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Can 4R Practices Limit the Nitrous Oxide Emissions from Increasing Fertilizer Use in Sub-Sahara Africa?

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Abstract

Increasing fertilizer use is required for meeting future food demands for the growing population in sub-Saharan Africa (SSA). However, increased fertilizer nitrogen use can raise N_2O emissions. 4R Nutrient Stewardship promotes Best Management Practices (BMPs) that optimize fertilizer use and minimize N_2O emissions while increasing yields.

We conducted a scenarios analysis on the potential effects of increased adoption of 4R Nutrient Stewardship BMPs customized to control on-farm N_2O emissions in SSA by 2030 and 2050. Data on projected greenhouse gas (GHG) emissions from the application of synthetic fertilizer for 2030 and 2050 were downloaded from the Food and Agriculture Organization of the United Nations (FAO) FAOSTAT database. Potential emission reductions were calculated by country using three different 4R practice adoption rates for each timeline (10, 20 and 30% for 2030; and 30, 40 and 50% for 2050 based on arable cropping areas) and five different emission reduction rates representing increased specificity and efficacy of 4R practice adoption (5, 10, 15, 20 and 25%).

Our results revealed that large amounts of N_2O emissions could be avoided with increased adoption of the 4R Framework. Annual N_2O emission reductions of up to 1,229 and 3,418 kt CO_2e by 2030 and 2050, respectively, could be achieved in SSA with 30% and 50% adoption rates of 4R Nutrient Stewardship at a 25% emission reduction rate. These correspond to overall emission reductions of 7.5% by 2030 and 12.5% by 2050 from total FAO annual N_2O emission projections for SSA of 16,392 ktCO_2e and 27,345 ktCO_2e, respectively.

The adoption of 4R Nutrient Stewardship practices has material climate change mitigation potential through reduced N_2O emissions and will help SSA to sustainably intensify food production and improve soil health in the region.

Keywords: 4R, nitrous oxide, best management practices, climate smart, sub-Saharan Africa

1. Introduction

The need to sustainably increase food production to meet the needs of a rapidly increasing population is a major challenge in sub-Saharan Africa (SSA). Although agriculture is the lifeblood of most economies in this region – contributing 32% to GDP and 65% to employment (Chauvin et al., 2012) – sustainable food production is a critical issue in SSA where the population is expected to double by 2050 (Hall et al., 2017).

Food production in SSA does not meet current demands since more than one-third of the people in the world affected by hunger in 2020 are found in Africa and one in five people in SSA, totaling to a population of 282 million, is undernourished with respect to basic caloric needs (FAO et al., 2021). This is mostly due to large yield gaps between attainable yields and current yields obtained by smallholder farmers across SSA, owing to diverse production constraints (Van Ittersum et al., 2016; Njoroge et al., 2017). Crop production constraints in SSA include low inherent soil fertility (Smaling et al., 2015), soil erosion (Lal, 1995; Pimentel and Burgess, 2013), and recurring droughts and flooding (Shi and Tao, 2014). These edaphic and climatic constraints are compounded by inappropriate management practices such as low applications of fertilizer or organic nutrient inputs, sub-optimal agronomic practices, and ineffective policies including general neglect of agriculture relative to industrialization (Breman et al., 2019). These constraints are further exacerbated by increased pressure on lands resulting from population growth, leading to reduced landholdings (Jayne et al., 2003; Chamberlin et al., 2014; Jayne et al., 2018).

Soil nutrient mining is pervasive in SSA, resulting from the non-application or application of low quantities of fertilizer nutrients that are not sufficient to offset nutrient removal by crops (Smaling et al., 2015). The average rate of fertilizer-nutrient applications to croplands in SSA, excluding South Africa, is approximately 20 kg ha^{-1} year^{-1}, with high variability among and within countries (Vanlauwe and Dobermann, 2020). This is less than one tenth of the world average. Greater amounts of nutrients are being taken up by crops and removed with harvested products than are applied to fields, causing soil nutrient depletion, land degradation and low agricultural productivity (IFA 2014). Negative soil nitrogen, phosphorus and potassium balances of -22, -2.5 and -15 kg ha^{-1}yr^{-1}, respectively, were found on average for African soils by Smaling et al. (2015). This means that on average African soils needed a minimum of 22 kg N, 2.5 kg P and 15 kg K per hectare per year to compensate for nutrient removals. This is far larger than the average fertilizer-nutrient application of 20 kg ha^{-1}. During the Abuja Fertilizer Summit in 2006, SSA countries committed to increase fertilizer use from the then average of 8 kg ha^{-1} to an average

of at least 50 kg ha^{-1} by 2015. Kenya, Mali, Zambia, and South-Africa achieved this target by 2017 (Vanlauwe and Dobermann, 2020). Ethiopia, Malawi, Botswana, and Zimbabwe have increased average fertilizer use levels to between 30 and 50 kg ha^{-1} year[1]. Nevertheless, fertilizer use intensity remains low and inadequate, and is the main factor contributing to high rates of nutrient and soil organic matter depletion, large yield gaps, and low nutrient contents of harvested products described by Lal (2004) continuing into the 21st Century. Compared to other regions of the world, SSA's apparent nitrogen use efficiency (NUE) trends over 100%, significantly higher than NUE in USA, China, India, and other countries with more intensive cropping systems (Figure 1). This high apparent NUE indicates significant mining of soil N sources, particularly the mineralization of soil organic matter resulting in soil degradation.

**Figure 1. Typical evolution of NUE over time. SSA is trending in the mining phase for NUE (IFA, 2020)**
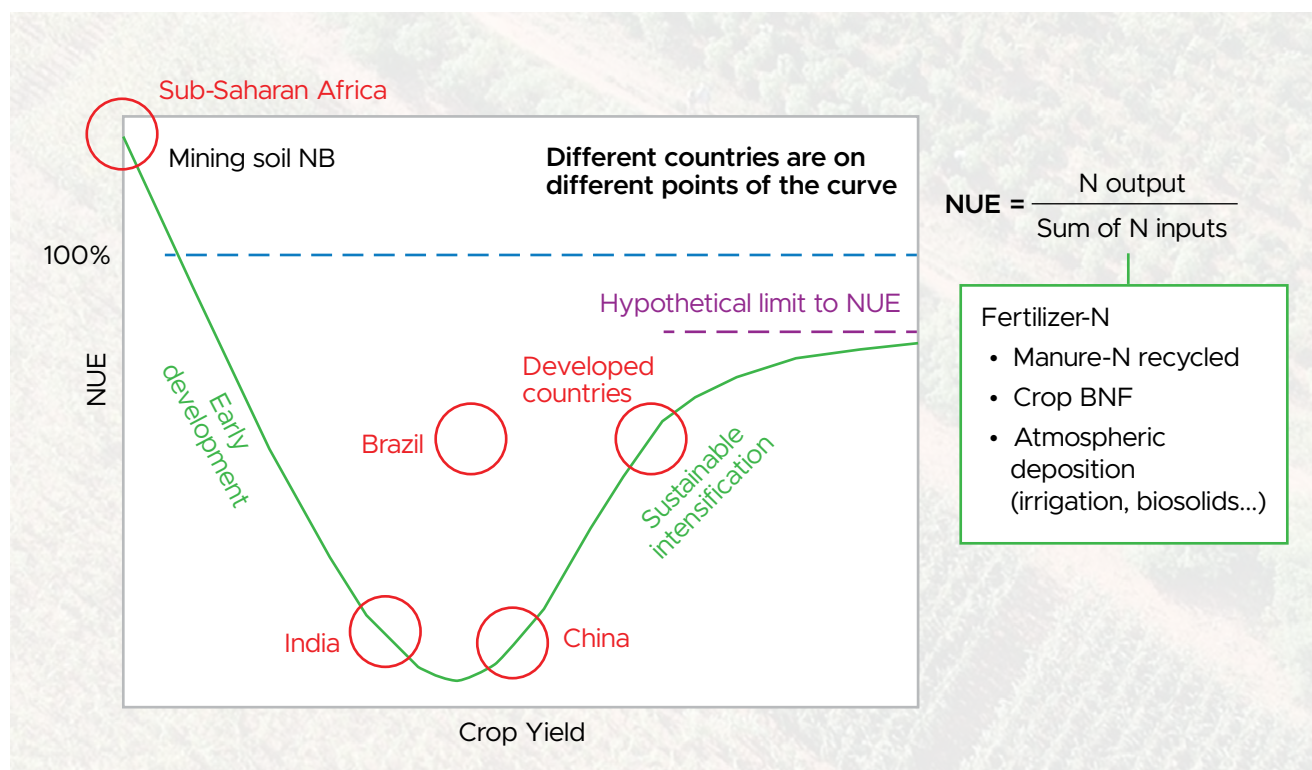
Moreover, since site-specific fertilizer recommendations are generally not available even for major crops, fertilizer applications in SSA are characterized by blanket recommendations that do not take into consideration spatial and temporal diversity of soil fertility at various scales, weather, cultivar differences, economics, and management practices (Breman et al., 2019). The use of blanket fertilizer rates is inappropriate given the highly heterogenous nature of African farming systems (Giller et al., 2011). Applying insufficient

rates of fertilizer causes soil nutrient mining (Smaling et al., 2015), while applying a fertilizer nutrient where the given nutrient is not limiting crop growth is a waste of resources and can increase nutrient losses to the environment (Wang et al., 2019). At present, soil mining and the accompanying loss of soil fertility is the more pressing challenge in SSA, given the prevalence of low fertilizer-nutrient use, which is embedded within a system of poor management practices such as minimal use of improved cultivars, inappropriate planting densities, and ineffective weed and pest control.

While there is a strong argument for increasing fertilizer use particularly nitrogen fertilizers in SSA, higher nutrient application rates without improved management practices may cause environmental problems including greenhouse gas (GHG) emissions (Hickman et al., 2015). Application of nitrogen fertilizers results in direct and indirect emissions of nitrous oxide (N_2O) (De Klein et al., 2006) that contributes to stratospheric ozone depletion and climate change (Ravishankara et al., 2009; Tian et al., 2020). Nitrous oxide is a potent GHG with a long average lifetime estimated at 116 ± 9 years in the atmosphere (Prather et al., 2015), and a 100-year global warming potential that is 298 times higher than for a molecule of CO_2 (Myhre et al., 2013).

The production of N_2O following application of nitrogen fertilizers occurs naturally during nitrification (Blackmer et al., 1980) and denitrification processes (Knowles, 1982) as illustrated in Figure 2.

Figure 2. Microbial processes in the soil giving rise to N_2O emissions (Brentrup and Pallière, 2008)
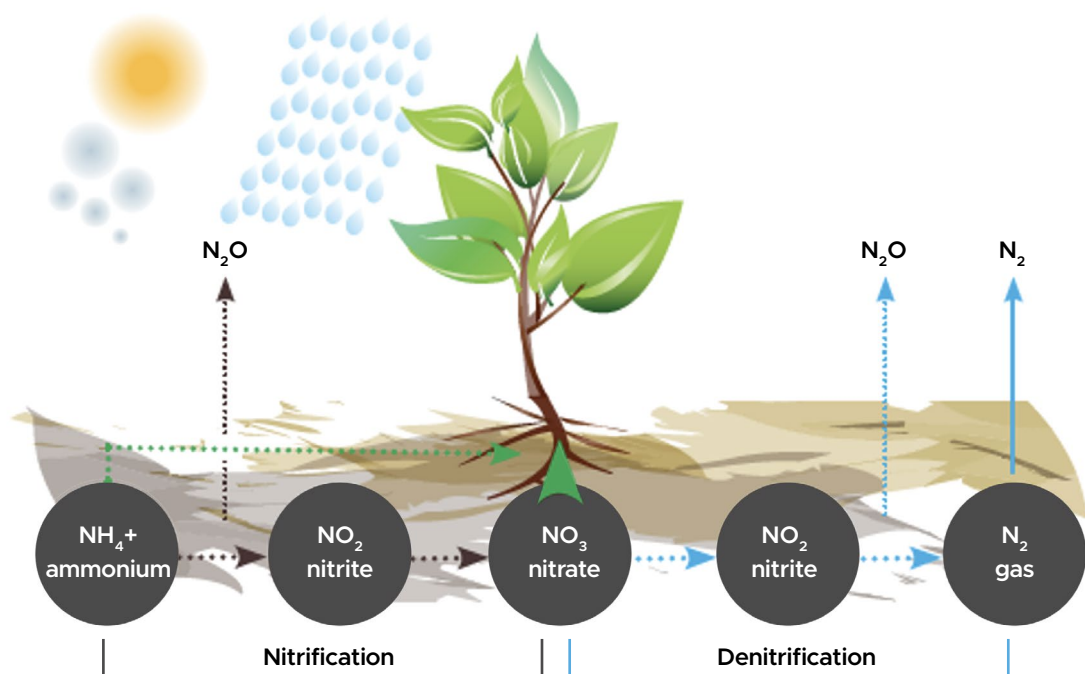
Annual global human-induced emissions of nitrous oxide have increased by 30% over the past four decades to 7.3 (4.2–11.4) teragrams of nitrogen per year, driven in large part by N additions to crop lands (Tian et al., 2020). Current contribution of SSA agriculture to global anthropogenic N_2O emissions is estimated to be less than 5% (Hickman et al., 2011). Part of this anthropogenic N_2O emission, estimated at 10%, comes from fertilizer use (Hickman et al., 2015). The Intergovernmental Panel on Climate Change (IPCC) default Tier 1 emission factor for direct N_2O loss is equivalent to 1% of the applied nitrogen fertilizer (De Klein et al., 2006). However, the mean emission factor for SSA, derived from 70 site-years of measurements, is only 0.2% (CCAFS SAMPLES website - https://samples.ccafs. cgiar.org/n2o-dashboard/). Hickman et al. (2015) observed exponential emission increases in response to increasing fertilizer N additions to maize in Kenya but found that emission factors even at fairly high N rates were well below the IPCC default of 1%. They concluded that cropping systems in Western Kenya could be managed for higher yield without large increases in N_2O emissions, if N rates were kept below 100 kg N ha^{-1}.

Sustainably intensifying SSA crop production through increased fertilizer nutrient application requires a balanced approach. The 4R Nutrient Stewardship framework aims to achieve economic, social, and environmental sustainability by matching nutrient supply with crop requirements to maximize crop uptake and minimize nutrient loss, including losses of N_2O (IPNI, 2016; Bruulsema et al., 2019; Fixen, 2020). The 4Rs – the right fertilizer source applied at the right rate, at the right time and in the right place – uses an integrated and locally adapted set of best management practices (BMPs) to optimize the efficiency of fertilizer use. Determination of 4R BMPs is site-specific and takes into consideration many cropping system factors, such as the state and type of soil, topography, inherent limitations in crop fields as well as practical limitations arising from source availability and access to application equipment. For maximum benefits, 4R Nutrient Stewardship should be supported by other good agronomic management practices including the choice of crop and cultivars, pest management, land preparation, etc.

Recent research showed the positive agronomic and economic benefits of timely application of the right source of fertilizer, at the right rate at the right place through site-specific fertilizer recommendations compared to blanket fertilizer recommendation in SSA. These benefits included increased crop yields and incomes for various commodities including cereals and root crops (Ezui et al., 2016; Rurinda et al., 2020). The positive effect of 4Rs on reducing N_2O emissions through in-field practice improvements has been reviewed by Snyder et al. (2014), who identified the use of enhanced efficiency nitrogen sources, variable rate approaches, and moving application timing closer to the period of

high crop demand among others as mitigating practices. Robertson and Vitousek (2009) suggested that asynchronous timing of N application with crop demand (time and rate) was likely the greatest contributor to N_2O emission from fertilizer. Asynchronous timing and rate of fertilizer application also explained yield losses in SSA, against which fertilizer rate splitting and application of micro doses targeted per plant at specific crop growth stages were recommended (Hayashi et al., 2008; Djaman et al., 2018).

Urea, prepackaged NPK blends, and sometimes DAP (diammonium phosphate) are the common sources of (nitrogen-based) fertilizers found on the markets in SSA. Limited sources make it more difficult for farmers to adapt nutrient rates and ratios to the specific requirements of their cropping systems. Rate recommendations are often pan territorial or regional, and growers have little access to technologies such as soil testing to help determine appropriate field specific rates. Moreover, farmers' capacity to invest in fertilizer depends on their resource endowment or financial considerations. While better resource endowed farmers may have the capacity to invest sufficiently following existing recommendations, lower resource endowed farmers are limited in the quantity they can purchase, resulting in significantly suboptimal rates. They also tend to opt for only a given type of fertilizer, resulting in poor nutrient balance. The result is low productivity for subsistence or near subsistence growers, and lost opportunities to grow and profit from production surplus to their needs. Poor placement of fertilizer is also at the origin of nutrient losses and reduced yield response in SSA. Inappropriate applications at the surface without incorporation is a common practice, exposing the fertilizer to nitrogen volatilization and runoff losses.

Enhanced-efficiency nitrogen fertilizers (EENF: controlled-release, slow-release, nitrification inhibitors, and urease inhibitors) have been shown to reduce nitrogen losses to the environment including N_2O emissions (Akiyama et al., 2010; Halvorson et al., 2014; Ruser and Schulz, 2015; Gilsanz et al., 2016). These findings, summarized from meta-analyses of large numbers of published measurements globally, are generalizable and likely applicable to cropping systems in SSA. Although EENF sources are more expensive per unit of N, given the generally low rates of N currently used and likelihood of volatilization and runoff losses in SSA, the improved nitrogen use efficiency and reduced losses provide opportunities to increase yields per unit of N. Broader access and policy that encourages EENF will be required to increase their adoption and generate both economic and environmental benefits.

The 4R Nutrient Stewardship framework can be adapted to control N_2O emissions over a wide range of farming conditions, from small scale, low-tech farming in Africa to sophisticated digital Ag technologies at large scales in developed nations. From an implementation perspective in SSA, establishing guidelines for changing current sub-optimal practices to locally specific and relevant BMPs based on local agronomic advice is a critical need. With local extension advice, the system can be flexible in applying the most current and best-fit systems for local soils, climate, cropping systems and capabilities of farmers in targeted geographies. For example, the Canadian Co-operative Association and Fertilizer Canada, with support from the Canadian government, are working in partnership with governments, agricultural input companies, research institutions, developmental organisations, and small farmer co-operatives to introduce the 4R Nutrient Stewardship Approach in three African countries (Ethiopia, Ghana and Senegal) through the 4R Nutrient Stewardship Project. Working together, researchers, smallholder farmers and agricultural extension workers are developing locally adapted tools and practices to help implement the 4Rs, and farmers will benefit from increased crop productivity while responsibly managing GHG emissions. Benefits from increased yields and access to markets through co-operatives will sustainably increase their business, production, and handling capacity. Consolidating these gains will accrue benefits to farmers of all genders within the target geographies. In parallel, government and research institutions will engage in research and outreach programs to increase recognition of the benefits of using 4Rs resulting in broader adoption across SSA and integrating Africa into the global 4R network of sustainable crop production.

Eligible best management practices within any geography are those that have been shown through empirical research to improve NUE and concomitantly reduce nitrous oxide emissions through management of N source, rate, time, and place. While change to any one of the 4Rs can improve NUE and reduce emissions, 4R practices tend to work synergistically and are typically grouped together as suites of practices in three tiers (basic, intermediate, and advanced), based on increasingly more precise management of N. As the sophistication of N management increases, the level of N_2O emissions has been demonstrated to decrease (Abalos et al., 2016; Banger et al., 2020).

The studies cited above are a small part of a large body of work demonstrating the capacity of the 4Rs for reducing N_2O emissions while increasing crop yields and profitability. However, very few studies have directly measured N_2O emissions in SSA, likely due to lack of funding and research facilities. While direct measurement data is not widely available across the region, estimates of N_2O emission from synthetic nitrogen fertilizer additions to croplands are available by country covering the period of 1961 to 2015, with

annual updates, and projections to 2030 and 2050 (FAO, 2020). These estimates were computed using a default emission factor value of 1% following the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (De Klein et al., 2006). IPCC revised these guidelines in 2019 to include the use of nitrification inhibitors as reduction modifiers for the standard emission coefficients (Shukla et al., 2019). But their inclusion in GHG emission inventories is still challenging, particularly in SSA, due to scarcity of data on where and how much of these inhibitors are used.

There is currently no published data on potential future impact of adoption of 4R practices on reducing N_2O emissions in SSA. The purpose of the present study is to conduct an ex-ante analysis of the potential for nitrous oxide emissions reductions associated with adoption of 4R practices at scale across SSA. Exploring these possible future trends relative to the projected 2030 and 2050 baselines is important for guiding strategic decision making for sustainable agricultural production in SSA.

The present study uses scenario analysis to estimate the potential effects of increased adoption of 4R Nutrient Stewardship on N_2O emissions in SSA through 2030 and 2050. We used historical data and projections on future N_2O emissions from synthetic nitrogen fertilizer additions to croplands as baseline data and then applied reduction modifiers to the baseline to estimate potential N_2O reductions. Given the lack of SSA data on N_2O reductions attributable to 4R practices, a bracketing approach is used with emission reductions rates falling within the range of what has been observed in cropping systems under 4R management in other regions.

2. Methodology

2.1. Projections of greenhouse gas emission

Data on projected greenhouse gas (GHG) emissions from synthetic N fertilizer for 2030 and 2050 were downloaded from the Food and Agriculture Organization of the United Nations (FAO) FAOSTAT database (FAO, 2020) (see Appendix A). Synthetic N fertilizer refers to annual fertilizer consumption data often recorded as fertilizer sales and/or as domestic production and imports (De Klein et al., 2006). The FAOSTAT emissions database is computed using N_2O emission factor of 1% following Tier 1 IPCC 2006 Guidelines for National GHG Inventories (vol. 4, ch. 11). Projections for 2030 and 2050 were computed using a 2005-2007 average baseline and applying percentage growth rates from FAO studies (Alexandratos & Bruinsma, 2012). The estimates reflect direct and indirect GHG emissions. Direct emissions refer to N_2O microbial processes-based emissions (nitrification and denitrification) taking place within the cropping system where nitrogen fertilizer was applied. Indirect emissions consider volatilization and leaching processes removing N from the application site with conversion to nitrous oxide occurring outside the cropping system. Emission estimates are provided for the majority of SSA countries except Cape Verde, Chad, Comoros, Djibouti, Equatorial Guinea, Eswatini, Guinea-Bissau, Lesotho, Liberia, Mauritania, Reunion Island, Sao Tome & Principe, Sierra Leone, Somalia, Sudan, and South Sudan.

2.2. Potential emission reductions

Potential emission reductions were calculated by country using three different 4R Nutrient Stewardship adoption rates for each projected future year (10, 20 and 30% for 2030; and 30, 40 and 50% for 2050) and five different emission reduction rates (5, 10, 15, 20 and 25%) (Table 1). We hypothesized that if a proportion of the farmers adopt 4R Nutrient Stewardship practices, they will contribute to reduction of N_2O emissions while the remaining farmers with current practices will keep N_2O emissions trends as they were before. The calculations were based on hypothesis using the following equations 1-5.

$$ER = Ei - Ew \qquad (Eq.1)$$
$$Ew = Ea + Eb \qquad (Eq.2)$$
$$Ea = Ei \times Ar \times Rr \qquad (Eq.3)$$
$$Eb = Ei (1 - Ar) \qquad (Eq.4)$$
$$Rr\_SSA = ER/Ei \qquad (Eq.5)$$

Where: ER is the potential emission reduction; Ei the initially projected potential emission following current nutrient management practices, the 'baseline emissions' (Appendix A); Ew the calculated potential emission considering 4R Nutrient Stewardship adoption rates (Ar, Table 1) and emission reduction rate (Rr, Table 1); Ea is the potential emission from the proportion of the farmers adopting 4R Nutrient Stewardship within the country; Eb the potential emission from the remaining proportion of farmers who have not adopted 4R Nutrient Stewardship but kept their current nutrient management practices. ER, Ei, Ew, Ea and Eb are all expressed in $MtCO_2e$, and Ar and Rr in percentage. The overall ER for SSA (Rr_SSA) is expressed in percentage.

ER calculations were made for different scenarios (Table 1) selected to assess the range of potential emission reductions that could be achieved from 4R Nutrient Stewardship adoption in SSA. Actual on-farm emission reduction rates will vary depending on soil type, texture, topography, and climate, as well as the level of sophistication used in implementing the 4R Nutrient Stewardship BMPs. Based on current available research, emission reductions of 5 to 25 percent are conservative relative to the real reductions that could be achieved (Akiyama et al., 2010; Drever et al., 2021). The results were calculated for the whole SSA, as well as for seven countries selected independently to cover geographical differences, namely Ethiopia, Democratic Republic of Congo, Kenya, South Africa, Nigeria, Ghana, and Senegal.

Table 1: Potential 4R Nutrient Stewardship Emission Reduction Scenarios.

Rr[1] (%)	2030 Ar[2] (%)				2050 Ar (%)	
	SCENARIO #1	SCENARIO #2	SCENARIO #3	SCENARIO #4	SCENARIO #5	SCENARIO #6
5%	10%	20%	30%	30%	40%	50%
10%	10%	20%	30%	30%	40%	50%
15%	10%	20%	30%	30%	40%	50%
20%	10%	20%	30%	30%	40%	50%
25%	10%	20%	30%	30%	40%	50%

[1] Rr stands for emission reduction rate

[2] Ar is the adoption rate of the 4R Nutrient Stewardship

3. Key findings

A total annual potential N_2O emissions of 82 to 1,220 $ktCO_2e$ by 2030 and 410 to 3,418 $ktCO_2e$ by 2050 could be avoided across SSA through the adoption of 4R Nutrient Stewardship practices (Table 2). These correspond to Rr_SSA (overall emission reduction in SSA) of 0.5 to 7.5% by 2030 and 1.5 to 12.5% by 2050 of total annual FAO projected N_2O emission of 16,392 $ktCO_2e$ and 27,345 $ktCO_2e$, respectively (Appendix A). Potential annual emission reductions (ER) were not surprising given the assumed higher adoption rates for 2050 compared to 2030. ER increased as the adoption rate (Ar) of the 4R Nutrient Stewardship rose as shown in scenarios 1 to 3 for year 2030 and scenarios 4 to 6 for year 2050. Higher emission reduction rates (Rr) also corresponded to larger quantities of emissions that could be avoided. Hence, as expected, the best scenarios for reducing N_2O emissions were scenarios 3 and 6 (Ar 30% and 50% adoption of 4R Nutrient Stewardship by 2030 and 2050, respectively) at Rr 25% emission reduction, which gave the highest amounts of annual emission reductions of 1,229 $ktCO_2e$ by 2030 and 3,418 $ktCO_2e$ by 2050. A breakdown of the results for Rr 25% across the pilot countries and the whole SSA is presented in Table 3. Results by pilot country showing similar trends are also provided in Appendix B. Potential annual emission reductions were larger in South Africa, Nigeria, and Ethiopia (Table 3). The lowest potential emissions reductions were recorded in the Democratic Republic of Congo, followed by Senegal and Ghana. These differences in emission reductions reflect differences in projected total amounts of synthetic fertilizer use among these countries.

Table 2: Potential emission reductions (ER) as affected by emission reduction rates (Rr) for different scenarios of adoption of 4R Nutrient Stewardship practices across SSA by 2030 and 2050

RR (%)	ER 2030 ($ktCO_2e$)			ER 2050 ($ktCO_2e$)		
	SCENARIO 1 (Ar 10%)	SCENARIO 2 (Ar 20%)	SCENARIO 3 (Ar 30%)	SCENARIO 4 (Ar 30%)	SCENARIO 5 (Ar 40%)	SCENARIO 6 (Ar 50%)
5%	82	164	246	410	547	684
10%	164	328	492	820	1094	1367
15%	246	492	738	1231	1641	2051
20%	328	656	984	1641	2188	2734
25%	410	820	1229	2051	2734	3418

Table 3: Potential emission (Ew), emission reductions (ER) and overall emission reduction (Rr_SSA) following different adoption rates (Ar) scenarios for 4R Nutrient Stewardship in seven countries and the whole SSA assuming 25% emission reduction rate (Rr).

COUNTRY	Ew 2030 POTENTIAL EMISSION BY SCENARIO			Ew 2030 POTENTIAL EMISSION REDUCTIONS BY SCENARIO			Ew 2050 POTENTIAL EMISSION BY SCENARIO			Ew 2050 POTENTIAL EMISSION REDUCTIONS BY SCENARIO		
	#1 Ar 10%	#2 Ar 20%	#3 Ar 30%	#1 Ar 10%	#2 Ar 20%	#3 Ar 30%	#4 Ar 30%	#5 Ar 40%	#6 Ar 50%	#4 Ar 30%	#5 Ar 30%	#6 Ar 50%
	ktCO$_2$e											
Democratic Republic of Congo	31	30	30	1	2	2	69	67	65	6	7	9
Ethiopia	1640	1597	1555	42	84	126	2793	2718	2642	226	302	3779
Ghana	268	261	254	7	14	21	381	371	361	31	41	52
Kenya	1013	987	961	26	52	78	1650	1605	1561	134	178	223
Nigeria	2328	2268	2208	60	119	179	3632	3534	3436	295	393	491
Senegal	154	150	146	4	8	12	316	307	299	26	34	43
South Africa	3821	3723	3625	98	196	294	4282	4167	4051	347	463	579
Other SSA countries	6727	6556	6383	172	345	517	12171	11841	11512	986	1316	1644
SSA	**15982**	**15572**	**15162**	**410**	**820**	**1229**	**25294**	**24610**	**23927**	**2051**	**2734**	**3418**
Rr_SSA				**2.5%**	**5.0%**	**7.5%**				**7.5%**	**10.0%**	**12.5%**

4. Discussion of key findings and proposed solutions

4.1. Projected impacts of 4Rs on N_2O emissions by 2030 and 2050

The reduction of N_2O emissions through best management practices within a 4R Nutrient Stewardship framework is widely reported (Robertson and Vitousek, 2009; Akiyama et al., 2010; Venterea et al., 2010; Snyder et al., 2014; Ruser and Schulz, 2015). The current study estimates the positive effects of 4R Nutrient Stewardship on reducing greenhouse gas emissions.

Our scenario analysis based on FAO projections of annual N_2O emissions from synthetic fertilizers shows that substantial amounts of N_2O emissions could be avoided with increased adoption of 4R Nutrient Stewardship. Annual N_2O emissions reductions of up to 1,229 and 3,418 $ktCO_2e$ by 2030 and 2050, respectively, with 30% and 50% adoption rates of the 4R Nutrient Stewardship at 25% emission reduction rate could be achieved in SSA. These correspond to overall emission reductions of 7.5% by 2030 and 12.5% by 2050 over total FAO annual N_2O emission projections for SSA of 16,392 $ktCO_2e$ and 27,345 $ktCO_2e$, respectively (Appendix A). Given the growing demand for food production within SSA and the key role N fertilizer plays in increasing yield per unit of land, reducing N_2O emission by 7.5% and 12.5% by 2030 and 2050, respectively, would be a considerable achievement. Moreover, in achieving these N_2O emissions reduction levels by 2030 and 2050, SSA has the potential to generate carbon offsets with a potential value of CAD\$209M to \$581M per year, given for example a carbon price of CAD\$170 (USD\$130) per tonne of CO_2e by 2030 as used in Canada. Even at a more modest carbon price of CAD\$65 (USD\$50) per tonne CO_2e by 2030, there is potential to generate CAD\$80M (USD\$61M) per year across the region with a significant portion of that amount returning to farmers. Returns to farmers from carbon sales would help offset the costs of adopting 4R practices in addition to the economic benefits likely to accrue from increased yield per unit of fertilizer N.

The findings of this study demonstrate the potential of 4R Nutrient Stewardship approaches to mitigate the nitrous oxide emissions resulting from increased nitrogen applications in SSA. Current government expenditures on research and knowledge dissemination in SSA represent the second largest share, averaging 18%, of total expenditures on food and agriculture after farm subsidy programmes with 23% (Pernechele et al., 2021). Directing a portion of these expenditures towards development and adoption of regionally appropriate 4R practices will provide economic returns to farmers, while preserving the environment.

4.2. Challenges to achieving high emission reductions

The reduction rates used were in line with the positive effects of 4R practices on GHG emissions reported in the global literature (Stehfest and Bouwman, 2006; Akiyama et al., 2010; Hickman et al., 2011; Hickman et al., 2015). Empirical evidence on the effectiveness of source, rate, time, and place practices on N_2O emission reductions is not widely available in SSA. There is, however, a large body of evidence globally across a broad range of soil and climatic conditions and diverse cropping systems suggesting that the approach is universally applicable and effective. SSA is a large agriculturally diverse region and actual emission reduction rates and quantities of N_2O emissions avoided will vary widely based on climate, soil, crops, N fertilizer use, and BMPs adopted locally. While conducting extensive direct measurements of the effects of different potential BMPs on N_2O reductions may not be possible, the simpler approach of calculating N balance and/or N use efficiency tends to correlate well with actual emissions and is a reasonable proxy for determining the relative merits of different practices (Maaz et al. 2021). Research and demonstration efforts should be channeled into identifying and promoting practices that optimize fertilizer nitrogen use efficiency as there is a high probability that they will also minimize direct and indirect N_2O emissions as well as reducing pollution of surface and ground water from runoff and leaching. There are several approaches to estimating nitrogen use efficiency that are adaptable to the farm or field level can be used by growers and extension workers to rank the efficacy of practices in reducing nitrous oxide. The concept of NUE along with the different approaches and their uses was recently reviewed by Congreves et al. (2021).

The promotion of 4R BMPs will require creation of learning opportunities that improve understanding of 4R Nutrient Stewardship concepts by farmers, farm advisors such as extension service providers and input dealers, and researchers. It will involve improving access to locally tailored recommendations based on the right source, the right rate, the right time, and the right place of fertilizer application since blanket recommendations across crops, fields, and regions or even a whole country, are still common practice in SSA. It will require investing in policies and programs that ensure improved access to fertilizer, improved seeds and planting materials, and crop protection technologies. This requires also policies facilitating improved access to credit and subsidies, which will increase farmers financial capacity to buy inputs. Improved infrastructure like roads is also important for facilitating connectivity and access to markets, hereby reducing post-harvest losses, and ensuring that any on-farm surpluses arising from improved fertilizer use create both on-farm

and broader social benefits. These challenges highlight the important roles that research, extension service providers, input dealers, credit institutions, and policy makers must play and the required involvement of both government and the private sector in enabling the adoption of 4R Nutrient Stewardship.

Adoption of innovations or new technologies by farmers in SSA is often very challenging. Awareness and advocacy campaigns should include local demonstration plots that emphasize 4R fundamentals while illustrating practical N management improvements to farmers as well as their advisors. Facilitating learning in the following areas would be beneficial to SSA farmers: best planting windows; nutrient deficiency symptoms and sources of fertilizer nutrients; timing of fertilizer applications and split applications in relation to crop growth stages and nutrient requirements; methods of fertilizer placement to reduce nutrient losses, heterogeneity of soils within / across farms in relation to yield potential and fertilizer rates. A strong emphasis should be put on farmer to farmer and participatory learning approaches. It is important to increase farmers understanding and capacity to implement practices that improve or maintain their yield while ensuring environmental sustainability in particular reducing greenhouse gas emissions. Adoption of regionally appropriate BMPs within a 4R Nutrient Stewardship framework is a key tool in achieving the goal of sustainable intensification and low carbon food production both globally and within SSA.

4.3. Co-benefit and consequences of adopting 4R Nutrient Stewardship

Increased adoption of 4R Nutrient Stewardship in the SSA could contribute to building up soil nutrient stocks given the current low fertilizer input (Vanlauwe and Dobermann, 2020) compared to high nutrient output through harvest products (Smaling et al., 2015). Proper crop residue management plus the right combination of mineral fertilizers with available organic resources to meet nutrient demands by the plant will increase biomass production, resulting in greater return of crop residues, and build-up of soil organic matter (Vanlauwe and Giller, 2006). This not only reduces soil mining but has potential to create a virtuous circle where improved soil fertility and soil health leads to further gains in yield and residue returns, improved nutrient use efficiency, and better economic returns to the farmer. With the increased productivity induced from the adoption of 4R Nutrient Stewardship, there is scope to reduce the clearance and burning of native vegetation, which will also contribute to mitigating N_2O emissions (Tian et al., 2020).

Given the need to boost crop production to meet food demands throughout SSA by 2030 and 2050, fertilizer use, and particularly N use, is expected to rise substantially over the next three decades. This may lead to increased N_2O emissions (Hickman et al., 2015). However, while absolute reductions from current levels is likely not possible, the adoption of 4R Nutrient practices, which improve nitrogen use efficiency and yields, is a viable way for mitigating higher N_2O emissions in SSA and reducing emission intensities. In addition to significant extension efforts, research efforts must be multiplied and directed towards developing technologies that further enhance 4R BMPs with the goal of continually reducing emissions per unit of N applied and crop produced.

4.4. Dealing with uncertainties of the estimates

Uncertainties in estimates of N_2O emissions are likely due to uncertainties in the estimate of amount of synthetic fertilizer consumed annually per country and of the emission factors. The computation of the annual consumption of synthetic N fertilizers as an annual balance of N production and net trade does not account for fertilizer type, cropping system, climatic regime, etc., which can influence N_2O emissions (De Klein et al., 2006).

Estimates of GHG emissions used in this study were based on Tier 1 IPCC 2006 Guidelines for National GHG Inventories (vol. 4, ch. 11), which uses an N_2O emission factor of 1% as the proportion of the nitrogen fertilizer that is emitted (De Klein et al., 2006). This assumes a linear relationship between the amount of N applied and the amount N_2O emitted. The linearity of this relationship is supported by Albanito et al. (2017) who obtained an overall emission factor of 1.2% for the tropics and subtropics, but 1.4% for Africa. However, Hickman et al. (2015) found that this relationship is rather exponential and obtained lower emission factor values, ranging from 0.01 to 0.11%. Similar low values of emission factor were obtained for SSA with an overall mean value of 0.2% across 70 site-year measurement points (CGIAR-CCAFS SAMPLES: https://samples.ccafs.cgiar. org/n2o-dashboard/), with some country level differences: Zimbabwe 0.13% (Chikowo et al.; Mapanda et al., 2011), Kenya 0.37% (Millar et al., 2004; Baggs et al., 2006), and Mali 0.94% (Dick et al., 2008). Other studies also recommended country-specific emission factors (Van Groenigen et al., 2010; Shcherbak et al., 2014). As the countries of SSA move towards more regionally specific emission factors, emission estimates will likely decline in drier regions and increase in wetter regions. Larger emission factors would increase our estimates of N_2O emission and emission reductions attributable to fertilizer N use, whereas low emission factor would decrease the values we estimated in this study.

It is noteworthy that alternative pathways exist. They include FAO emission projections by 2050, which consider some mitigation strategies with gradually declining emission factors towards 2050 (FAO, 2018); and the shared socioeconomic pathways that consider differences in socioeconomic (country-specific changes in population and income) and emissions pathways (low, medium and high emission pathways, RCP4.5, RCP6.0 and RCP8.5, respectively) (Wiebe et al., 2015). These alternative pathways will definitely generate some relative changes to the N_2O emissions and reductions we projected in this study. However, what will not change is the overall positive effect the adoption of 4R Nutrient Stewardship will have on reducing N_2O emissions and achieving the lower emission intensities in these alternative pathway scenarios.

4.5. Guiding principles for implementing 4R Nutrient Stewardship

The effective implementation of the 4R Nutrient Stewardship in SSA requires a stepwise approach following three tiers or performance levels: basic, intermediate, and advanced. Efforts should be put first in ensuring basic level of 4R Stewardship implementation is achieved by most farmers, then move to intermediate and advanced levels. The specific practices within the various levels can be adjusted based on the prevailing circumstances within a region while still adhering to 4R principles (Table 4 and 5). Some general criteria encompassing grower adoption are proposed below:

- **Basic** – Practices are generally consistent with 4R principles. Basic practices should be accessible to a large proportion of farmers with minimal changes in on-farm technology. Although nutrient management practices in SSA are still suboptimal in most cropping systems, proper education and policy initiatives can remove barriers and drive adoption rates larger than 30% of cropped area in the region by 2030.

- **Intermediate** – Practices are fully consistent with 4R principles and may be transitional to advanced practices. Adoption of intermediate level practices may occur in commercial crops over the medium-term (>5 years) particularly when they involve investment in new technology. But most cropping systems are still far from this in SSA, although recent advances in digital farming in the region can boost adoption of 4R solutions. Relatively low-tech solutions may be available in moving from basic to intermediate as the goal is improved productivity and nitrogen use efficiency not adoption of technology per se.

- **Advanced** – Practices are fully consistent with 4R principles and may be considered aspirational and/or best in class. Adoption of a full suite of advanced level practices may occur over a longer time frame (>10 years) particularly when they involve investment in new technology. Not all farmers will achieve this level, but it is recommended for big commercial farms.

Determining what practices are included in a given performance level needs to consider the crops, the regional climate, and other localized factors such as soil types. Consequently, there is an element of risk-based flexibility in determining what practices are acceptable for the different performance levels. This means that practices that are Right for a set of crops in one agro-ecological zone may not be Right in another. This also allows a given practice to be included at a higher performance level when there is sufficient regional evidence to demonstrate low risk and excluded when the evidence indicates high risk. For example, the application of unprotected nitrogen may be appropriate for rainfed upland rice production where risk of N loss is relatively low whereas slow-release N fertilizers are more appropriate for lowland (wetlands) production where risk of loss is considerably higher.

In addition to adherence to 4R principles and the performance level concepts outlined above, it is important to consider the following concepts:

- Practices need to cover all nitrogen sources: integrating local organic nitrogen sources such as manure into the 4R framework is an important aspect of developing regional 4R BMP frameworks. Cropping systems within SSA where manure is regularly applied as a nutrient source have significantly different management requirements than systems that are managed with commercial fertilizer alone. These include considerations such as accounting for ongoing nitrogen mineralization in the crop cycles following the application; and developing time and place practices around spreading and incorporation that ensure minimum N loss.

- Targeting specific environmental issues while improving efficiency and return on investment is an important aim of 4R in all cropping systems. Practices should be selected based on their potential to improve productivity as well as their potential to reduce direct GHG emissions from soils and indirect emissions arising from volatilization and movement of N to surface and groundwater.

- Efficiency increases with performance level: moving from basic to advanced should follow a trajectory of improved nutrient use efficiency. Although source, rate, time and place practices do not necessarily all change from one level to the next, the changes that are made should lead to higher efficiency overall for each level in the progression. Some of the common themes across cropping systems are shown in Table 4.

- Flexible to accommodate unusual circumstances: 4R plans are directional and based on adaptive management. Farmers adopting 4R consistent practices improve over time and reach a higher level of performance in their nutrient use. Farmers may need to break from their intended 4R practices on occasion to accommodate unusual circumstances caused by inclement weather, equipment limitations, lack of product etc. Temporary adoption of practices at a lower performance level than planned or non 4R practices due to uncontrollable factors will in some cases be unavoidable.

Table 4. Overview of general practice changes from basic to advanced.

PERFORMANCE LEVEL	SOURCE	RATE	TIME	PLACE
Basic	Identified nutrient type. Measured or estimated content. Known mode of action.	Field specific – the rate is set considering the unique factors in each field (preceding crops, soil type, weather, nutrient management history, etc.).	Reduce high risk timings. At least two split applications at recommended timing following high crop nutrient demands.	Exclude high risk placement, low efficiency placements. Avoid surface application without covering the fertilizer. Place at adequate distance from the plant stand.
Intermediate	Enhanced efficiency sources (if available) in high-risk situations.	Rate adjusted for subfield variation in soil supply and risk of off-site movement.	Move application timing closer to period of highest crop demand.	Concentrate placement in subsurface bands.
Advanced	Enhanced Efficiency Sources in all but low risk situations.	Rate optimized for subfield variation.	Multiple applications to synchronize timing with crop demand and growing season conditions.	Concentrate placement in subsurface bands in optimal configuration with rooting zone.

Table 5. Key scientific principles guiding the development of 4R BMPs for Nutrient Application.

RIGHT SOURCE	RIGHT RATE
1. Consider Rate, Time and Place 2. Ensure Balanced Supply 3. Suit Soil Chemical and Physical Properties 4. Supply Nutrients in Plant Available Form 5. Recognize Synergisms Amont Nutrients 6. Recognize Blend Compatability 7. Recognize Effects of Associated Elements 8. Recognize Effects of Non-Nutrient Elements	1. Consider Source, Time and Place 2. Assess Plant Nutrient Demand 3. Assess Soil Nutrient Supply 4. Assess All Available Nutrient Sources 5. Predict Fertilizer Use Efficiency 6. Consider Soil Resource Impacts 7. Consider Rate Specific Economics

RIGHT TIME	RIGHT PLACE
1. Consider Source, Rate and Place 2. Assess Timing of Plant Uptake 3. Assess Dynamics of Soil Nutrient Supply 4. Recognize Dynamics of Soil Nutrient Loss 5. Evaluate Logistics of Field Operations	1. Consider Source, Rate and Time 2. Consider Where Plant Roots are Growing 3. Consider Soil Chemical Reactions 4. Suit the Goals of the Tillage System 5. Manage Spatial Variability

5.   Conclusion and perspectives

Fertilizer N use in SSA will continue to rise over the next three decades driven by the increasing food demands of a growing population. As a result, nitrous oxide emissions associated with on farm fertilizer use will also rise. While absolute reductions from current emission levels are likely not possible, increased adoption of 4R Nutrient Stewardship has significant potential to reduce N_2O emissions associated with increased N fertilizer use in SSA below the projected business-as-usual levels. In our projections, nitrous oxide emissions could plausibly be reduced by 7.5% by 2030 and 12.5% by 2050 relative to the business-as-usual scenario through improved nitrogen management using 4R Nutrient Stewardship principles and practices. As carbon offsets, these emissions reductions have potential values of CAD$209M to $581M per year. Returns to farmers from carbon sales would help compensate the costs of adopting 4R practices in addition to the economic benefits likely to accrue from increased yield per unit of fertilizer N. While we did not explicitly build out the economic benefits of improved productivity through extensive adoption of BMPs, we made the qualitative case for investing in policy, research and extensions mechanisms that support the implementation of 4R Nutrient Stewardship in SSA. We are hopeful that this paper stimulates discussion and leads to collective actions towards promoting 4R as a climate-smart approach which optimizes nutrient use, reduces greenhouse gas emissions and other environmental pollution, while sustainably intensifying food production, for the benefit of the peoples of SSA.

6.   Acknowledgements

7. References

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Appendix A: FAO estimates for 2015 to 2017, and projections for 2030 and 2050 of potential Annual Emission across Sub-Saharan African countries.

In this study, emphasis is put on seven countries selected independently, which are shown here in light green.

COUNTRY	EMISSIONS (ktCO$_2$e) (SYNTHETIC FERTILIZERS)				EI (FAO EMISSION PROJECTION, ktCO$_2$e) (SYNTHETIC FERTILIZERS)	
	2015	2016	2017	AVERAGE	2030	2050
Angola	164.6	134.1	172.4	157.0	130.1	273.8
Benin	1.2	91.6	0.3	31.0	5.0	8.6
Botswana	136.6	136.6	136.6	136.6	0.0	0.0
Burkina Faso	329.8	436.6	376.3	380.9	461.9	766.1
Burundi	29.8	52.2	65.5	49.2	21.9	51.1
Cote D'Ivoire	274.7	301.0	213.2	263.0	190.2	393.2
Cameroon	274.5	256.6	299.9	277.0	347.4	581.1
Central African Republic	1.4	1.4	0.6	1.1	4.5	7.7
Congo		2.1	2.1	2.1	0.6	1.5
Democratic Republic of Congo	116.7	73.0	103.6	97.8	31.9	74.5
Eritrea	10.3	12.4	11.5	11.4	9.0	13.6
Ethiopia	900.7	999.5	1013.3	971.2	1681.5	3019.9
Gabon	25.0	23.7	50.0	32.9	50.0	9.8
Gambia	0.9	0.8	0.2	0.7	20.9	47.1
Ghana	275.5	407.4	407.4	363.5	274.7	412.1
Guinea	15.6	41.2	151.0	69.3	61.3	115.0
Kenya	857.3	642.6	540.8	680.2	1039.4	1783.7
Madagascar	0.0	0.0	202.6	67.5	122.3	237.8
Malawi	459.6	459.6	459.6	459.6	1307.3	2678.9
Mali	981.2	1080.4	966.2	1009.3	1184.4	1923.0
Mauritius	42.4	58.4	54.1	51.6	54.1	54.1
Mozambique	77.9	123.9	145.9	115.9	270.1	527.6
Namibia	66.9	126.8	121.6	105.1	18.2	36.4
Niger	43.4	41.6	41.6	42.2	95.5	296.5
Nigeria	1265.8	1863.8	2870.4	2000.0	2387.6	3927.0
Rwanda	71.6	28.0	28.0	42.5	47.1	94.2
Senegal	182.7	182.7	182.7	182.7	157.5	341.3
Seychelles	0.4	0.3	0.3	0.3	0.3	0.6
South Africa	2599.9	2599.9	2599.9	2599.9	3919.4	4629.7
Togo	3.7	79.7	27.6	37.0	83.6	143.3
Uganda	13.5	55.1	49.1	39.2	64.7	147.0
Tanzania	494.2	694.3	684.3	624.3	726.4	1639.8
Zambia	1068.4	1214.2	1359.9	1214.2	946.1	1957.0
Zimbabwe	275.0	375.0	375.0	341.7	676.8	1151.9
Total SSA	**11063.1**	**12596.2**	**13713.5**	**12457.6**	**16391.9**	**27344.8**

Appendix B: Potential Annual Emission Reductions from Adoption of 4R Nutrient Stewardship in Seven Pilot Sub-Saharan African countries.

Ethiopia - Potential Annual Emission Reductions (ktCO$_2$e)

EMISSION REDUCTION (%)	2030			2050		
	SCENARIO #1 (10% ADOPTION)	SCENARIO #2 (20% ADOPTION)	SCENARIO #3 (30% ADOPTION)	SCENARIO #4 (30% ADOPTION)	SCENARIO #5 (40% ADOPTION)	SCENARIO #6 (50% ADOPTION)
5%	8	17	25	45	60	75
10%	17	34	50	91	121	151
15%	25	50	76	136	181	226
20%	34	67	101	181	242	302
25%	42	84	126	226	302	377

South Africa - Potential Annual Emission Reductions (ktCO$_2$e)

EMISSION REDUCTION (%)	2030			2050		
	SCENARIO #1 (10% ADOPTION)	SCENARIO #2 (20% ADOPTION)	SCENARIO #3 (30% ADOPTION)	SCENARIO #4 (30% ADOPTION)	SCENARIO #5 (40% ADOPTION)	SCENARIO #6 (50% ADOPTION)
5%	20	39	59	69	93	116
10%	39	78	118	139	185	231
15%	59	118	176	208	278	347
20%	78	157	235	278	370	463
25%	98	196	294	347	463	579

Kenya - Potential Annual Emission Reductions (ktCO$_2$e)

EMISSION REDUCTION (%)	2030			2050		
	SCENARIO #1 (10% ADOPTION)	SCENARIO #2 (20% ADOPTION)	SCENARIO #3 (30% ADOPTION)	SCENARIO #4 (30% ADOPTION)	SCENARIO #5 (40% ADOPTION)	SCENARIO #6 (50% ADOPTION)
5%	5	10	16	27	36	45
10%	10	21	31	54	71	89
15%	16	31	47	80	107	134
20%	21	42	62	107	143	178
25%	26	52	78	134	178	223

Democratic Republic of Congo - Potential Annual Emission Reductions (ktCO$_2$e)

EMISSION REDUCTION (%)	2030			2050		
	SCENARIO #1 (10% ADOPTION)	SCENARIO #2 (20% ADOPTION)	SCENARIO #3 (30% ADOPTION)	SCENARIO #4 (30% ADOPTION)	SCENARIO #5 (40% ADOPTION)	SCENARIO #6 (50% ADOPTION)
5%	0	0	0	1	1	2
10%	0	1	1	2	3	4
15%	0	1	1	3	4	6
20%	1	1	2	4	6	7
25%	1	2	2	6	7	8

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IMPLEMENTING PARTNERS

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Co-operative Development Foundation of Canada

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