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Impacts of intensifying or expanding cereal cropping in sub-Saharan Africa on greenhouse gas emissions and food security

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Abstract

Cropping is responsible for substantial emissions of greenhouse gasses (GHGs) worldwide through the use of fertilizers and through expansion of agricultural land and associated carbon losses. Especially in sub-Saharan Africa (SSA), GHG emissions from these processes might increase steeply in coming decades, due to tripling demand for food until 2050 to match the steep population growth. This study assesses the impact of achieving cereal self-sufficiency by the year 2050 for 10 SSA countries on GHG emissions related to different scenarios of increasing cereal production, ranging from intensifying production to agricultural area expansion. We also assessed different nutrient management variants in the intensification. Our analysis revealed that irrespective of intensification or extensification, GHG emissions of the 10 countries jointly are at least 50% higher in 2050 than in 2015. Intensification will come, depending on the nutrient use efficiency achieved, with large increases in nutrient inputs and associated GHG emissions. However, matching food demand through conversion of forest and grasslands to cereal area likely results in much higher GHG emissions. Moreover, many countries lack enough suitable land for cereal expansion to match food demand. In addition, we analysed the uncertainty in our GHG estimates and found that it is caused primarily by uncertainty in the IPCC Tier 1 coefficient for direct N_2O emissions, and by the agronomic nitrogen use efficiency (N-AE). In conclusion, intensification scenarios are clearly superior to expansion scenarios in terms of climate change mitigation, but only if current N-AE is increased to levels commonly achieved in, for example, the United States, and which have been demonstrated to be feasible in some locations in SSA. As such, intensifying cereal production with good agronomy and nutrient management is essential to moderate inevitable increases in GHG emissions. Sustainably increasing crop production in SSA is therefore a daunting challenge in the coming decades.

KEYWORDS
fertilizer, food self-sufficiency, intensification, land use conversion, nitrogen, nutrient use efficiency, yield gaps

1 | INTRODUCTION

Globally, agriculture is estimated to be responsible for substantial emissions of greenhouse gasses (GHGs), that is, ca. 12% directly, for example, through methane emissions from livestock and rice production and N_2O emissions through the use of fertilizers (Barker et al., 2007; Smith et al., 2007; Vermeulen, Campbell, & Ingram, 2012) and another ca. 15% indirectly through land use conversion to increase agricultural production (Barker et al., 2007; Van der Werf et al., 2009; Vermeulen et al., 2012). Currently, agricultural production and associated agricultural GHG emissions are relatively low in sub-Saharan Africa (SSA) in comparison to other parts of the world (FAO, 2019). However, GHG emissions from agriculture are expected to increase in this region, as food production needs to rise in the coming decades to keep up with the strongly growing food demands (Smith et al., 2007). Until the year 2050, the cereal demand is projected to more than triple relative to 2010 due to population increase and dietary changes (van Ittersum et al., 2016). SSA has already seen a continuous increase in emissions from agriculture-driven deforestation between 1990 and 2015 (Carter et al., 2017), as agriculture is considered the dominant driver of deforestation (Curtis, Slay, Harris, Tyukavina, & Hansen, 2018). The central aim of the Paris COP21 Agreement—adopted by 195 nations—is to keep global warming below 2°C and to pursue efforts to stay within 1.5°C above pre-industrial levels (IPCC, 2018), while the sustainable development goals emphasize that climate change mitigation will have to go hand in hand with achieving food security (United Nations, 2016). This will be challenging as it has been argued that for SSA, the effects on food security of stringent climate change mitigation measures may be larger than the effects of climate change itself (Hasegawa et al., 2018).

Over the past decades, food production in SSA has been increased by significant area expansion and slowly increasing yields (FAO, 2019). This led to large increases in GHG emissions, mainly due to the land use change (Bennetzen, Smith, & Porter, 2016). It is often stated that intensification on existing cropland is the preferred way to go in terms of biodiversity loss and GHG emissions (Cassman, 1999; Cassman, Dobermann, Walters, & Yang, 2003), as intensified agriculture has in general the lowest emission per unit of product produced (Bennetzen et al., 2016). More specifically, sustainable intensification of crop production by narrowing the yield gap, that is, the gap between actual farmers' yields and potential yield (Van Ittersum et al., 2013), is proposed. Nutrient limitation is amongst the main causes of yield gaps in SSA (Kassie et al., 2014; Sanchez, 2015). Current nutrient inputs are low in SSA (FAO, 2019), and intensification will therefore require substantial increases in (nitrogen) fertilizer input (ten Berge et al., 2019). Nitrogen is, in quantitative terms, the most important crop nutrient and its production and use is strongly related to emissions of the GHGs CO_2 and N_2O. As a result of this increased fertilizer input, GHG emissions will increase irrespective of whether mineral or organic fertilizers are used (Palm et al., 2010). Today's nutrient use efficiencies in SSA remain low, potentially aggravating emissions from increased fertilizer use (Reay et al., 2012).

A relevant question is thus how GHG emissions are related to different scenarios of increasing food production, ranging from intensifying production to agricultural area expansion. We address this question by assessing GHG emissions from cultivation of five main cereals in SSA (i.e. maize, millet, rice, sorghum and wheat), considering different combinations of intensification and crop area expansion to achieve cereal self-sufficiency by the year 2050. Ten countries across SSA are included in this analysis (i.e. Burkina Faso, Ethiopia, Ghana, Kenya, Mali, Niger, Nigeria, Tanzania, Uganda and Zambia), representing 52% of the population and 58% of the cropland area in SSA (FAO, 2019). In addition, for maize cultivation, the most important cereal in SSA, we assess (a) the influence of agronomic nitrogen use efficiency (N-AE, i.e. extra grain yield per kg of N applied) on GHG emissions, where N-AE expresses the level of agronomic management; (b) the optimal balance between intensification and crop area expansion with respect to GHG emissions; and (c) how these analyses are affected by uncertainties in modelling parameters.

2 | MATERIALS AND METHODS

2.1 | Four scenarios which achieve cereal self-sufficiency in 2050

In this study, we used four scenarios to assess GHG emissions as affected by agricultural intensification or area extension for 10 countries in SSA (i.e. Burkina Faso, Ethiopia, Ghana, Kenya, Mali, Niger, Nigeria, Tanzania, Uganda and Zambia) and five cereals (i.e. maize, millet, rice, sorghum and wheat). The underlying principles of the scenarios are consistent with those used in van Ittersum et al. (2016), but were updated to the reference year 2015—Scenario 1: In 2050, cereal yields are the same as today (the year 2015); Scenario 2: Actual cereal yield trends over the period 1991–2014 are extrapolated to 2050; Scenario 3: In 2050, cereal yields are 50% of water-limited potential yield (Y_w); Scenario 4: In 2050, cereal yields are 80% of Y_w. Actual and water-limited potential cereal yields for each of the scenarios were obtained from the Global Yield Gap Atlas (www.yieldgap.org; Grassini et al., 2015; Van Bussel et al., 2015) as also used in van Ittersum et al. (2016).

2.2 | Cereal yields and cereal areas required for self-sufficiency

For each of the four scenarios, we take the view that individual countries aim for self-sufficiency in cereal production in 2050. While we acknowledge that full self-sufficiency of cereals is generally not an explicit aim, it is generally agreed that substantial dependence on food imports is only possible if economic development is sufficient to afford them, while economic development of low-income countries to support such imports requires a strong agricultural development (Chang, 2012; Johnston & Mellor, 1961). Here, we briefly describe how calculations regarding self-sufficiency were performed; a complete overview can be found in van Ittersum et al. (2016).

Self-sufficiency is calculated as the ratio between domestic cereal production and cereal demand and is equal to 1 to obtain full self-sufficiency. Cereal demands for 2050 were derived from recent population projections (medium fertility variant of the UN population projections; United-Nations, 2015), and per capita consumption (Robinson et al., 2015). The predicted per capita cereal consumption includes direct human consumption of cereals, but also cereals as used for animal feed and other purposes like bioenergy and brewing. Predicted increased consumption per capita in Robinson et al. (2015) is similar to other forecast studies such as that of Alexandratos and Bruinsma (2012). In all forecast studies, predicted increase in cereal demand for 2050 compared to 2015 is mainly determined by the population growth in SSA, and to less extent to the increased per capita consumption of livestock products (Alexandratos & Bruinsma, 2012; van Ittersum et al., 2016). We expressed production and demand data at standard moisture content (maize: 15.5%; rice, sorghum, millet: 14%; wheat: 13.5%).

Each scenario has a different intensification level, with corresponding cereal yield and necessity to expand the production area to achieve self-sufficiency. We assumed that higher levels of intensification come with higher cereal yields per hectare, and therefore, less area needs to be converted to agricultural land to obtain full self-sufficiency. In our scenarios, cereal area expansion occurs through conversion of present grassland and/or forest (in proportion of current availability per country), and it is assumed that the productivity of newly converted land is equal to that of existing cereal land. Data on current areas of cereals, grassland, and forest were obtained from FAOSTAT (FAO, 2019). For estimations of GHG emissions in 2015, we included recent land conversion, considering any land conversion which occurred in the last 20 years (1995–2015) for cereal production (the default time period used in IPCC calculations for the transition between SOC equilibrium values; IPCC, 2006b).

The potential area available for expansion of crop production was taken from Chamberlin, Jayne, and Headey (2014), who considered per country the land area suitable for cropland expansion as land which is currently not cultivated, not part of a national park or other gazetted area, not of a low-yield potential and with a low population density. The potential cereal area for expansion was the land area suitable for cropland expansion multiplied by the current share of cereal land in the total cropland.

2.3 | Nitrogen input requirements

Data on current N inputs were obtained from FAOSTAT (FAO, 2019; which is the average N input for all arable and permanent crops, as it is not specified per crop type). N input requirements for the future scenarios were estimated with two methods: (a) minimum nitrogen input requirements (i.e. high-efficiency variant); and (b) nitrogen input requirement using a current mean value of agronomic nitrogen use efficiency (N-AE, i.e. extra grain yield per kg of N applied) in SSA (i.e. low-efficiency variant). Both variants use the underlying principles of ten Berge et al. (2019) and are briefly explained below.

2.4 | Minimum N input requirement (high-efficiency variant)

In the high-efficiency variant, N input for each of the scenarios (S1–S4) is estimated by the minimum nutrient input approach. It is postulated that the annual application rates of macronutrients (N, P, K) should at least be equal to total nutrient uptake in the aboveground crop biomass (grain and stover) of a given target yield, Y_T.

The nutrient input requirements for a given Y_T are calculated from: (a) coefficients to express physiological efficiency (kg grain per kg uptake), uptake efficiency (kg uptake per kg applied) and agronomic efficiency (kg grain per kg applied) of each nutrient (Table S2); (b) balanced nutrition implying that overall efficiency is best served if the different nutrients (N, P, K) are taken up in optimum stoichiometric ratios to one another; (c) the above efficiency coefficients and the crop nutrient ratios are constant up to a given relative target yield (Y_T/Y_w; here 0.62); and (d) beyond this point, the efficiency coefficients decrease non-linearly to a minimum value reached when the target yield approaches the yield ceiling Y_w. The constant efficiency values in the yield domain below Y_T/Y_w = 0.62 are referred to as 'initial' values. This variant is suitable for long-term calculations as it assumes soil N content being in equilibrium with a given input regime. This approach implies N-AE values of 52 kg/kg for Scenarios 1–3, and 46 kg/kg for Scenario 4.

2.5 | N application rate under current mean N-AE in SSA (low-efficiency variant)

In the low-efficiency variant, N input is estimated by the short-term nutrient input requirement, and assuming an initial N-AE of 14.3 kg/kg. This value corresponds with the mean value currently found for maize in on-farm field trials or on-station experiments in SSA (ten Berge et al., 2019). Thus, our N input requirement first increases linearly with target yield according to the SSA-mean N-AE, and then increases more steeply for relative target yields exceeding 0.62. This variant does not assume a steady-state equilibrium of soil N but accounts, instead, for current soil N supply. This method is therefore more compatible for short-term assessments. Soil N uptake was estimated in two steps: (a) extrapolation of current actual N inputs and yields with N-AE (14.3 kg/kg) to obtain yield at zero N input; (b) from this yield level at zero N input, the crop N uptake from soil was calculated using the physiological efficiency (Section 2.4).

2.6 | GHG emissions

Total GHG emissions from cereal production consist of emissions from land (forest or grassland) conversion to cereal area, the use of fertilizer, the production of mineral fertilizer and from flooding of rice fields. GHG emissions from removal of crop residues are not included. All emissions were converted to CO_2 equivalents. For GHG emission calculations and parameter values, we used the IPCC tier 1 approach, unless it is specifically indicated that another data source was used (Tables S1 and S2).

2.7 | CO_2 emission from land use change

Emission from land use change from either forest area or grassland to cereal cropland in the year 2050 is the total emission due to change in soil organic carbon (SOC) content, removal of forest biomass, and/or removal of grassland biomass. Data on the fraction of forest and grassland area in the specific country are obtained from FAOSTAT (FAO, 2019). We assume that the land use change from 2015 until 2050 is linear, and that the default time period for transition between equilibrium SOC values is 20 years (IPCC, 2006b). This means that the total forest or grassland area which needs to be converted to cropland to obtain full self-sufficiency in 2050 is equally distributed over the years.

The CO_2 emission from removal of forest is the aboveground carbon content of the forest times the land use change area (discounted over 20 years) and the proportion of forest of the total forest and grassland area in the specific country. We obtained aboveground forest biomass (AGB) per country by combining a forest cover map (forest defined as more than 10% tree cover; Hansen et al., 2013) with a biomass map (Zarin et al., 2016). Both maps have a resolution of 30 m, and are dated circa 2000. Average AGB was converted to aboveground forest carbon content by using a conversion factor of 0.5.

The CO_2 emission from the removal of grassland is similarly defined, namely the aboveground biomass of the grassland times the land use change area (discounted over 20 years) and the proportion of grassland of the total forest and grassland area in the specific country.

The CO_2 emission from SOC loss due to land use change depends on the SOC before conversion minus SOC after conversion. SOC before conversion is the total carbon content from the forest minus the aboveground carbon content. The total carbon content of the forest was obtained from conversion of the total biomass content of the forest using a conversion factor of 0.5. The total biomass map was derived from the AGB density map by applying the equation: Total biomass = AGB + $0.489\text{AGB}^{0.89}$ (Saatchi et al., 2011). SOC stock after land use conversion was obtained by multiplying the SOC stock before conversion with the relative stock change factors for cropland for land use, tillage and inputs used (Tables S1 and S2).

2.8 | N_2O emission from fertilizer use

Total emission from nitrogen input is composed of direct N_2O-N emission from applied fertilizer, indirect N_2O emission through NH_3 and NO_x volatilization and indirect N_2O-N emission from leaching and run-off. For brevity, we assumed that all nitrogen inputs come from mineral fertilizer only (see Section 2.3).

The direct N_2O-N emission from fertilizer application was estimated as the mineral fertilizer N applied multiplied by the emission factor for direct N_2O emission. The indirect emission of N_2O-N by volatilization of N as NH_3 and NO_x, was estimated as the mineral fertilizer N applied multiplied by the fraction of NH_3 and NO_x volatilized and the emission factor for N volatilization. The indirect emission of N_2O-N by leaching and run-off from land of N was estimated as the mineral fertilizer N applied multiplied by the fraction of N leached and run-off and the emission factor for leaching and run-off (Table S1).

2.9 | CO_2 emission from production of mineral fertilizer

The CO_2 emission from the production of mineral fertilizer was calculated as the amount of mineral fertilizer of a specific type multiplied by the emission factor for that specific type of fertilizer. We took world average emission factors for all fertilizer types (Table S2). The types of fertilizer used are based on FAOSTAT (FAO, 2019), and were assumed to remain the same in 2050 compared to 2015.

2.10 | CH_4 emission from rice fields

The CH_4 emission from rice cultivation was calculated as the default world CH_4 emission constant multiplied by a scaling factor for either irrigated or rainfed cultivation (Table S2).

2.11 | Negative emissions

We assumed that cereal area is converted to either forest and/or grassland area when the land area required to obtain full self-sufficiency of cereals in 2050 is less than the current cereal area (country by scenario). This means uptake of CO_2 (indicated with negative emissions) due to change in SOC content, sequestration of carbon in forest biomass, and/or sequestration of carbon grassland. Recovery of SOC of forest until equilibrium takes also 20 years similar to what was assumed for SOC breakdown (Guo & Gifford, 2002), but for SOC of grassland, it was assumed to take 53 years (Guo & Gifford, 2002). Recovery of grass biomass was assumed to take 20 years, and natural regeneration of forest 100 years, but carbon increment is fastest in first 20 years and differs per climate type (Albanito et al., 2016).

2.12 | Uncertainty and sensitivity analysis

2.12.1 | Uncertainty analysis

For each scenario, total GHG emissions were computed based on estimates of the model parameters. Therefore, any uncertainty in the model parameter values leads to uncertainty in the predicted emissions. To assess this prediction uncertainty, we performed an uncertainty analysis.

The uncertainty of the model parameter values is expressed in terms of a probability distribution for each parameter (Table S1). To assess the resulting uncertainty of model predictions, we drew 1,000 samples from parameter space using a replicated Latin hypercube design (Pleming & Manteufel, 2005). For each sample, we computed the resulting model predictions. These predictions were summarized in terms of the mean and a tolerance interval containing 95% of all model predictions.

2.12.2 | Sensitivity analysis

We performed a sensitivity analysis based on the same samples that were used for the uncertainty analysis. Sensitivity analysis is aimed at decomposing the uncertainty of model predictions into terms that are attributed to the model parameters. Thus, sensitivity analysis helps us to identify influential parameters.

The decomposition is based on a regression function with the model parameters as independent variables and the model predictions as dependent variable (Jansen, WaH, & Daamen, 1994). The regression function was acceptable when a fit of $R^2 > 0.9$ was obtained. Based on the regression function, we computed for each parameter the top marginal variance and bottom marginal variance. The top marginal variance estimates the proportion of the output variance that would disappear if a parameter were known exactly, that is, the variance that is explained by that parameter. The bottom marginal variance estimates the proportion of the output variance that would disappear if all other parameters were known exactly, that is, the variance that cannot be explained without that parameter.

The top marginal variance of a parameter is computed by fitting the regression function with that parameter as single explanatory variable, and comparing the explained variance to the full regression function. The bottom marginal variance is computed by fitting the regression function with all other parameters as explanatory variables, again comparing the explained variance to the full regression function (Jansen et al., 1994).

3 | RESULTS

3.1 | GHG emissions from intensification and land use conversion—high-efficiency variant

Analysis revealed that cereal intensification to 80% yield gap closure (Scenario 4) will require an enormous increase in nitrogen (N) application per hectare of at least 16 times the current use in SSA (Table 1). Current N input is very low (< 10 kg N/ha) (Table 1), and therefore does not even compensate for N offtake in actual yields. We estimate that just to sustain current yields, N input per hectare has to increase by almost a factor 4 (Scenario 1).

The increase in N application as a result of cereal intensification through yield gap closure will come with substantial GHG emissions (Figure 1). The fertilizer-induced emission (grey bars in Figure 1) consists for the largest part of direct N_2O emission from soils and CO_2 emission due to the production of fertilizer, respectively, on average across the four scenarios 45% and 41%. Indirect N_2O emission through leaching and run-off, and from NH_3 and NO_x volatilization accounted, respectively, for 10% and 4%. Area expansion results in large GHG emissions especially due to the removal of C from standing biomass of forest, which accounted on average across the scenarios for 63% of the total emissions from land use change (green bars in Figure 1). CH_4 emission from rice is the largest emitter of GHGs per unit area compared to the other cereal crops, followed by maize, wheat, sorghum and millet; therefore, for countries with rice cultivation, this is a substantial part of the total emissions (yellow bars in Figure 1).

For all countries, Scenario 1 in which yields do not increase has the largest GHG emissions (Figure 1). For the 10 countries jointly, emissions from Scenario 1 are more than threefold those of Scenario 4, while Scenarios 2 and 3 take intermediate positions. In Tanzania and Nigeria, the largest GHG emissions are projected; the share of both countries together in the total GHG emissions of the 10 SSA countries is on average 56% across the scenarios. This is due to their high population and large cereal demand in 2050 and current limited cereal area, and thus relatively more cereal area expansion is needed (Table S3).

Irrespective of the scenario chosen, GHG emissions of the 10 countries jointly for 2050 are always higher compared to 2015; for Scenario 1, they are almost sixfold more, while for Scenario 4, they are 1.5 times more (Figure 1). The increase between 2015 and 2050 differs, however, hugely between countries. In countries which faced relatively rapid crop area expansion over the past decades (Ethiopia, Tanzania, Burkina Faso and Mali), our estimated emissions in 2050 for intensification scenarios are lower than estimated emissions in 2015, as still CO_2 is omitted originating from this expansion.

TABLE 1 Weighted average current (2015) and estimated future (four scenarios) N input (high efficiency variant) on cereal land, total cereal area and land use expansion needed for full self-sufficiency in 2050 for five cereals[a] and 10 countries in sub-Saharan Africa (SSA)[b]

	Current: 2015	Scenario 1: actual yields	Scenario 2: yield trends	Scenario 3: 50% potential yield	Scenario 4: 80% potential yield
Average N input (kg/ha)	8	28	39	63	127
Total area SSA (Mha)	54.91	211.00	142.26	90.38	62.10
Total cereal land area expansion needed for SSA (Mha)[c]		156.09	87.35	35.47	7.19

[a]Maize, millet, rice, sorghum, wheat.

[b]Burkina Faso, Mali, Ghana, Kenya, Ethiopia, Niger, Nigeria, Zambia, Tanzania, Uganda.

[c]Potential cereal area available for expansion for the 10 SSA countries is 34.85 Mha (source potential area: Chamberlin et al., 2014).

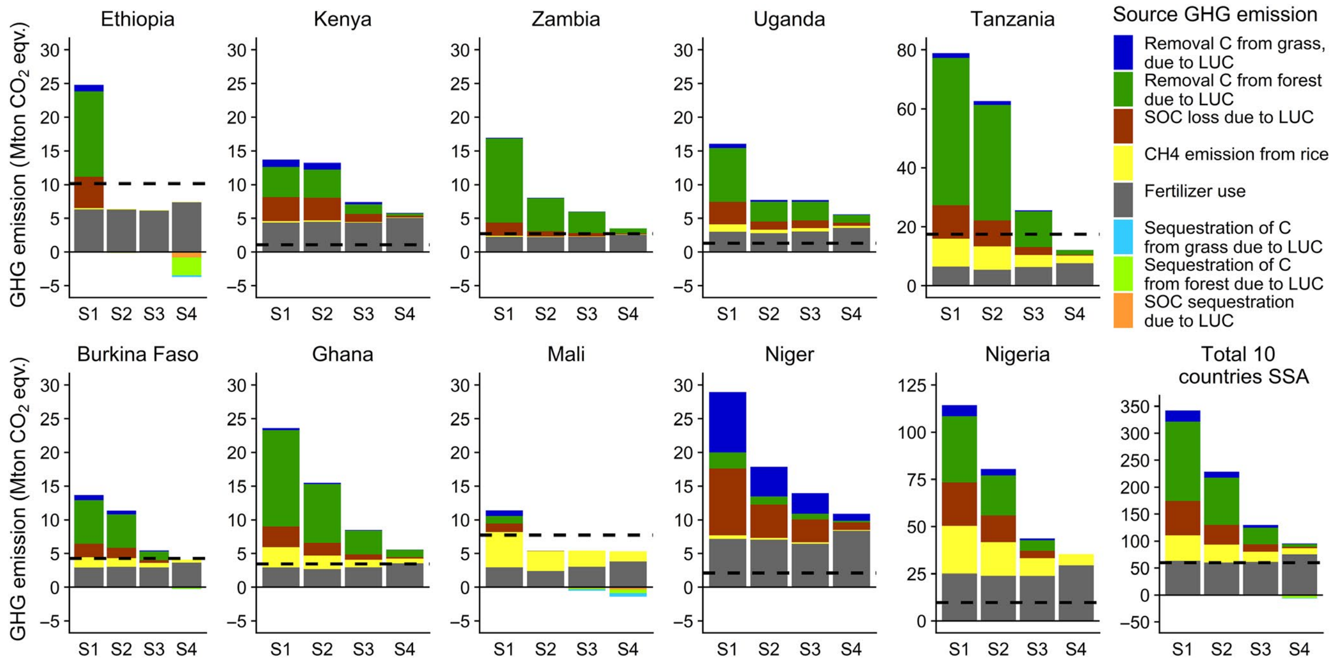

FIGURE 1 Total greenhouse gas (GHG) emission from cereal production in 2050 for four intensification scenarios (S1–S4) in 10 sub-Saharan Africa countries and the aggregated result (total 10 countries SSA), and for 2015 (dashed lines). Different colours indicate the estimated level of the different origins of GHG emission (LUC, land use change: either expansion or contraction of cereal area; SOC, soil organic carbon). Negative GHG emissions indicate C sequestered by conversion of cereal land back to forest or grassland. Nitrogen input is calculated according to the high-efficiency variant

For Ethiopia, Burkina Faso and Mali, intensification on current cropland (Scenario 4) is assessed to result in more production than required for full self-sufficiency, and potentially land savings and reforestation could take place (apparent through the negative GHG emissions). Nevertheless, for most countries, Scenario 4 still requires land use conversion to meet self-sufficiency in 2050 (Table S3). The results of the analysis at the national level also reveal that matching food demand through land use conversion, instead of intensification, is not always an option as land area required for such expansion is not available in most SSA countries (Table 1; Table S3). For example, Niger and Uganda do not have the required cropland area for any of the scenarios, while only Zambia potentially has the land area required for land use conversion for all four scenarios. For the 10 SSA countries jointly, there is only sufficient land suitable for land use conversion for Scenario 4.

3.2 | Robustness of scenario results for maize

In the previous section, we used the high-efficiency variant to estimate N input requirements for all cereals and scenarios. This implies that for maize, an agronomic nitrogen use efficiency (N-AE, extra grain yield per kg of fertilizer applied) was assumed of 52 kg/kg for Scenarios 1–3, and 46 kg/kg for Scenario 4 (ten Berge et al., 2019). In reality, such efficiencies are currently not achieved in SSA, and hence, larger N applications may be necessary than we assumed. Therefore, we also estimated N input requirements with a low-efficiency variant for maize only, using an initial N-AE of 14.3 kg/kg which is the mean current N-AE found for maize in farmer field trials in SSA (ten Berge et al., 2019). The high-efficiency variant (Section 3.1) results in minimum N application rates; N application and thereby also GHG emission are much lower than in the low-efficiency variant for Scenarios 2–4 (Figure 2a,b). However, for Scenario 1 the GHG emissions are higher in the high-efficiency variant because the latter sustains—unlike the low-efficiency variant and today's practice—soil N supply by extra N input (Table S4; Figure 2a,b).

Scenarios which reach self-sufficiency mainly with land use conversion (both forest and grassland) had much larger GHG emissions than scenarios which mainly rely on intensification of current agricultural land, according to the high-efficiency variant. Using the low-efficiency variant, intensification still leads to lower GHG emissions until Scenario 3 (50% of Y_w), but not anymore with Scenario 4 (80% of Y_w; Figure 2b; note that Scenario 4 is still superior to Scenarios 1 and 2). However, the standard deviation of the total GHG emission arising from the uncertainty in model parameters (represented by the error bars in Figure 2a,b) is large. While with the high-efficiency variant, the trend—that intensification results in less GHG emissions compared to extension—is robust when accounting for uncertainty, the trend of the low-efficiency variant is highly uncertain. We decomposed the uncertainty to identify model parameters that attribute most to the total uncertainty (Figure 2c,d). For both variants, the main source of uncertainty in Scenario 1 is emissions from forest biomass, and for Scenarios 3 and 4, emissions from fertilizer use (Figure 2c,d). Within fertilizer use, the main contributors to uncertainty are the estimation of the direct N_2O emission factor for the high-efficiency variant (Figure 2c), and of N-AE for the low-efficiency variant (Figure 2d).

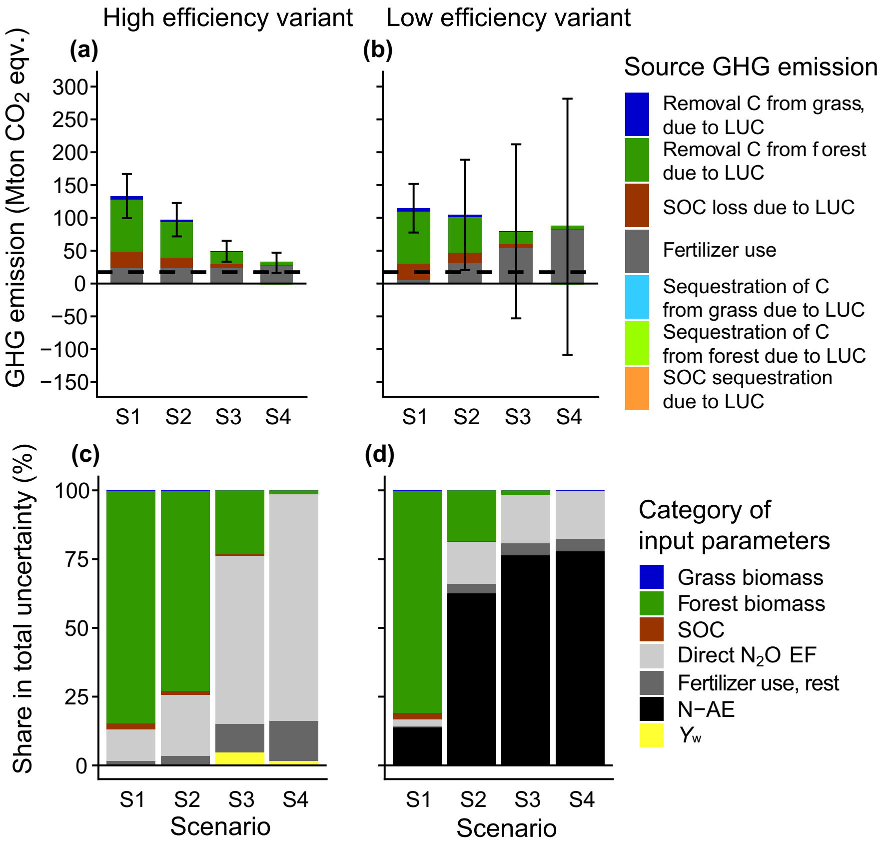

FIGURE 2 Total greenhouse gas (GHG) emission from maize production in 10 sub-Saharan Africa countries with its uncertainty, and the contribution of different input parameter categories to this uncertainty. Total GHG emission in 2050 for the different intensification scenarios (panels a, b), and for 2015 (dashed lines). Error bars represent the standard deviation. Contribution of all categories of input parameters to the total uncertainty (panels c, d) as represented by the error bars in panels (a) and (b). Panels (a) and (c) refer to the nitrogen input as calculated according to the high efficiency variant, and panels (b) and (d) to the low efficiency variant. EF, emission factor; LUC, land use change: cereal area expansion or contraction; (initial) N-AE, initial agronomic nitrogen use efficiency; SOC, soil organic carbon; Y_w, water-limited potential yield

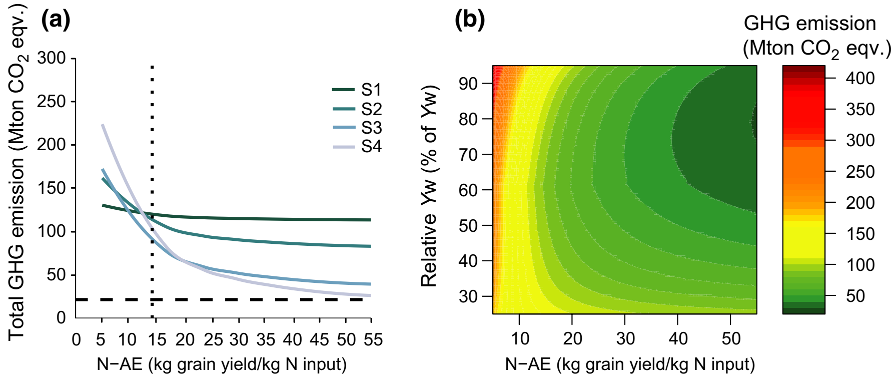

FIGURE 3 Total greenhouse gas (GHG) emission (including fertilizer and land use change emissions) from maize production in 10 sub-Saharan Africa (SSA) countries by 2050 for different agronomic N use efficiencies (N-AE) and intensification levels. GHG emission for different values of N-AE for (a) the intensification scenarios S1–S4 (dashed line indicates estimated current GHG emission and dotted line indicates observed N-AE in on-farm experiments), and for (b) different yield levels, expressed as a percentage of water-limited potential yield (relative Y_w; red colours indicate large emissions of GHGs, while green colours indicate low GHG emissions). Nitrogen input is calculated using the assumptions of the low-efficiency variant, but a range of N-AE values is used as input instead of current SSA-mean N-AE

3.3 | Maize intensification and agronomic N use efficiencies

The effects of initial N-AE on the outcomes were further explored for maize, by using a range of initial N-AE values instead of the fixed value of 14.3 kg grain yield kg/N as assumed in the low-efficiency variant. Figure 3 shows for maize at which initial N-AE value intensification is still superior to land use conversion in terms of GHG emissions. As already noted, with current nutrient management (i.e. an initial N-AE of 14.3 kg grain yield/kg N), Scenario 3 results in less GHG emission than Scenario 4, and we estimate that it would be most optimal in terms of minimum GHG emissions to intensify maize production until ca. 60% of Y_w, leading to a total GHG emissions of 92 Mton CO_2 eqv. (Figure 3b). When initial N-AE exceeds 20 kg grain yield/kg N, Scenario 4 results in less GHG emission than Scenario 3 (Figure 3a). With an initial N-AE of 30 kg grain yield kg/N, intensifying maize production until ca. 70% of Y_w would be most optimal and emissions would be reduced to 50 Mton CO_2 eqv. Note that at an initial N-AE of 30, Scenarios 3 and 4 are clearly superior to Scenarios 1 and 2 (Figure 3a).

4 | DISCUSSION

This study provided insight into the consequences for GHG emissions of achieving future cereal self-sufficiency in SSA through scenarios with different levels of intensification and/or area expansion and different nutrient management variants. Evidently, irrespective of the investigated scenarios, GHG emissions in SSA will increase towards 2050 compared to present values, due to the tripling demand for cereals. We showed that for the 10 studied countries jointly GHG emissions from cereal cropping can increase up to 500% in 2050 compared to 2015 for scenarios in which area expansion is a main pathway to increase production (which has been the case in recent decades). Note that this assumes high nutrient use efficiency; a low nutrient use efficiency would lead to even larger increases. Such increases would have a large impact on the total GHG emissions from SSA, as cereal cropping alone would then already increase the total GHG emissions from SSA by 20% (CAIT, 2017). We also show that intensification of cereal production with efficient use of fertilizers will moderate the increase in GHG emissions, although it requires a large increase in nutrient inputs. In this study, we only investigated the role of agricultural production in mitigation of GHG emissions, but additional mitigation benefits could be gained from the whole value chain, for example, by improved waste management, and more efficient distribution and transportation.

4.1 | Nutrient inputs

There is currently extensive soil nutrient depletion, which is general practice in SSA (Giller, Witter, Corbeels, & Tittonell, 2009), due to low nutrient inputs. We showed that a large increase in nitrogen (N) application is required to sustain current yields. Intensifying cereal production will require even more N application, thereby reaching application levels which are similar to European Union average values (Van Grinsven et al., 2012).

Irrespective of the scenario chosen, increased N input should always come with efficient nutrient management, as inefficient nutrient management (i.e. low values of agronomic N use efficiency, N-AE) results in high emissions of GHGs (plus other types of nutrient losses) from fertilizer use independent of the intensification level. The N-AE is of key importance in determining whether intensification is more favourable than area expansion for climate change mitigation and how much. If current N-AE of 14 kg grain yield kg/N would be increased to 30 kg grain yield kg/N, this would on average across the scenarios already result in a reduction of 26% in GHG emissions. We suggest that an N-AE of 30 kg grain yield kg/N can be well achieved in SSA, as in some locations, it is already obtained (ten Berge et al., 2019), and it is also a common efficiency achieved in for instance the United States (Ciampitti & Vyn, 2012). Yet, such enhanced use efficiency requires substantial improvements in current management practices, including good seed quality of the right crop cultivars, good planting densities, balanced crop nutrition, integrated soil fertility management (Vanlauwe et al., 2010) and improvements in controls of weeds, pests and diseases. There is thus a need for farmers to adopt new strategies, but adoption of these measures is currently already difficult for smallholder farmers and might become more difficult in the future as more climate variability is expected (Burke & Lobell, 2010). This points at the need to invest in research and development on nutrient management to go hand in hand with good agronomy to enhance the nutrient use efficiency of fertilizers.

4.2 | Avoiding crop area expansion

Our study reveals that compared to scenarios in which area expansion is the main pathway to increase production (which has been the case in recent decades), intensification of cereal production with efficient use of fertilizers will lead to much lower GHG emissions and might conserve forest and/or permit reforestation. Forest conversion to agriculture might conflict with SSA countries' global commitments set out in the Cancun Agreements on REDD+ (Reducing Emissions from Deforestation and Forest Degradation and forest conservation, sustainable management of forests and enhancement of forest carbon stocks) in order to address the challenge of climate change (UNFCCC, 2010). It contradicts also with the SSA countries' strategic response to climate change effects (e.g. Ethiopia's climate resilient green economy strategy; Federal-Democratic-Republic-of-Ethiopia, 2011), and to the national targets set in their National Determined Contribution. While we show that intensification results in lower emissions because of reducing the need for area expansion, we also note that higher yields may not necessarily spare land for nature, and might end up driving deforestation rather than reducing it (Ewers, Scharlemann, Balmford, & Green, 2009). Whether yield increases spare land or stimulate expansion depends on various factors such as markets for agricultural products and forest governance and conservation policies (Ewers et al., 2009).

4.3 | Methodological considerations and uncertainties

We showed how our results depend on various assumptions and uncertainty in parameters. The IPCC tier 1 estimate for direct N_2O emissions, which is directly linked to mineral fertilizer N applied (IPCC, 2006a), contributed most to the uncertainty in the resulting GHG emissions of each scenario. Despite a recent meta-analysis of the N_2O emission factor (Albanito et al., 2017), it is widely recognized that especially for Africa, a better estimate for the N_2O emission factor is required, due to the limited availability of data in the region (Albanito et al., 2017; Reay et al., 2012). More attention should therefore be given in future research to obtain more precise estimates of this emission factor.

In this analysis, we assumed that mineral fertilizer is used to fulfil the nutrient input requirements, but other sources of nutrients can also be used, such as leguminous crops and animal manure. Per kg of N applied, animal manure results in similar direct N_2O emissions (IPCC, 2006a), but have additional GHG emissions from amongst other storage and methane emissions from animals (Monteny, Bannink, &

Chadwick, 2006), while no CO_2 emissions from fertilizer production. The specific size of the effect of including animal manure on GHG emissions is therefore unknown, but generally manure is only sparsely available in most of SSA. In each of the four presented scenarios, the available amount of manure which can be used will be similar, thereby probably not changing the observed trends and our main conclusions.

Inclusion of leguminous crops in cropping systems can reduce the mineral fertilizer N requirement for the subsequent crop (Jensen et al., 2012). A meta-analysis for SSA revealed that this residual effect of legumes can result in 450–700 kg/ha extra maize yield (Franke, Van Den Brand, Vanlauwe, & Giller, 2017). This potentially lowers the input of mineral fertilizer by 0–51 kg N/ha resulting in 0.03–12.18 Mton CO_2 eqv. less total GHG emissions depending on the scenario. However, Palm et al. (2010) showed for two contrasting sites in SSA that GHG emissions per unit maize produced is lower if only mineral fertilizer is used in comparison to using only green manure. Apparently, the increased N_2O emissions from legume residue incorporation outweigh the benefits of reduced needs for mineral fertilizer inputs.

In this study, we included current climate variability, but did not consider the implications of long-term climate change. In addition, we also did not take into account the adoption of technological and genetic improvements which may partly offset negative effects of climate change. Furthermore, until 2050, the projected effect of climate change is not only highly uncertain but also relatively small compared to the large yield gaps (see van Ittersum et al., 2016 for more details). It seems likely that due to climate change, potential yields will be affected (varying between a slightly positive impact, up to 10%, in high elevation regions of east SSA to negative impact up to approximately 20% elsewhere in SSA; Niang et al., 2014; Porter et al., 2014), but how climate change will affect N-AE, and thus, N requirements remains unclear. If we assume climate change has no effect on N-AE, it will result in the need for more area expansion (assuming average yields will somewhat decrease), and thus, climate change will favour intensification scenarios rather than expansion scenarios in terms of GHG emissions. If N-AE is negatively affected by climate change, the sensitivity analysis of N-AE revealed that this will favour the expansion scenarios, but at the same time, climate change results in the need for more expansion because of lower yields. So, overall, we argue that short-term climate change is likely to have neutral to aggravating effects on relative advantages of intensification scenarios over expansion scenarios.

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