Assessing non-CO₂ climate-forcing emissions and mitigation in sub-Saharan Africa

Jonathan E. Hickman^{1,*}, Robert J. Scholes², Todd S. Rosenstock³, Carlos Pérez García-Pando^{4,5}, Justice Nyamangara⁶

¹ Agriculture and Food Security Center, Earth Institute, Columbia University, Palisades, NY USA

² Council for Scientific and Industrial Research, Pretoria, South Africa

³ World Agroforestry Centre, Nairobi, Kenya

⁴ NASA Goddard Institute for Space Studies, New York, USA

⁵ Department of Applied Physics and Applied Math, Columbia University, New York, USA

⁶ International Crops Research Institute for the Semi-Arid Tropics, Matopos Research Station, Bulawayo, Zimbabwe

* To whom correspondence should be addressed: jeh2179@columbia.edu, +1 718 473-9793

Abstract

22 There are few direct measurements of anthropogenic climate-forcing emissions
23 in Africa, making it difficult to accurately assess current emissions and to anticipate
24 changes in future emissions. Emissions databases suggest that sub-Saharan Africa
25 (SSA), home to less than 15% of the world's population, is responsible for 11% of
26 anthropogenic methane (CH₄) and 18% of anthropogenic nitrous oxide (N₂O)
27 emissions globally, though this includes substantial emissions from biomass burning
28 that would occur in the absence of contemporary anthropogenic activity, and which
29 may be over-estimated. SSA is also an important source of precursors to the
30 greenhouse gas tropospheric ozone, and of mineral dust, which has a range of impacts
31 on climate. Eliminating food insecurity and poverty is likely to take priority over
32 greenhouse gas mitigation in the region, so innovations in mitigation must focus on
33 ways to reduce emissions as an ancillary benefit of improving livelihoods.

36 **Introduction**

37 Evaluating current anthropogenic emissions and climate mitigation options in
38 sub-Saharan Africa (SSA) is challenging; certainly Antarctica is the only continent
39 with fewer direct measurements of climate-forcing emissions. Because of this paucity
40 of data, African countries rely on the IPCC Tier I emission factors for developing
41 national greenhouse gas (GHG) inventories. IPCC Tier I methods are a "best guess,"
42 informed by whatever scientific information is available. That best guess may be
43 particularly wanting in SSA, since the defaults are based on measurements conducted
44 primarily in temperate ecosystems, and of those measurements conducted in tropical

ecosystems, almost none are from SSA [1]. The Emissions Database for Global Atmospheric Research (EDGAR) aggregates national estimates of annual emissions of greenhouse and other gases to the atmosphere derived from IPCC emission inventories to create a database of global emissions ([2]; Table 1). Because of its reliance on Tier I methods for Africa, the EDGAR estimates must be interpreted only as a starting point for directing research and implementation efforts into the most important sectors.

The EDGAR inventories point to agriculture and biomass burning as the sources of the overwhelming majority of non-CO₂ trace gas fluxes, and of N₂O and CH₄ in particular (Table 2). EDGAR attributes 18% of global anthropogenic nitrous oxide (N₂O) and 11% of global anthropogenic methane (CH₄) emissions to SSA, with the majority of emissions coming from agriculture and biomass burning (Table 1, 2). The same is true of ammonia (NH₃) and NO_x (nitric oxide [NO] + nitrogen dioxide [NO₂]), both of which can affect the mass, chemistry, and reflectivity of aerosols, which play an important but still uncertain role in climate forcing (Table 2). NO_x is also a precursor to tropospheric ozone, a short-lived GHG, and contributes to the removal of CH₄ from the atmosphere.

Agriculture

With some of the largest non-CO₂ climate-forcing fluxes in SSA coming from agriculture (Table 1), reducing the uncertainties associated with agricultural fluxes and mitigation potentials should be a high priority for GHG research in the region. For example, although livestock are responsible for 80% of agricultural N₂O and 93% of agricultural CH₄ in SSA (Table 2), and there is considerable uncertainty regarding the

effects of livestock on soil emissions of N_2O [3], there have no measurements directly investigating the effects of livestock on emissions in these systems.

Crop production is a minor source of the major non- CO_2 GHGs in SSA, which is unsurprising given the low fertilization rates typical of the continent. Farmers in SSA apply less than $7 \text{ kg nutrients ha}^{-1}$ [4], extending a decades-long history of nutrient mining and soil fertility decline when much of the rest of the world is struggling to manage the effects of excessive nutrient applications [5]. It is hoped that this trend is beginning to reverse with the late arrival of a Green Revolution in SSA. This African Green Revolution, which is already underway and increasing yields across parts of the continent [6,7], would boost productivity (and potentially reduce agricultural expansion) through improved varieties, extension training, and increased nutrient inputs. If successful, the African Green Revolution would include new inputs of reactive N to agricultural ecosystems on the order of 10 Tg N annually (increasing inputs to 75 kg N ha^{-1} on existing cereal land alone represents an increase of 6 Tg N over current input levels [4,8]). This change may represent the largest perturbation to N cycling in SSA in coming decades. While N inputs tend to increase fluxes of N trace gases, they also tend to increase biomass production, can affect soil CH_4 consumption [e.g., 9], and in some cases reduce the conversion of natural land to agriculture [10,11], requiring an integrated analysis of multiple fluxes to and from the land surface to understand the net effect of N cycle changes on climate [e.g., 12,13].

There are roughly 20 published studies of N_2O and NO fluxes from African agriculture, including a number of laboratory incubations (Figure 1; Table 3 provides cumulative flux data for each published measurement). As in other tropical areas, soils

in SSA can be highly weathered and can be variably charged; in addition, many agricultural systems in SSA have been subjected to nutrient mining for decades [14,15]. These factors may make it more difficult to predict how N cycling and emissions of trace N gases will change with large new additions of N. Existing data show that with a few exceptions, N₂O fluxes are considerably lower than would be assumed using the IPCC Tier I 1% emission factor default when fertilization rates are less than 200 kg N ha⁻¹ (Figure 2, Table 3), but the geographic clustering of measurements means that existing data are unlikely to be representative of the continent more broadly (Figure 1). Any overestimation by the IPCC defaults may be even larger than these data suggest, since the proportion of fertilizer N lost as N₂O tends to be lower at low fertilization rates such as those that predominate in SSA [16,17]. Fluxes of N₂O from unfertilized cropland are also lower in these studies than an estimated global mean of ~1 kg N ha⁻¹ [16], with a mean estimated flux of 670 g N ha⁻¹ yr⁻¹ and a median of 450 g N ha⁻¹ yr⁻¹ (Table 3).

Satellite retrievals suggest that soils are a major source of NO_x for the continent, with fluxes estimated to be equivalent to those from biomass burning, though the anthropogenic contribution remains uncertain and is likely small [18]. The single published study of NO responses to fertilizer inputs in SSA suggests that fertilizer-induced NO may become an important source, with emissions increasing by up to an order of magnitude following low (16 kg N ha⁻¹) N inputs relative to unfertilized soils [19]. However, the regional effects of intensification on tropospheric ozone concentrations may be small, though data are extremely limited. EDGAR attributes anthropogenic NO_x emissions almost entirely to combustion. But if annual

N inputs increase by 10 Tg and 2.5% of added N is lost as NO [20], the increase in N inputs would result in a doubling of agricultural NO emissions in SSA, equal to roughly 10% of current emissions from transportation in the region [2].

There are also few published measurements of NH₃ [21,22], and CH₄ fluxes from agriculture [23-27], especially rice [28,29]. Inverse modeling using satellite retrievals attributes the majority of soil CH₄ fluxes in SSA to wetlands and rice production [30].

Biomass burning

Africa is dubbed the ‘fiery continent’, since about half of all fires detected by satellite observations occur in SSA, in the broad region of savannas, dry woodlands and grasslands which lie between the moist tropical forests and the subtropical deserts [31]. Paleoecological and evolutionary evidence suggests that a frequent, low-intensity fire regime is a defining feature of these ecosystems [32], and there is no clear evidence that the fire frequency or area burned has systematically changed over the past century. African ‘wild fires’ constitute an important part of the global pyrogenic emission budget, but although they are generally deliberately ignited by people, they are not ‘anthropogenic’ in the sense of having increased due to human actions since pre-industrial times; there is evidence that burned area fraction *decreases* at human densities above 15/km² [33]. The dominant controls on the burned area are environmental rather than human [33]. Wild fires are generally not net emitters of CO₂, but wild fires are net sources of CH₄, N₂O, and NO_x since the C and N is recycled in a different form (for instance as wet-and-dry deposited nitrate). African

grassland and forest fires generate relatively little N₂O because the N content of the dry grass and wood is very low.

Three other sources of pyrogenic emissions *have* clearly changed due to human agency in SSA (see Table 4 for their relative importance): those from use of wood and charcoal as fuel, those from land use changes (largely deforestation), and those from burning agricultural residues. In general, crop residues are too valuable in SSA to be widely burned. Wildfires and residue burning have similar low emission factors, since they represent unconfined, oxygen-rich fires, whereas fuel burning and land use emissions generate higher emissions, especially of partial-combustion products, per unit of mass burned.

There remains controversy over the amount of biomass actually burned in SSA. There is a risk of double counting between categories of burning: for instance demand for domestic fuel drives much of the land clearing in the region, thus emissions should not be counted in both categories. To a satellite-borne thermal sensor, agricultural residue burning, land clearing and wild fires are hard to distinguish from one another. The data in global databases populated by inventory data (such as FAOSTAT and EDGAR) tends to suggest much larger amounts of biomass burned than that compiled from in situ studies [34], while dedicated fire emissions databases (such as GFED), which are largely informed by models, lie somewhere in between. Table 4 presents a new set of estimates for emissions of N₂O and NO_x from different categories of biomass burning based on a recent review of emissions [34] and recent reviews of emission factors [35]; estimates from GFED and EDGAR are also presented for comparison.

Dust

Africa could also be called the “dusty continent”—roughly half of global mineral dust aerosol emissions come from the Sahel, Sahara, and North Africa [36]. There are important interactions between dust aerosols and species of reactive N that affect climate, and which are directly affected by human alteration of the N cycle. Satellite retrievals show that anthropogenic dust sources (i.e. dust sources attributed to agricultural areas) are coincident with high levels of NH_3 [37]. Therefore, increases in livestock holdings and fertilizer use in the Sahel can be expected to increase NH_3 emissions and mixing with dust. NH_3 is a precursor to heterogeneous chemical reactions associated with the uptake of nitrate aerosols and ammonium salts onto the surface of dust particles. Increases in the mass of NH_3 associated with large dust particles increases the reflectivity of these particles [37], and these NH_3 coatings can make dust particles more efficient nuclei for the growth of cloud droplets. In addition, agricultural soils tend to be more weathered and enriched in clays and iron oxides relative to natural dust sources. Iron oxides have large absorption potential at visible and UV wavelengths [38], and the acidity of nitrate coatings on dust particles favors the conversion of iron into soluble forms that can drive plankton growth in high-nutrient low-chlorophyll (i.e., low iron) ocean regions, leading to the removal of carbon dioxide from the atmosphere [39]. Human activity is believed to make an important—but highly uncertain—contribution to the doubling of dust deposition during the 20th century [40]. Up to 50 % of dust emissions from the Sahel and northern

Africa have been attributed to anthropogenic soil degradation, with a more recent and refined method estimating a figure around 10 % [41-44].

Innovations for mitigation

Reducing food insecurity and poverty must take priority over climate change mitigation in African agriculture. Within this context, any consideration of mitigation in SSA should focus on the practical potential rather than the more theoretical technical potential, and it is critical to consider barriers to adoption of any new technology, which may take any number of forms (e.g., cultural, socio-economic, political, or environmental constraints [45,46]). Consequently, the best-fit mitigation options for SSA may not be those with the largest technical potential. The application of compound metrics that internalize food-environment trade-offs (such as emissions intensity) could be helpful in guiding pro-poor development pathways in SSA [47,48]. Here we discuss three examples of mitigation measures that present important opportunities for SSA and may require innovations in terms of technology, social institutions, and/or incentives to capitalize on their mitigation potential and improve livelihoods: decreasing food losses, improving diets of livestock, and avoiding rangeland degradation.

The significance of food losses for climate change mitigation is categorically different in SSA than in the developed world. In the developed world, post-consumer food waste is the major source of food loss (95-115 kg per capita); approximately 40% of food losses take place at the consumer and retail levels [49]. In contrast, food waste at the end of the supply chain only represents 6-11 kg food per person per year in SSA,

205 where poor harvesting and postharvest techniques result in large, avoidable losses
206 prior to the consumption stage [49]. These losses can be stemmed using existing low-
207 cost technologies, many of which have been adopted widely in other parts of the
208 developing world, but which have poor penetration in SSA [50,51]. Assuming the
209 relationship between losses and mitigation is proportional, a nominal pre-consumer
210 decrease in food losses to 25 percent would represent a 10% reduction in emissions.
211 No other activities may offer such cross-commodity opportunities to improve
212 livelihoods and reduce emissions immediately, and at scale.

213 Livestock may represent another potential leverage point for reducing
214 emissions intensities while increasing productivity: livestock are responsible for the
215 largest fraction of anthropogenic non-CO₂ emissions in SSA (Table 2), but
216 productivity of livestock in SSA is often less than 20% of that in developed countries,
217 contributing to a high GHG intensity for the milk and meat produced [52]. Managing
218 feeds - including intensifying diets with high protein fodder species and digestible
219 energy, introducing dietary supplements, or improving pasture species composition—
220 may be the intervention with the greatest potential to increase productivity and reduce
221 the GHG intensity of the livestock sector in SSA [53,54]. Thornton and Herrero [54]
222 estimate that improved feeding can reduce the CH₄ intensity of milk and meat
223 production by 14 to 18% depending on the animal and feeding strategy (e.g., stover
224 digestibility, grain supplementation, or leguminous shrubs). Though technically
225 promising, the capacity of farmers to improve livestock diets is limited by forage
226 availability and by labor, land, and cultural barriers to cultivating improved fodder
227 [55]. In addition, increasing fodder production runs the risk of putting the food needs

of production livestock into direct competition with the food needs of people. For example, to increase grain supplements from 0.5 (current practice) to 2.0 kg head⁻¹ day⁻¹, would require an additional 0.5 Mg grain head⁻¹ y⁻¹ [54], a nontrivial amount within the context of small land-holdings and average grain yields in the mixed crop-livestock systems of SSA (~1 Mg maize grain ha⁻¹ y⁻¹ [4]). Besides the marginal increases in performance per cow, much of the improved feeding argument hinges on the assumption that increased productivity allows farmers to reduce herd size (which would be aided by increased reproductive efficiency, shifting herd composition in favor of cows and calves, reduced pre-maturity mortality, and slaughtering beef cattle soon after maturation), and hence make dramatic reductions in CH₄ emissions. However, there is little evidence that this would actually occur in SSA, where livestock serve multiple household, social, and cultural purposes [56]. Only to the extent that innovative approaches can be found that align socioeconomic benefits and cultural norms with improved feed technologies will the mitigation potential of improved feeding be achieved.

An often-cited mitigation opportunity for SSA is restoration of degraded rangelands [e.g., 54, 57]; overgrazed grassland currently represents roughly 10% of grasslands in SSA [57]. A number of techniques, including introducing legumes or improved grass species, fertilization, or more controlled grazing, can be used to better manage and revitalize grazing lands, improving N cycling and C storage [57].

Optimistic estimates suggest that C sequestration in SSA may translate to as much as 96.7 Mt CO_{2eq} across 136,448 km² of degraded rangeland [54]. However, degraded lands represent a relatively small share of grasslands, and several studies in Brazil

found that degradation of grazing land does not always result in a decline in soil C [58]. Restoration often requires significant upfront effort and opportunity costs, may require institutional changes to achieve, takes decades to achieve potential [59,60], faces issues of permanence [61], and soil C levels will eventually saturate [62]. An alternative approach would be to shift focus from hotspots of degradation to incrementally improving management and preserving soil C stock across all grasslands in SSA. Improved management has the potential to increase soil C by roughly 15 to 20% in weathered tropical soils over natural vegetation [58, 63], in addition to any potentially beneficial effects of managed grazing on N₂O emissions [3]. Such an approach may, on aggregate, have a greater cumulative benefit on climate services with the added benefit of maintaining productive ecosystems.

One of the largest mitigation opportunities relates to the likely many-fold increase in land use-related emissions from Africa in the coming three decades. Programs such as REDD aim to reduce forest conversion, but the insatiable demand for agricultural land in Africa, by Africans and the global market, will limit the degree of protection that can be achieved. The key practical intervention is to channel the land-clearing biomass into less greenhouse-gas generative forms than burning on site or inefficiently converting it to charcoal. Using a greater fraction for long-lived timber products, upgrading the traditional charcoal-making processes to modern charcoal kilns (several times more efficient [62]), or converting clearing residues to biochar [63] could likely halve the per-hectare emissions, which under scenarios of accelerating landuse change, could add up to close to 1 PgCO_{2eq}/y mitigation potential. The demand for charcoal will decline only after clean, affordable energy is available in

African urban areas. It is likely both impossible and undesirable to eliminate wildfires in savannas and grasslands, but it may be possible to alter their emission characteristics marginally by changing the season and intensity of burning, as has been suggested in Australian savannas [64]. Fire emissions from burning agricultural residues are small in Africa; generally they could be nearly eliminated with little consequence.

We have estimated mitigation potentials for a range of additional agricultural activities in SSA based on estimates from a number of different studies (see SI for an explanation of the underpinning logic and underlying studies). Unsurprisingly, there are large differences in the estimated technical potentials and economic potentials at \$20 t⁻¹ CO₂. These estimates are highly uncertain, and include considerable expert guesswork and estimation; they should be viewed only as a coarse guide to the relative contribution of different mitigation activities in the region. Changes in management of cropland could have a technical mitigation potential of 0.321 Gt CO_{2eq} y⁻¹ and an economic potential of 0.092 Gt CO_{2eq} y⁻¹ (technical potentials of 0.01, 0.158, and 0.153 Gt CO_{2eq} y⁻¹ and economic potentials of 0.005, 0.082, and 0.005 for N management, residue and tillage management, and rice management, respectively). Technical and economic potentials for livestock are 0.037 and 0.017 Gt CO_{2eq} y⁻¹; for manure management, the estimates are 0.024 and 0.001 Gt CO_{2eq} y⁻¹. In other areas of restoration, they are 0.078 and 0.02 Gt CO_{2eq} y⁻¹ respectively for restoring degraded croplands and 0.014 and 0.003 Gt CO_{2eq} y⁻¹ for restoring organic soils. Guiding land use change may provide large opportunities for mitigation: land sparing resulting from agricultural intensification may mitigate 0.96 Gt CO_{2eq} y⁻¹ (both technical and

economic), while agroforestry could add another 0.66 Gt CO_{2eq} y⁻¹ (technical) or 0.1 Gt CO_{2eq} y⁻¹ (economic). Bioenergy also has potential in the region, largely through the production of biochar (0.324 Gt CO_{2eq} y⁻¹ technical and 0.081 Gt CO_{2eq} y⁻¹ economic) and fossil fuel substitution (2.3 and 0.078 Gt CO_{2eq} y⁻¹), with some potential benefits to soil C sequestration from bioenergy crop production (0.036 Gt CO_{2eq} y⁻¹ and 0.009 Gt CO_{2eq} y⁻¹). Cumulatively, these activities would represent an estimated technical potential of roughly 4.8 Gt CO_{2eq} y⁻¹ and an economic potential of roughly 1.4 Gt CO_{2eq} y⁻¹.

Conclusion

Emissions of non-CO₂ GHG's in SSA remain relatively poorly constrained; additional measurements are needed for improved estimates of emissions from livestock, biomass burning, and other sectors. Our new estimates of N₂O and NO emissions from biomass burning suggest that existing databases may overestimate the area burned, and underestimate fluxes from certain types of burning. Existing data on N₂O emissions from croplands in SSA suggest that emissions may remain low with fertilization rates of below 100 or 150 kg N ha⁻¹, though this may not be true for all agroecological zones or soil types, and may change as soil N stocks increase. Changes in agriculture and food management probably have the potential to mitigate between 5 and 6 Gt CO_{2eq} y⁻¹, but economic, social, and cultural constraints will severely limit the practical amount of mitigation possible. Efforts at mitigating emissions should focus on opportunities such as reducing food waste that can make a direct contribution to alleviating poverty and food insecurity in the region.

320

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Table 1. Emissions of non-CO2 greenhouse and other gases from the EDGAR 4.2 database (<http://edgar.jrc.ec.europa.eu/>).

	CH ₄ (Tg CO ₂ eq)	N ₂ O (Tg CO ₂ eq)		N ₂ O-N (Tg)	NO _x -N (Tg)	NH ₃ -N (Tg)
Global	7644	3317		6.51	37.2	40.5

Africa	998	649		1.27	5.17	6.78
SSA	862	604		1.19	4.78	6.26
SSA excluding South Africa	795	580		1.14	4.35	6.03

Table 2. Trace gas emissions from for different source categories as a percentage of total emissions for each gas from sub-Saharan Africa (EDGAR v4.2; <http://edgar.jrc.ec.europa.eu/>)

	Agriculture, including livestock (%)	Livestock (%)	Burning (%)	Waste (%)	Manufacturing, chemical, and metal production (%)	Fugitive emissions from fuels (%)	Transportation (%)	Public & other energy industry, residential sector (%)	Non-agricultural indirect N ₂ O emissions (%)
N ₂ O	27.99	22.48	56.53	1.42	4.48	0.19	0.23	1.91	7.27
CH ₄	31.97	29.73	36.47	11.01	0.11	14.85	0.05	5.51	N/A
NO _x	1.44	0.07	79.83	0.00	1.75	0.23	6.89	9.86	N/A
NH ₃	27.78	3.67	66.62	0.00	0.08	5.30	0.06	0.16	N/A

Table 4. Nitrogenous emissions from biomass burning in sub-Saharan Africa from three data sources. ‘This study’ combines a recent review of the quantity of biomass burned (Scholes et al 2011) with recent reviews of emission factors. The Global Fire Emissions Database combines satellite-based fire mapping, with modeled fuel loads and a database of emission factors. EDGAR is an emissions database largely oriented towards industrial and agricultural emissions, but which has some biomass components represented.

	This study			GFED			EDGAR		
	Biomass Tg/y	N-NO _x ^b Gg/y	N-N ₂ O ^c Gg/y	Biomass ^l Tg /y	N-NO _x Gg/y	N-N ₂ O Gg/y	Biomass ^l Tg/y	N-NO _x	N-N ₂ O
Wild fires	800	1456 ^b	193 ^c	2236^k	1340 ^k	133 ^k	4900	3220	272
Fuelwood	500	241 ^d	96 ^e	N/A	N/A	N/A	N/A	N/A	N/A
Land use change	46	55 ^f	11 ^g	183^l	106 ^l	13 ^l	1388^m	547 ⁿ	44 ⁿ
Agricultural residues	50	73 ^h	12 ⁱ	31	20	1	24	25	0.5
All sources	1396	1824	312	2450	1467	144	6312	3790	317

Notes

- From Scholes et al 2011. Only the ‘best estimate’ is tabulated, for consistency with the other sources. The ranges are 716-881, 435-565, 18-74 and 35-75 Tg/y for wildfires, fuel use, land change and residues respectively
- Assuming mean emission factor (EF) for savanna wildfires of 1.82 g N-NO /kg DM (Akagi et al 2011, converted to represent N fraction only)
- Assuming EF factor of 0.24 g N-N₂O/kg DM for savanna wildfires (Akagi et al 2011 estimate for extra-tropical forests, expressed as N only)

- d. Assuming half is burned as wood ($EF = 0.66 \text{ g N-NO/kg DM}$) and the rest is first converted to charcoal ($EF = 0.22 \text{ g N-NO /kg DM}$) with a 30% mass yield (Pennisse et al 2001), and the charcoal is then burned with $EF=0.66 \text{ g N-NO /kg DM}$ (all EFs from Akagi et al 2011)
- e. Assuming half is burned as wood ($EF = 0.312 \text{ g N-N}_2\text{O/kg DM}$, Bertschi et al 2011) and the rest is first converted to charcoal ($EF = 0.025 \text{ g N-N}_2\text{O /kg DM}$) with a 30% mass yield, and the charcoal is then burned with $EF=0.153 \text{ g N-N}_2\text{O /kg DM}$. The latter two EFs are guesses, based on the general observation that emissions as N_2O (whole gas basis) are about a fifth of emissions as NO
- f. Forest estimate $EF = 1.19 \text{ g N-NO/kg DM}$ (Akagi et al 2011 in N-only terms)
- g. Forest estimate $EF = 0.242 \text{ g N-N}_2\text{O /kg DM}$ (Akagi et al 2011, in N-only terms)
- h. $EF = 1.45 \text{ g N-NO/kg DM}$ (Akagi et al 2011 in N-only terms)
- i. $EF = 0.242 \text{ g N-N}_2\text{O /kg DM}$ (Akagi et al 2011, in N-only terms)
- j. Fuel biomass reverse calculated from the C emissions as CO_2 , CH_4 and CO , divided by 0.42 (the C content of biomass fuels)
- k. C or N lost from grassland, open savanna, woodland, and non-deforestation & degradation forest fires
- l. C or N lost from deforestation & degradation fires
- m. C lost from all forest fires and peat degradation (includes emissions from non-deforestation forest fires)
- n. N lost from all forest fires (includes emissions from non-deforestation forest fires)

Figure 1. Map of published measurements of trace gas emissions from agriculture in Sub-Saharan Africa. Included are field measurements of N_2O (grey triangles), NO (black asterisk), and CH_4 (grey squares) as well as laboratory measurements of N_2O (grey circles) and NO (black cross).

Figure 2. Estimates of emission factors from published field measurements of direct N_2O and NO emissions from agricultural systems in sub-Saharan Africa. For studies lacking a control, background emissions were assumed to be $500 \text{ g N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$. For studies that were conducted for a full year or which reported annual emission factors, N_2O is represented as a black circle. For studies that were conducted for less than a year, minimum (grey triangle) and maximum (grey plus symbol) emission factors were estimated for N_2O . “Minimum” emission factors assume that all emissions from N inputs occurred during the measurement period. “Maximum” emission factors assume that emissions from N inputs during the measurement period were representative of emissions for the entire year. Maximum (open diamond) and minimum (asterisk) NO emission factors were also calculated. The true emission factors may be likely to be closer to the minimum estimates, as studies conducted for less than one year were conducted during the rainy season and during the period following fertilizer applications, when emissions may be expected to be highest; dry season emissions are

607 generally expected to be extremely low. The horizontal line represents the IPCC Tier 1
608 default emission factor for N₂O of 1%.
609
610

Figure 1

Figure 2