decarbonization pathways for energy intensive industries and use innovative technology options to cut GHG emissions across basic materials and value chains.

Findings of this study in addition revealed that the carbon footprint of N fertilizer imports on the EA bloc was also determined by the types of N fertilizers and the number of types of N fertilizers imported by the region. These include AN, CAN, ANS, CN, AS, DAP, urea, UAN, NPK and mono ammonium phosphate (MAP). Kenya the highest importer of N fertilizers brings in all types of N fertilizers except one. Uganda despite bringing in only 3.5% of total N fertilizer imports on the EA bloc, imports all ten types. The tenth most common fertilizer imported by Uganda is MAP which is a key fertilizer for Highland banana (*Musa* spp.), the countries staple food (*matooke*). However the question lies in whether there is need to import all types of N fertilizers, if the primary objective is to improve Nitrogen in the soils. This is because each type of fertilizer is a product of Ammonia from reforming natural gas or coal that leaves a high carbon footprint in industrial emissions annually. The study found that the 'dirtiest' of N fertilizers that accounted for the highest carbon footprint on the bloc were UAN and CN, NPK and AS. To place this observation into perspective one needs to understand the blends required to produce UAN, as an example. The components required to produce UAN include ammonia, 100% nitric acid, urea and an ammonium nitrate melt. All components require specific energy inputs that accumulate to the overall industrial carbon footprint. In addition, dolomite ($CaMg(CO_3)_2$ (limestone) used as a filler for certain fertilizer products, contains 45% CO_2 and depends on heavy fuel oil and energy to mine (GaBi, 2013; IEA, 2011a). On application the CO_2 in dolomite is released on agricultural soils. The choice of N fertilizers that the EA bloc imports can be a priority strategy for emissions reduction in the bloc's NDCs. This strategy can be further strengthened by improving N fertilizer management on agricultural fields by identifying and adopting technologies and practices that can make fertilizer use more efficient. There is evidence that N fertilizer management on agricultural fields can significantly help reduce emissions of nitrous oxide in agriculture (Shcherbak *et al.*, 2014). Carbon dioxide is the source of 11% of GHG emissions from agricultural land, which is less than that from nitrous oxide (36%) and methane (53%) (Beach *et al.*, 2015).

Policy recommendations for decarbonization

This study observed that the carbon footprint of N fertilizer imports of the East African Bloc are significantly driven by three factors: (i) the production process of the country of origin that the fertilizers come from, (ii) freight distance and (iii) choice and number of N fertilizers each country imports. To reach net-zero emissions from fertilizer imports in the East African Bloc, this study suggests following policy implications for decarbonization using three pathways: 1) New Process pathways, 2) Circular Economy pathways and 3) Decarbonization of land-based freight transport. New process pathways will include embracing new paradigms for fertilizer production to meet local demand. Scenario analyses show that significant cuts in GHG emissions and even close to net zero emissions from energy intensive industry such as ammonia can be achieved by deploying multiple and available options (IPCC, 2018). This can be through energy efficiency to transformational changes in energy and feedstock sourcing, materials efficiency and circular economy. For instance, energy efficiency in the production of N fertilizers can be achieved though by-passing the hydrogen process such as modern plasma technology for N fixation.

Plasma-assisted N fixation was first used in Norway as early as 1905 (Birkeland, 1906; Eyde, 1912) but was abandoned for the more efficient Harber-Bosch process in splitting hydrogen for ammonia synthesis. Plasma is considered as the fourth state of matter which makes up 99% of the visible universe (Fridman, 2008; Lieberman & Lichtenberg, 2005). Plasma is generated by ionization of gases by an electric current. Plasma-assisted N fixation is the reaction of N with oxygen or hydrogen to produce N oxide (nitric acid) or ammonia, respectively, under plasma conditions (Lakshmi, 2016). Plasma-assisted N fixation technology provides a simple and energy efficient process for the preparation of N compounds that can be assimilated by plants. In plasma-assisted N fixation technology synthesis, the raw material is air (N + oxygen), which is abundantly available. A recent study, Patil (2017) demonstrated that plasma-assisted N fixation technology process is inherently a lower energy demand process and contains the prospect to use alternative energy sources such as wind, solar or bio energy. Plasma-assisted N fixation technology/process uses low-cost raw material (air) and does not need extra heating or pressurization equipment. The utilization of solar energy (abundant in Africa) makes the fertilizer even more affordable and highly sustainable. Econometric calculations have assessed that following adoption, plasma-assisted N could reduce the retail cost of fertilizers in Africa by at least 40% (Anastasopoulou *et al.*, 2016a; Anastasopoulou *et al.*, 2016b). In addition it is a one-step synthesis, a fast reaction, instant control, and suitable for small-scale and decentralized production (Fauchais & Rakowitz, 1979). Decentralized production can significantly save emissions from the H-B process, costs and transportation. The small output (1–10% N) of the plasma process implies that it cannot industrially compete with the H-B process, but has the capability to point to a new process pathway that can lead to the decarbonization of the fertilizer sector of the EA bloc through low cost on-site fertilizer production for poor farmers. The author is demonstrating onsite N fertilizer production using plasma-assisted N fixation using solar energy for poor rural farmers in Uganda.

Circular economy pathways will include actions to reduce food waste, increase fertilizer use efficiency and switch to organic farming. It is estimated that 3.3 gigatons of CO_2 equivalent are emissions from food waste alone (FAO, 2013). In Africa, food waste is as a result of post-harvest loses that have been estimated to range from 20%–40% (Abass *et al.*, 2014). SSA alone loses about $4 billion every year in food grains post-harvest loses (Zorya *et al.*, 2011). These loses impact the environment in such a way that land, water and agricultural inputs such as fertilizers are wasted alongside food waste. Fertilizer or nutrient use efficiency is focused on application of the right nutrient source, at the right rate, in the right place and at the right time (IPNI, 2012). The objective of nutrient use is to increase the overall performance of cropping systems by providing economically optimum nourishment to the crop while minimizing nutrient losses and supporting sustainable land management (Fixen *et al.*, 2015). For instance, conservation agriculture (CA) using cover crops reduces fertilizer inputs, limits water contamination from leaching and enhances soil biological activity (González-Sánchez *et al.*, 2012). Specifically, leguminous cover crops are important sources of easily absorbed nitrogen for crops in rotations and for promoting microbial diversity and soil structure and stability. Across Africa, CA is being practiced on 1.8 million ha in almost 20 African countries (Kassam & Derpsch, 2019). There is evidence that the potential estimate of annual carbon sequestration in African agricultural soils through CA amounts to 524 Tg CO_2 $year^{-1}$, three times higher than that in Europe (189 Tg CO_2 $year^{-1}$), (González-Sánchez *et al.*, 2019). On the EA Bloc, technological progress in CA is uneven among countries, which calls for policies that create opportunities for the EA community to enhance its ambition for wide dissemination of bio-sequestration options that are important for NDCs of the Bloc. In addition, the EA bloc can also decarbonize by switching to organic farming that relies on ecological processes, biodiversity and cycles adapted to local conditions. Rather than the use of inputs with adverse effects, organic agriculture combines tradition, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved. Organic farming systems contribute to climate change mitigation through better management of nutrients and, hence, the reduction of GHG emissions. There is evidence that nitrous oxide and carbon dioxide emissions were clearly lower on organic farms with much higher carbon sequestration (Gomiero *et al.*, 2008). Globally, the potential to reduce emissions in agriculture from not using mineral fertilizers is about 20% (Muller *et al.*, 2017), a key factor for NDCs.

Decarbonization of Land-based freight transport on the EA bloc will require a concerted move from the traditional use of Diesel to power heavy-duty trucks to alternative sources. A study by Quiros *et al.* (2017) in the USA, assessed CO_2, CH_4, and nitrous oxide NO measured from seven heavy-duty trucks on-road including diesel, hybrid diesel, and natural gas. It was observed that NO was ten times higher for diesel trucks with selective catalytic reduction and that natural gas and hybrid diesel vehicles had lower CO_2-eq. The EAC can pass legislation for standards to import only fuel efficient heavy-duty trucks. A study by Zhao *et al.* (2013) found that hybridization of land-based freight transport could save fuel by 16% through improvements in engine efficiency, aerodynamic drag and rolling resistance of heavy-duty trucks. On the other hand, freight rail is also a major mode for the inland movement of goods. Trains are more energy efficient (on the basis of ton/km) than trucks, so expanded use of rail system could provide carbon abatement opportunities. While diesel-based locomotives are still the major propulsion used in freight rail, interest in low-carbon propulsion technologies is growing. Such technologies may include biofuels, natural gas, electricity, or hydrogen.

Conclusions

Over 93% of fertilizers imported to the East African Bloc are nitrogenous fertilizers, they leave a carbon footprint of 4.9 megatons CO_2-eq of which Kenya is responsible for 70% of the total emissions. For every metric ton of N imported, results in a carbon footprint of 4.5 metric tons CO_2-eq. Ship and land-based freight distance, the Ammonia production process of countries exporting to the bloc and the types and number of nitrogenous fertilizers imported to the bloc are a significant determinants of greenhouse gas (GHG) emissions to NDCs of the East African community. The study recommends that to reach net-zero emissions from fertilizer imports, the East African Bloc recommends the following policy implications for decarbonization using three pathways: 1) new process pathways, 2) circular economy pathways, and 3) decarbonisation of land-based freight transport pathways. This transition will require investments and will vary significantly by pathway. There is need for scenario analysis of the three pathways and the kind of investment required for each pathway. The EA bloc can experiment with tried-and-tested solutions but policy will play an important role in enabling the transition to a net-zero nitrogen sector.

Data availability

Underlying data

All data underlying the results are available as part of the article and no additional source data are required.

Extended data

Harvard Dataverse: Carbon foot print of Fertilizer imports to the East African Bloc and Policy recommendations for Decarbonization. https://doi.org/10.7910/DVN/MMNU0S (Kabiri, 2020).

This project contains the following extended data:

- Fertilizer imports statistics for Uganda, Kenya, Tanzania, Rwanda and Burundi.
- Pearson's correlation analysis.
- Stepwise application of the carbon footprint calculator (CFC) for fertilizer production tool.

References

Abass AB, Ndunguru G, Mamiro P, *et al.*: **Post-harvest food losses in a maize-based farming system of semi-arid savannah area of Tanzania.** *Journal of Stored Products Research.* 2014; **57**: 49–57.
Publisher Full Text

ADB: **Abuja Declaration on Fertilizer for the African Green Revolution.** *African Development Bank Group.* 2017; accessed Dec 2019.
Reference Source

AfricaFertilizer.org: Fertilizer Statistics Overview RWANDA 2013 - 2017, KENYA 2012 - 2015, TANZANIA 2013 - 2017, Uganda 2011 - 2014 and Burundi, BURUNDI 2013 - 2017. 2018.
Reference Source

Anastasopoulou A, Butala S, Lang J, *et al.*: **Life Cycle Assessment of the Nitrogen Fixation Process Assisted by Plasma Technology and Incorporating Renewable Energy.** *Ind Eng Chem Res.* 2016a; **55**(29): 8141–8153.
Publisher Full Text

Anastasopoulou A, Butala S, Patil B, *et al.*: **Techno-Economic Feasibility Study of Renewable Power Systems for a Small-Scale Plasma-Assisted Nitric Acid Plant in Africa.** *Processes.* 2016b; **4**(54).
Publisher Full Text

Appl M: In 50th Anniversary. IFA Technology Conference: 25. 1997a.

Appl M: **The Haber-Bosch Heritage: The Ammonia Production Technology**. In Proceedings of the 50th Anniversary of the IFA Technical Conference, Sevilla, Spain, 25–26 September 1997. 1997b.
Reference Source

Appl M: Ullmann's Encyclopedia of Industrial Chemistry: 139–225. 2012.
Reference Source

Beach RH, Creason J, Ohrel SB, *et al.*: **Global mitigation potential and costs of reducing agricultural non-CO_2 greenhouse gas emissions through 2030.** *Journal of Integrative Environmental Sciences.* 2015; **12**(sup 1): 87–105.
Publisher Full Text

Birkeland KR: **On The Oxidation of Atmospheric Nitrogen In Electric Arcs.** *Trans Faraday Soc.* 1906; **2**: 98–116.
Publisher Full Text

Canfield DE, Glazer AN, Falkowski PG: **The evolution and future of Earth's nitrogen cycle.** *Science.* 2010; **330**(6001): 192–196.
Publisher Full Text

Cherkasov N, Ibhadon AO, Fitzpatrick P: **A Review of The Existing and Alternative Methods for Greener Nitrogen Fixation.** *Chem Eng Process Process Intensif.* 2015; **90**: 24–33.
Publisher Full Text

Christensen B, Brentrup F, Hoxha A, *et al.*: **Assessing the Carbon Footprint of Fertilisers, at Production and Full LCA.** *IFS Proceedings.* IFS (International Fertiliser Society), York, UK. p 19. FS Proceedings . IFS (International Fertiliser Society), York, UK, 2014; 19.
Reference Source

Erisman JW, Sutton MA, Galloway J, *et al.*: **How a century of ammonia synthesis changed the world.** *Nature Geoscience.* 2008; **1**(10): 636–639.
Publisher Full Text

Eyde S: **Oxidation of Atmospheric Nitrogen and Development of Resulting Industries in Norway.** *Ind Eng Chem.* 1912; **4**: 771–774.
Publisher Full Text

FAO: **Food Wastage Footprint—Impacts on Natural Resources.** *Food and Agriculture Organization of the United Nations FAO.* 2013; Rome, Italy, 2013.
Reference Source

FAOSTAT: **Inputs.** 2014.
Reference Source

Fauchais P, Rakowitz J: **Physics on Plasma Chemistry.** *J Phys Colloq.* 1979; **40**(C7): 289–312.
Publisher Full Text

Fixen P, Brentrup F, Bruulsema T, *et al.*: **Nutrient/fertilizer use efficiency: measurement, current situation and trends.** 2015; 8–38.

Fridman A: **Plasma Chemistry.** Cambridge University Press, New York. 2008.
Publisher Full Text

GaBi: **GaBi LCI database.** PE International (now Thinkstep). Leinfelden-Echterdingen, Germany. 2013.
Reference Source

GaBi: GaBi Database & Modelling Principles. Thinkstep AG, Hauptstr. 111 – 113 70771 Leinfelden-Echterdingen, Germany. 2017.
Reference Source

Gomiero T, Paoletti MG, Pimentel D: **Energy and Environmental Issues in Organic and Conventional Agriculture.** *Critical Rev Plant Sci.* 2008; 27(4): 239–54.
Publisher Full Text

González-Sánchez EJ, Ordóñez-Fernández R, Carbonell-Bojollo R, *et al.*: **Meta-analysis on atmospheric carbon capture in Spain through the use of conservation agriculture.** *Soil Tillage Research.* 2012; **122**: 52–60.
Publisher Full Text

González-Sánchez EJ, Veroz-González O, Caneway G, *et al.*: **Meta-analysis on carbon sequestration through conservation agriculture in Africa.** *Soil & Tillage.* 2019; **190**: 22–30.
Publisher Full Text

IEA: **CO2 Emissions from Fuel Combustion 2011.** OECD Publishing, Paris. 2011a.
Publisher Full Text

IEA: **CO2 emissions from fuel combustion.** Highlights. 2011b.
Reference Source

IEA: **The future of Hydrogen.** 2019.
Reference Source

IFS: **The Carbon Footprint of Fertiliser Production: Regional Reference Values.** *International Fertilizer Society.* 2019.
Reference Source

IPCC: IPCC 2006, **2006 IPCC Guidelines for National Greenhouse Gas Inventories.** Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T., and Tanabe K. (eds). IGES, Japan. 2006.
Reference Source

IPCC: **Climate change 2007 synthesis report.** In : Pachauri, R.K., Reisinger, A., editors. Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland. 2007.
Reference Source

IPCC: **Global Warming of 1.5 °C an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change.** 2018.
Reference Source

IPNI: **4R Plant Nutrition: A Manual for Improving the Management of Plant Nutrition**. (T.W. Bruulsema, P.E. Fixen, G.D. Sulewski, eds.), International Plant Nutrition Institute, Norcross, GA, USA. 2012.
Reference Source

Kabiri S: **Carbon foot print of Fertilizer imports to the East African Bloc and Policy recommendations for Decarbonization.** *Harvard Dataverse, V1.* 2020.
http://www.doi.org/10.7910/DVN/MMNU0S

Kassam A, Friedrich T, Derpsch R: **Global spread of Conservation Agriculture.** *Int J Environ Stud.* 2019; **76**(1): 29–51.
Publisher Full Text

Lakshmi PKG: **Process for combustion of nitrogen for fertilizer production**. Google Patents. 2016.
Reference Source

Lieberman MA, Lichtenberg AJ: **Principles of Plasma Discharges and Materials Processing**. Wiley. 2005
Reference Source

Makan H, Heyns GJ: **Sustainable supply chain initiatives in reducing greenhouse gas emission within the road freight industry.** *Journal of Transport and Supply Chain Management.* 2018; **12**.
Publisher Full Text

MaterialEconomics: **Industrial Transformation 2050: Pathways to net-zero emisisons from EU Heavy Industry**. 2019.
Reference Source

Muller A, Schader C, El-Hage Scialabba N, *et al.*: **Strategies for feeding the world more sustainably with organic agriculture.** *Nat Commun.* 2017; **8**(1): 1290.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**

Okalebo JR, Othieno CO, Woomer PL, *et al.*: **Available technologies to replenish soil fertility in East Africa.** Dordrecht: Springer Netherlands. 2007; 45–62.
Publisher Full Text

Patil BS: **Plasma (catalyst) - assisted nitrogen fixation : reactor development for nitric oxide and ammonia production**. PhD Thesis Eidhoven University of Technology. 2017.
Reference Source

Ports: **World sea ports database, sea transportation, marine and ports market place, sea distances and routes**. 2019.
Reference Source

Quiros DC, Smith J, Thiruvengadam A, *et al.*: **Greenhouse gas emissions from heavy-duty natural gas, hybrid, and conventional diesel on-road trucks during freight transport.** *Atmos Environ.* 2017; **168**: 36–45.
Publisher Full Text

Schnitkey G: **Current Fertilizer Prices and Projected 2016 Fertilizer Costs**. *farmdoc daily.* 2015; (5): 232. Department of Agricultural and Consumer Economics, University of Illinois. University of Illinois at Urbana-Champaign.
Reference Source

Shcherbak I, Millar N, Robertson GP: **Global Metaanalysis of the Nonlinear Response of Soil Nitrous Oxide (N_2O) Emissions to Fertilizer Nitrogen.** *Proc Natl Acad Sci U S A.* 2014; **111**(25): 9199–9204.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**

SPSS: **SPSS for Windows, Version 16.0**. 2007. Chicago, SPSS Inc.
Reference Source

Stork M, Beer DJ, Lintmeijer N, *et al.*: **Chemistry for Climate: Acting on the need for speed**. 2018. Roadmap for the Dutch Chemical Industry towards 2050.
Reference Source

Tanabe Y, Nishibayashi Y: **Developing More Sustainable Processes for Ammonia Synthesis.** *Coord Chem Rev.* 2013; **257**(17–18): 2551–2564.
Publisher Full Text

Yeh S, Mishra GS, Fulton L, *et al.*: **Detailed assessment of global transport-energy models' structures and projections.** *Transp Res D Transp Environ.* 2017; **55**: 294–309.
Publisher Full Text

Zhao H, Burke A, Miller M: **Analysis of Class 8 truck technologies for their fuel savings and economics.** *Transp Res D Transp Environ.* 2013; **23**: 55–63.
Publisher Full Text

Zorya S, Morgan N, Rios LD, *et al.*: **Missing Food: The Case of Postharvest Grain Losses in Sub-Saharan Africa**. The international bank for reconstruction and development/the world bank: Washington, DC, USA. 2011.
Reference Source

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✗ **Edgar G. Hertwich**
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The results that are presented are not credible. The paper presents as a results that emissions on the order of 60 t CO2-eq per ton N. These numbers are far higher than those reported elsewhere in the literature, which are a factor of 10 or more lower. For example, Skowrońska and Filipek (2014[1]) report emissions of 2-6 tons. Similarly, the EcoInvent database, which is the most well-recognized database, provides a value of 6. Yara, a Norwegian fertilizer producer, reports that they emit 4 kg CO2e per kg N, while the European average is 6. The transportation is just a small fraction of the total emissions. Attention to the regional origin is relevant where regional energy-related emissions differ.
https://www.yara.com/crop-nutrition/why-fertilizer/environment/fertilizer-life-cycle/

References

1. Skowrońska M, Filipek T: Life cycle assessment of fertilizers: a review. *International Agrophysics*. 2014; **28** (1): 101-110 Publisher Full Text

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and is the work technically sound?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?

Partly

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Industrial ecology, life cycle assessment, carbon footprinting, input-output analysis, trade and environment, materials efficiency.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

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The paper by Stella Kabiri provides an interesting overview of the climate impact of fertilizer use in East Africa. It is, to my knowledge, the first account of such an impact and clearly data, procedure and results are worthwhile to be published. At this point in time, major omissions, possibly even errors and misleading information characterize much of the discussion and conclusions. In order to avoid wrong information to be propagated, proper correction and, where appropriate, further explanation of detail will be required before I can recommend final indexing. This will require significant changes and adaptation, but I hope the author is willing to undergo and provide a cleaned-up and significantly revised version of the manuscript.

Key problems:

- The author argues that footprints are being assessed in order to guide NDC's under the Paris agreement. However, NDC's refer to *domestic mitigation measures*, not to reduce emissions along the production chain. Hence, measures to reduce emissions from fertilizer production in China or Switzerland will be part of the NDC's provided by these two countries, not of the NDC's of the importing countries (https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement/nationally-determined-contributions-ndcs#eq-4).

- Correctly fixation of N in the Haber-Bosch process is described as the key factor to provide N to soils and plants. It is, however, surprising that the author never ever mentions the importance of biological nitrogen fixation (BNF) in this context. On p. 14 “leguminous cover crops” are shortly mentioned. But totally omitting the source that currently is mostly responsible to provide N to SSA agriculture points towards a lack in grasping the connections. Possibly it is useful to consult some of the relevant literature here (Galloway *et al.*, 2004[1], Fowler *et al.*, 2013[2] and 'The European Nitrogen Assessment' - Cambridge University Press, 2011[3]).

- It is not fully clear which system boundaries are being used. The analysis looks at GHG footprints (industrial emissions during fertilizer production, transport between production site and seaport, and between seaport and destination point (simplified to a country’s capital). However at least in one case (p.13, first column, bottom) also GHG emissions from fertilizer application (CO2, N2O, and also CO2 from land use and CH4) are mentioned.

- The correlation analysis (Table 7) seems to indicate that results are as expected, but are nearly not explained (p. 6, bottom). It turns out that there is a very strong correlation between the amount of fertilizer imported and total GHG footprint – one would expect that. For the specific GHG emission (per ton N) the author finds a weaker, but significant relationship to freight distance. Also this makes sense, as fuel emissions have been aggregated along this distance. What is fully missing is a display of shares of the emission categories – how much is due to production, due to sea transport, due to land transport? This data must be there, they are part of the analysis. It would probably show that by far the largest contribution is from fertilizer production.

- In the discussion and conclusion, a strong argument is being made for a novel technique of fertilizer production (plasma-induced oxidation). However the author fails to recognize that this is a rather experimental technology that is far from being commercially implemented – there are good reasons why Haber-Bosch nitrogen still dominates the market. It is true that it is worthwhile to discuss such new technologies (like also electrocatalytical nitrogen reduction, by the way: Andersen *et al.*, 2019[4]), especially as renewable wind or solar electricity could drive such processes, avoiding the need of natural gas. Here also the author mentions “conservation agriculture”, but failing to refer to BNF as an important aspect of that.

Minor issues (list is not comprehensive):

- Tables would strongly benefit from proper units and description of columns. Specifically, fertilizer typically is presented in statistics as [t N] (or [t P2O5] or [t K2O]). For transport, however, it is important to report total mass [t fertilizer]. I believe this has been done correctly, but still it needs differentiation in each instance. See also Table 1: units are here correctly, but specific emissions per GJ are presented, differentiated between energy use and energy supply, - a bit unclear what this really means. Also, “Fuel stock” for china is given as Natural gas – while p. 13 (top quarter, first column) states: “China leaves the largest footprint in its N fertilizer production process as it involves coal”. What is correct?

- Transport distances are probably not too relevant, still there is room for questions: land transport – with KE, UG or TZ not producing fertilizer (except for SSP – phosphate, not N – in Kenya) all imports from these countries need to be re-exports. Do we have (some) double counting here? Some of the sea distances seem odd. Why is the difference for transport from Russia to Mombasa 3500 nm longer than to Dar es Salaam (which is a multiple of the distance between these harbours)? Why is the transport to Dar es Salaam from Estonia half as long as from Finland, two countries that are only 100 km apart)? Also, summing up the distances ("totals") does not seem to make any sense.

- Misleading are also the numbers presented on specific greenhouse gas emissions from fertilizer imports, by different countries (p. 8, 1st column, just before discussion). Having a discrepancy of a factor of 10 and more here is most probably a data error. E.g. looking at Table 10 there are lower imports to Tanzania from Saudi Arabia for each individual fertilizer type than from China – yet total GHG emissions from Saudi Arabia are more than three times as high. This is, despite of smaller transport distances, and the fact that China uses (to some extent) coal in fertilizer production and electricity generation, and hence would be expected to have the higher specific emissions.

- There is no opportunity to point out here a few technical glimpses (N2O is a relevant greenhouse gas, not NO; nitric acid is not the same as N oxide, though it is of course oxidized N; limestone is not the same as dolomite, and it is not used as a filler but for management of soil acidity).

References

1. Galloway J, Dentener F, Capone D, Boyer E, et al.: Nitrogen Cycles: Past, Present, and Future. *Biogeochemistry*. 2004; **70** (2): 153-226 Publisher Full Text
2. Fowler D, Coyle M, Skiba U, Sutton MA, et al.: The global nitrogen cycle in the twenty-first century.*Philos Trans R Soc Lond B Biol Sci*. 2013; **368** (1621): 20130164 PubMed Abstract | Publisher Full Text
3. The European Nitrogen Assessment. 2011. Publisher Full Text
4. Andersen SZ, Čolić V, Yang S, Schwalbe JA, et al.: A rigorous electrochemical ammonia synthesis protocol with quantitative isotope measurements.*Nature*. **570** (7762): 504-508 PubMed Abstract | Publisher Full Text

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and is the work technically sound?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: environmental chemistry, greenhouse gas inventories, nitrogen cycles

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.