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Current and future nitrous oxide emissions from African agriculture

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Most emission estimates of the greenhouse gas nitrous oxide (N_2O) from African agriculture at a continental scale are based on emission factors, such as those developed by the IPCC Guidelines. Here we present estimates from Africa from the EDGAR database, which is derived from the IPCC emission factors. Resulting estimates indicate that N_2O emissions from agriculture represented 42% of total emissions from Africa (though that rises to 71% if all savannah and grassland burning is included), or roughly 6% of global anthropogenic N_2O emissions (or 11% including burning). Emissions from African agriculture are dominated by grazing livestock; 74% of agricultural N_2O excluding biomass burning was from paddocks, ranges, and pasture. Direct soil emissions represent 15% of agricultural emissions; substantial changes in direct emissions from North Africa helped drive a 47% continental increase in direct soil emissions from 1970 to 2005. Future trends based on the Millennium Ecosystem Assessment scenarios indicate that agricultural N_2O emissions may double in Africa by 2050 from 2000 levels. Any regional or continental estimates for Africa are, however, necessarily limited by a paucity of direct measurements of emissions in sub-Saharan agro-ecosystems, and the heavy reliance on emission factors and other default assumptions about nitrogen cycling in African agriculture. In particular, a better understanding of livestock-related N inputs and N_2O emissions will help improve regional and continental estimates. As fertilizer use increases in sub-Saharan Africa, emission estimates should consider several unusual elements of African agriculture: farmer practices that differ fundamentally from that of large scale farms, the long history of N depletion from agricultural soils, seasonal emission pulses, and emission factors that vary with the amount of N added.

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Introduction

Agriculture is a major source of atmospheric nitrous oxide (N_2O), one of the three most important greenhouse gases [1]. In general, emissions of N_2O, which are produced not only during denitrification but also during nitrification [2], are most strongly influenced by nitrogen (N) availability and soil moisture, and to a lesser extent by factors such as temperature, pH, and the availability of reduced carbon [3]. In agricultural production systems, inputs of inorganic and organic N provide a source of ammonium and nitrate for nitrification and denitrification, while higher soil moisture levels provide the anoxic conditions required for denitrification, and slow the diffusion of nitric oxide (NO) through soils, creating further opportunities for its reduction to N_2O. Application of N fertilizers and animal production accounts for about 60% of the global N_2O emissions from agriculture [4]. Since 1970, N_2O emissions have grown mainly as a result of increased use of mineral fertilizers worldwide [5], but in Africa, N input via synthetic N fertilizers is among the lowest in the world, representing 3% of the world fertilizer consumption [6]. The African continent, and sub-Saharan Africa (SSA) in particular, makes a small contribution to global greenhouse gas emissions from agriculture: Africa has been estimated to produce only 15% of global agriculture soil N_2O emissions and 3% of emissions from animal production systems [7].

In part as a consequence of extremely low fertilizer inputs in Africa (an average of 8 kg nutrients ha^{-1} compared to 100 kg N ha^{-1} in the United States, and 220 kg N ha^{-1} in China) [8••], N removal through crop harvest and erosion over the last several decades has led to negative nutrient balances, declining grain yields, and consequently to insufficient food intake to meet dietary protein and energy requirements [9]. Currently 250 million people in SSA, 30% of the total African population, are chronically malnourished [10]. A greater input of N to the soil is urgently needed to satisfy the basic needs of an increasing African population. This increase in N inputs is likely to be the largest perturbation to the N cycle in Africa in coming decades. One inevitable impact of increasing N inputs is the growth of direct and indirect N_2O emissions, although the magnitude of these emissions may be influenced by environmental conditions (such as the retention of nitrate on anion exchanges sites in subsoils of certain soil types in SSA) or management practice (such as spatial and temporal targeting of fertilizer application to plant demand to increase rates of N uptake and reduce losses to the environment) [11–13].

Several recent successes have paved the way for a dramatic expansion of fertilizer use in SSA, which has gained momentum with Kofi Annan's call for an African Green Revolution. In Malawi, a national subsidy program providing smallholder farmers with vouchers for fertilizer and improved seed has consistently resulted in a doubling of national grain yields, and has helped the country shift from a maize production deficit to a surplus [14]. The Millennium Villages Project, which also promotes subsidized fertilizer use, has also demonstrated that in combination with improved maize varieties and extension services, increasing N application (post-intervention application rates for maize ranged from 45 to 130 kg N ha^{-1} in the different villages) can quickly double and triple maize yields across SSA [15•,16]. The implications of this increased application of N inputs to agricultural systems in Africa for N_2O emissions are still only partially understood. For example, there are no published studies from Africa examining the response function relating N_2O emissions to incremental increases in N inputs (e.g. [17•]).

Current estimates of N_2O emissions from African agriculture at the national, regional, and continental scale are mostly based on the IPCC Guidelines [7,18], which implicitly ignore important characteristics of African soils and management practices of smallholder farmers, both of which could alter emissions substantially. Some efforts have been made to improve the estimates by applying statistical and process-based models [19••,20,21]. However, these estimates are often hindered by a lack of the data needed as basic inputs for these models, and by the relatively small number of emission measurements made in SSA. In particular, the available weather station observations in sub-Saharan Africa (e.g. [22]) are plagued with large and numerous recording gaps, and current soil maps are generally based on sparse and often incomplete soil profile measurements, particularly in comparison to western countries [23]. Because N availability and soil moisture are the major determinants of N oxide emissions [24–26] and are related to basic soil properties, these data shortfalls make regional estimates of N_2O emissions challenging.

In this paper we review some existing estimates of the current and future trends in N input and N_2O emissions from African agriculture. Next we discuss limitations of the estimation methods for Africa and what is needed to address these limitations.

Trends in N inputs and nitrous oxide emissions

Current sources and rates

Agriculture is a source of N_2O through direct and indirect emissions from soils. First of all, N_2O production by bacteria in agricultural fields generally increases from soils where N is added, referred to as *direct* emissions from agriculture. In addition, N losses from agricultural systems through leaching, runoff, erosion, or emissions of ammonia or NO may result in N_2O production at remote sites, which is generally referred to as *indirect* emissions.

We present N_2O emissions from Africa as the sum of national N_2O inventories for 1970 and 2005 as compiled in the Emission Database for Global Atmospheric Research (EDGAR) [27,28]. The EDGAR database follows the 2006 IPCC Guidelines and uses a consistent set of emission factors for N_2O emission estimates from agriculture, energy, transport and industries. On the basis of these calculations, Africa contributed 15.5% to the total global anthropogenic emissions of N_2O in the year 2005 (1500 Gg N_2O). Agriculture contributed an estimated 42% of the African N_2O emissions, though that total rises to 71% if all emissions from grassland and savannah burning is included (Table 1).

Livestock sources

The largest source of agricultural emissions was livestock; combined emissions from paddocks, ranges, and pastures accounted for 74% of all African agricultural

Table 1

Regional N_2O emissions from agriculture soil, indirect agriculture emissions, manure management, pasture/range/paddock, and savannah and grassland burning in Northern Africa and sub-Saharan Africa (Eastern, Western and Southern) for 2005 and global N_2O emissions for the year 1970 and 2005 (EDGAR v.4.1). Regional decreases in Western and Southern Africa are largely due to decreases in savannah burning. Increases in Eastern Africa are primarily due to an increase in emissions from pasture/range/paddock of over 50%.

Region*	Total agric. N_2O (Gg yr^{-1})		N_2O emissions by category in 2005 (Gg yr^{-1})				
	1970	2005	Direct soil	Indirect	Manure management	Pasture/range/paddock	Savannah and grassland burning
Northern	36	81	32	11	1	38	0
Sub-Saharan Africa							
Eastern	211	343	16	16	3	192	115
Western	431	348	19	14	6	120	190
Southern	366	287	28	9	3	97	150
Global estimates	4230	6470	2610	858	324	1900	736

Source: [28].

N_2O emissions, excluding savannah and grassland burning; emissions from on-farm manure management (including handling, storage, and application) accounted for an additional 3% (Table 1).

Emissions from (less intensively managed) livestock holdings in the tropics are generally expected to be lower than those from (intensively managed) holdings in temperate ecosystems [29], and there may be reasons to be wary of the EDGAR estimates. Emissions of N_2O from animal production are mainly determined by manure management system, N excretion rate, animal density, animal type, and the percentage N lost as N_2O (which is independent of region) [29]. The large emissions from pasture compared to manure management is largely due to EDGAR's use of the 2006 IPCC guidelines for allocation of manure to different management systems: 83–100% of manure is assigned to the paddock/range/pasture category in Africa, but only 1–5% is assigned to manure management.

There may be a need to re-evaluate the N excretion rates used by EDGAR. Though the N content of manure in the tropics is commonly reported to be less than 1/3 as much as in temperate agroecosystems [30], the default IPCC factors for estimating N excretion rates in Africa are the highest or second highest in the world for most categories of livestock [18]. For example, the most recent IPCC guidelines estimate that 0.60 kg N day^{-1} is lost per 1000 kg of dairy cattle in Africa but only 0.35–0.48 kg N day^{-1} in Western Europe. Recent studies suggest that N excretion rate estimates are in need of revision: cattle in Sweden excreted N at rates 2–6 times higher than cattle in Kenya or Mali [30]. The 2006 IPCC default rates are also a stark reversal of the 1996 guidelines, in which dairy cattle in Western Europe and North America excreted an estimated 100 kg N $head^{-1}$ yr^{-1} compared to 60 kg N $head^{-1}$ yr^{-1} in Africa, though these may still be too high for Africa [30,31].

Livestock density in TLU km^{-2} tends to be low in Africa, ranging from 0 to 5 in pastoral system in arid/semi-arid regions to 35–55 TLU km^{-2} in temperate/tropical highlands [30]; densities are much higher in other parts of the world (e.g. 2 sheep ha^{-1} [32]). The low densities in Africa would be expected to contribute to relatively low emission rates per unit area (though livestock-related point sources (e.g. corrals) can become the dominant source of N_2O [32], but EDGAR does not address this level of spatial detail). But when calculated on a per unit area basis using FAO land-use classifications, the EDGAR mean emission rates from African pasture (0.16 kg N_2O-N ha^{-1} yr^{-1}) are roughly equal to emissions for North American and European pasture (0.16 and 0.17 kg N_2O-N ha^{-1} yr^{-1}, respectively) [33]. In contrast, observed emissions from intensively managed unfertilized dairy pasture in western countries found emission rates that ranged from 1 to 2 orders of magnitude higher than these averages [34,35], though there are others that range from roughly equal to these averages to 4 times higher [36]. Comparable measurements have not been published for sites in SSA.

On-farm manure management may make a small contribution to African agricultural N_2O emissions for several reasons. Application rates can be quite low because cattle may graze widely, making manure collection challenging compared to more intensive livestock operations, and farmers in some regions rarely use manure as fertilizer [12,30,37]; Liu *et al.* estimate that manure represents 15% of N inputs to crops in Africa [38]. Once collected, substantial N can be lost from manure during storage, leading to lower rates of N application to fields [30,39]. The losses during storage are primarily ammonia; N_2O emissions can be 5–10 times smaller than the ammonia emissions (which can lead to indirect N_2O emission), as observed for dung storage in Niger [40].

Other sources and sinks

Savannah burning and grassland fires represent an additional substantial source of N_2O emissions in Africa, roughly equivalent to emissions from livestock, much of which can be attributed to land preparation (Table 1). Burning of agricultural waste is the smallest source of N_2O from agriculture in Africa, which at 1.54 Gg is an order of magnitude smaller than emissions from manure management.

According to the EDGAR database, direct soil emissions from African agriculture compromise 15% of the total agriculture N_2O emissions excluding burning, and have been increasing linearly, from 42 Gg in 1970 to 95 Gg in 2005, largely from increases in Northern Africa (Table 1). The relatively small direct emissions can be attributed to the extremely low rates of inorganic fertilizer use in most of sub-Saharan Africa [8••]. Liu *et al.* estimate that of the anthropogenic N inputs in African cropland, 60% is from biological N fixation (BNF; 2.9 Tg yr^{-1}) and mineral N fertilizers (2.2 Tg yr^{-1}), 10% from atmospheric deposition, 15% from animal manure and 12% from crop residue [38]. The IPCC Guidelines indicate that N_2O emissions from soybean production are negligible, but there are indications that cultivation of other legumes used for enhancing soil N (e.g. cover crops, tree fallows) may result in higher N_2O emissions than emissions from applications of mineral fertilizers [24,41]. More complete studies are needed with mineral fertilizers and organic inputs on different soil types and different rates to determine the relative roles of mineral and organic fertilizers as well as BNF in N_2O emissions, especially as N inputs begin to increase (e.g. [24,25,42]).

In Africa, most N added to the landscape from any source is estimated to be lost through nitrate leaching [43], making rivers and riparian zones a potentially important indirect source of N_2O emissions [44•]. Most studies indicate that indirect agricultural N_2O emissions may account for about 25% of the global agricultural emissions [40–43,44•,45–47]. The estimate by EDGAR, however, suggests that African indirect N_2O emissions accounted for just 8% of the total African agricultural emissions in 2005.

Some soils can also act as sink of N_2O emissions at times, especially in wet and water logged conditions, though not enough to offset emissions at a regional scale [48,49]. National inventories for African countries and the EDGAR database do not consider soils as N_2O sink because our understanding of the sink strength of African soils is based on very few studies. One study in Mozambique [48] assumed soil uptake rate at 0.0087 kg N ha^{-1} yr^{-1} and indicates that 7–18% of total N_2O emissions could be consumed through soil processes.

A description and quantification of uncertainty in EDGAR 4.0 is currently in preparation, but has not yet been published [28]. Uncertainties in the emission factors for grazing animals and for indirect emissions have been identified to have a large effect on global N_2O emission estimates; for example, the estimated range of N lost from manure as N_2O spans nearly 2 orders of magnitude [49], and IPCC's uncertainties around estimates of N excretion rates are 50% [18]. The dominant role played by livestock in Africa N_2O emissions highlights the importance of reducing these uncertainties for improving continental emission estimates.

Future trends in increasing N inputs to African agriculture

Increasing N inputs to intensify agricultural production and satisfy demands for food in sub-Saharan Africa should result in increased N_2O emissions [7,10]. Here we present some projections of N inputs and the implications for N_2O emissions to 2050 from the Millennium Ecosystem Assessment (MEA) [50,51]. The four MEA scenarios include: Global Orchestration (GO), Order from Strength (OS), Techno-garden (TG) and Adapting Mosaic (AM). They differ with respect to whether globalization is assumed to be the dominant trend (as in GO and TG), or regionalization (as in OS and TG). In globalized worlds, the worldwide economies are more open than in regionalized worlds. Moreover, the scenarios differ in the assumed approach towards ecosystem management, which may be pro-active (as in AM and TG), or reactive (as in GO and OS). The scenarios with a pro-active approach towards ecosystem management either focus on large-scale technical solutions (in the globalized TG world), or more on small-scale, local solutions (in the regionalized AM world). This has consequences for the position of small holders and large-scale producers in agriculture.

In all four scenarios the African population and economies grow [52,53]. In 2000, 796 million people lived in Africa with an average GDP of 745 1995US\$ $person^{-1}$ yr^{-1}. The growth rates differ among scenarios. In GO, for instance, it is assumed that the population in 2050 is 80% larger than in 2000 (1.4 billion) while per capita has GDP tripled (2993 1995US\$ $person^{-1}$ yr^{-1}). In OS, on the other hand, the population increases more quickly (to 2 billion) while per capita GDP doubles (1488 1995US\$ $person^{-1}$ yr^{-1}).

Among other assumptions, the future scenarios assume changes in the human diets towards more meat consumption; in Africa, consumption of meat (animal protein) per capita increases by a factor of 2–3. The scenarios also assume an increase in the share of pork and poultry in total livestock production [52]. As a result of these assumptions, animal production as well as manure excretion increases in Africa. In addition, agricultural changes are envisaged that result in a more efficient use of fertilizers.

The MEA scenarios were quantitatively interpreted for the different continents up to the year 2050 (Table 2) [52]. Balances of N, estimated as the total inputs (fertilizer, manure, human N, N_2 fixation, and N deposition) minus N removed through harvest and grazing, increase

Table 2

N balances for the world and for Africa. Results are shown for 1970 and 2000, and for Millennium Ecosystem Assessment Scenarios for the year 2050: Global Orchestration (GO), Order from Strength (OS), Technogarden (TG) and Adapting Mosaic (AM).

Year	Global N balance (Gg N yr^{-1})	African N balance (Gg N yr^{-1})	African N balance (kg N ha^{-1} yr^{-1})*
1970	101 000	12 700	17
2000	157 000	18 200	18
2050 GO	231 000	42 400	26
2050 OS	211 000	36 800	23
2050 AM	154 000	25 600	20
2050 TG	172 000	37 000	22

Source: [52].

[*] For readers accustomed with other units: 1000 kg N km^{-2} = 10 kg N ha^{-1} yr^{-1}.

globally in all scenarios [52]. For most regions, however, the N balances decrease in the scenarios with a proactive attitude (TG and AM). Africa is an exception to this where there is an increase in all scenarios. These trends in African N balances result from the assumption that land degradation by nutrient depletion is reduced or halted through increased additions of N fertilizers and manures to agricultural land [52]. There are also increases in N balances per hectare of land in Africa, and they are relatively high compared to other world regions. In some parts of North Africa with intensive agriculture, N balances are comparable to those in industrialized countries.

The net effect of these assumed trends is that in Africa, the N inputs to agricultural fields (from inorganic fertilizer and manure) are 1.5–6 times the 2000 level in 2050. The N balances in 2050 are at least twice the 2000 level. This is an important change. Currently, N depletion is a problem in large parts of Africa. According to the MEA scenarios, active nutrient depletion will be less important in the future as a result of increased N inputs. The increasing N inputs also imply that the emissions of N_2O will increase during the 21st century. Assuming a linear relation between N inputs and N_2O emissions (as in most emission inventories), we may argue that N_2O emissions from African agriculture roughly double during the coming four decades, depending on the scenario. Indeed, the Integrated Model to Assess the Global Environment (IMAGE) model projects an increase in land use related N_2O emissions from Africa, increasing from 300 Gg in 1970, to 800 Gg in 2010 and 1200 in 2050 [54].

Considerations in applying different emission estimation approaches in Africa

Limitations of the IPCC Emission Guidelines

Though of great utility, there are important limitations of the IPCC Guidelines for application to N_2O emissions from African agriculture, as we touched on above with respect to livestock. The IPCC Guidelines provide a model for estimating N_2O fluxes based on calculations of mean emission rates: as a default, 1–2% of added N is assumed to be emitted as direct N_2O emissions, and roughly 1% is assumed to be indirect as N_2O emissions from N that has been transported off-farm. Top-down estimates based on changes in atmospheric N_2O suggest that the IPCC Guidelines underestimate actual emissions, and indicate instead that roughly 4% of atmospheric N newly fixed through natural or industrial processes is lost as N_2O [55]. However, evaluation against the atmospheric record suggests that using a constant emission rate does not adequately reflect the complexities of biogenic N_2O fluxes, even for the purpose of global estimates [56].

Recent changes in our understanding of the relationship between N inputs and N_2O emissions at the plot scale further highlight the limitations of applying emission factors widely, particularly to areas where much lower rates of N are applied. Mounting evidence suggests that the rate of soil N_2O emission varies nonlinearly in response to increasing N additions, with a smaller percentage of added N lost as N_2O at lower rates of fertilization and a larger percentage lost at higher rates: experimental and on-farm studies in temperate agro-ecosystems have demonstrated clear thresholds in N_2O emission responses to N inputs, with N_2O emissions increasing more rapidly once N inputs exceed plant demand, typically above 100–135 or 187 kg N ha^{-1} in high-input mechanized agro-ecosystems [17•,57,58]. In crop trials, inorganic fertilizer is typically applied to maximize yields, frequently at rates of 100–150 kg ha^{-1}, much more than the current 8 kg ha^{-1} average, or even the 70–80 kg ha^{-1} rates recommended by many countries in sub-Saharan Africa. If the nonlinear responses observed in temperate agro-ecosystems apply in Africa, one would expect a smaller percentage of added N to be lost as N_2O than is observed in the studies used to develop the IPCC emission factors. Experimental work in Africa has largely not included the multiple levels of N inputs needed to identify a non-linear N_2O response, except in studies where changes in the amount of N applied is confounded with the form of N applied (e.g. [24,59–61]), studies where inputs were applied only at high rates from 120 to 3800 kg N ha^{-1} (thus excluding the entire lower portion of the typical response curve, e.g. [60,61]), and studies where rates of N input were not reported at all (e.g. [42,62]). The one example with measurements of N_2O emissions from multiple levels of a single type of (inorganic) fertilizer included only three levels of fertilizer, limiting insights into the linearity of the fertilizer/emission relationship [25].

Emission rates from cropped soils can also be influenced by how well fertilizer applications are placed and timed to plant demand. IPCC emission factors may be substantially influenced by fertilizer application methods in studies used for the emission factor calculations. Smallholder farmers in sub-Saharan Africa apply fertilizer in a split application (to meet the timing of plant demand), and place the fertilizer strategically: in the seeding hole at planting, and immediately adjacent to each plant at topdressing. These practices are intended to synchronize N availability with plant N demand to increase N use efficiency, and may further reduce the percentage of N applied that is lost as N_2O and in other forms.

An additional consideration in applying IPCC emission factors to Africa is the fact that they were developed based on existing measurements of NO and N_2O emissions, few of which were conducted in tropical ecosystems, and hardly any in Africa. Sub-Saharan Africa is particularly poorly represented, with all the studies used by the IPCC conducted in South Africa and Zimbabwe [45,63], and only one — a study of NO emissions — conducted in an agricultural site [26]. Only one study of N_2O emissions from sub-Saharan Africa was used, from an unfertilized natural savannah [64].

In general, few measurements have been made of N_2O emissions from soils in sub-Saharan agricultural systems, and many of those that have been made provide an incomplete picture of the effects of various types of agricultural management on trace N gas emissions, or the flux response to increasing N inputs. Among studies directly measuring N_2O emissions in sub-Saharan agroecosystems, the majority have examined the effects of leguminous tree fallows on N_2O emissions (e.g., [60]), including several lab studies (e.g. [65]), while others have examined different fertilizer options [25], compared rainfed savannah to irrigated Acacia plantation [66], or examined N_2O fluxes from high-input urban vegetable gardens [58].

Emission factors can be an effective way to compare N_2O losses from agriculture in different regions, but estimating annual emission factors for these studies is challenging, as only three studies in Africa have conducted measurements over the course of an entire year [25,61,62]. Measurements that do not extend beyond the growing season present particular problems in seasonally dry natural systems, where emissions are generally believed to be low during the dry season, and where pulses associated with early wet-season precipitation events can be responsible for a substantial proportion of annual N trace gas fluxes [67]. Emissions of N_2O have approached 60 $\mu g\,N\,m^{-2}\,h^{-1}$ from a dry-season range of -0.2 to 3.4 $\mu g\,N\,m^{-2}\,h^{-1}$ in Malian cereal fields [62], and exceeded 150 $\mu g\,N\,m^{-2}\,h^{-1}$ during early season pulses in a Burkina Faso savannah; if sustained over a 24-hour period, this one-day pulse would represent over 5% of annual N_2O emissions from the savannah [25]. Consequently, studies in which measurements are not frequent enough to capture pulses, in which the frequency and timing of measurements result in mean flux rates that are disproportionately influenced by measurements of pulse emissions, or in which the sampling period excludes the dry season or the beginning of the rainy season are unlikely to accurately describe annual emissions. But assuming that periods measured are representative of emission rates throughout the rest of the year, emission factors are generally at the low-end of the 0.0–7.8% range observed in studies around the world [68], with less than 1% of added N estimated to be emitted as N_2O in many cases (e.g. [24,25,42,59,60]). There are exceptions, however, which include two of the three studies that conducted year-round measurements. In high-input vegetable gardens (473–3816 kg N ha^{-1}), losses ranged from 1.6% to 5.2% of added N annually [61], and in a Pearl millet field in Mali, 4.1% of the N added in a 50 kg urea treatment was lost as N_2O within the first year [62]. In a study on agroforestry in Kenyan maize fields, additions of 115 kg N ha^{-1} and 214.6 kg N ha^{-1} from leguminous fallows resulted in more than 1.49% and 1.82% of the added N being lost as N_2O over 84 days, though higher rates of organic N additions resulted in smaller emission factors of 0.45–0.56% [60].

Other soil factors in Africa may affect emissions. The nitrate retention capacity characteristic of the variable charge clays found in many soils in Africa may reduce N_2O emissions compared to soils without this property: if nitrate is retained in the subsoil rather than leached to groundwater (e.g. [13]), it could be made effectively unavailable for denitrifiers. The long history of nutrient depletion and loss of organic matter of agricultural soils in sub-Saharan may also make for different emission responses to N inputs than in temperate or well-managed systems [62]. There are few studies expressly investigating the effects of depleted soils on gas emissions, but there are several lines of speculation: it is possible that plant and microbial uptake may be more complete in soils where existing nutrient pools are limited; alternatively, it is conceivable that these soils lack the capacity to effectively retain N (e.g. lacking microbial populations that are capable of immobilizing large quantities of N), and may result in greater losses. It is also possible that denitrification in low SOC soils may proceed more completely to N_2 with additions of labile C and N [62], or that soils with low SOC (and lower capacity for water retention) may experience greater nitrate leaching rates. All these factors make predictions or estimations of emissions with currently available data difficult for soils with these characteristics.

Applying statistical and process-based models in the African context

Many of the limitations of the IPCC default values for N_2O emissions also apply to other emission estimation approaches such as statistical and process-based models of global trace N gas emissions. Process-based models have been applied at global scales to estimate N_2O emissions from agriculture, including emissions from Africa. For example, DAYCENT has been used to evaluate N_2O emissions from maize, wheat, and soybean under management practices for reducing greenhouse gas emissions [69], while the Terrestrial Ecosystem Model was used to evaluate the impacts of different scenarios of biofuel use on emissions [19••]. Simple emission factors have also been applied, and speak to the potential for agricultural intensification to prevent the extension of agriculture into natural habitat, resulting in lower net greenhouse gas emissions [70]. Because the value of these models is dependent on the data driving them, the poor availability of many data for Africa presents a serious challenge; for example, the Terrestrial Ecosystem Model simulations of Africa are based on parameterizations from South America (David Kicklighter, personal communication). Ongoing efforts at constructing a high-resolution digital soil map of Africa are an important step forward [71], and would be made even more valuable to modelers if paired with increased access to weather station observations and improved, spatially explicit information on agricultural management practices.

Conclusions

In this paper we reviewed estimates of current and future N_2O emissions from agriculture in Africa. These emissions have been increasing over the past thirty years, and future scenarios project this trend to continue with increasing N inputs to agricultural land. These estimates of N_2O are based on the IPCC guidelines, and though they provide an initial estimate, the current default values and assumptions of the IPCC are unlikely to accurately estimate emissions in Africa. Overall, it is evident that there are important knowledge and data gaps that must be addressed to improve current and future estimates of N_2O emissions, with improvements in estimating the various livestock contributions to emissions being of particular importance for a region where fertilizer use has been historically low. However, improved estimates of direct soil emission from fertilizer use will be increasingly important for estimating continental emissions if sub-Saharan Africa undergoes the change in land-use and land management associated with a burgeoning Green Revolution.

Although formal uncertainties for the EDGAR database are still being prepared, we have identified some basic uncertainties in the African N_2O budget related to a variety of factors: the size and nature of N inputs (which is also dependent on estimates of cropland area, crop management, and livestock populations and densities, each of which is plagued with its own uncertainties), the basic relationship between N inputs and N_2O emissions (particularly with the low rates of N currently applied in the continent), the response of N_2O emissions on N-depleted soils and soils with high potential to retain nitrate on variable charged clays, and perhaps the potential importance of soil sinks. These uncertainties can only be reduced by increasing the number of field measurements in Africa. Efforts such as the African Soil Information Service's Digital Soil Map of Africa project will provide some essential information for modelers, but greater effort at improving the availability of existing data (e.g. weather observations) and filling critical data and knowledge gaps is essential. Given the relatively small number of existing studies for the continent, coordinated efforts among African and international scientists are needed to improve estimates of N_2O emissions from the continent, as well as to improve a more general understanding of N dynamics in Africa. An interdisciplinary hierarchical approach that consists of strategically designed measurements, observations, experiments, and simulations at plot, farm, landscape, watershed, regional, and continental scales can be a powerful approach to understanding the flows and cycling of N from agriculture and livestock in African environments.

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Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

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