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REVIEW

Challenges and opportunities for enhancing food security and greenhouse gas mitigation in smallholder farming in sub-Saharan Africa. A review

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Abstract
Smallholder farmers struggle to achieve food security in many countries of sub-Saharan Africa (SSA). It is urgently required to find appropriate practices for enhancing crop production while avoiding large increases in greenhouse gas (GHG) emissions in SSA. This review aims to identify common smallholder farming practices for enhancing crop production, to assess how these affect GHG emissions and to identify strategies that not only enhance crop production but also mitigate GHG emissions in SSA. To increase crop production and ensure food security, smallholder farmers usually expand agricultural land, develop water harvesting and irrigation techniques and increase cropping intensity and fertilizer use. These practices may result in changing carbon stocks and GHG emissions, potentially creating trade-offs between food security and GHG mitigation. Agricultural land expansion at the expense of forests is the most dominant source of GHG emissions in SSA. While water harvesting and irrigation can increase soil organic carbon, they can trigger GHG emissions. Increasing cropping intensity can enhance the decomposition of soil organic matter, thus releasing carbon dioxide. Increasing nitrogen fertilizer use can enhance soil organic carbon, but also leads to increasing nitrous oxide emissions. An integrated land, water and nutrient management strategy is necessary to enhance crop production and mitigate GHG emissions. Among the most relevant strategies found, agroforesty practices in degraded and marginal lands could replace expanding agricultural croplands. In addition, water management, via adequate rainwater harvesting and irrigation techniques, together with appropriate nutrient management should be considered. Therefore, a land-water-nutrient nexus (LWNN) approach will enable an integrated and sustainable solution to increasing crop production and mitigating GHG emissions. Various technical, economic and policy barriers hinder implementing the LWNN approach on the ground, but these may be overcome through developing appropriate technologies, disseminating them through farmer to farmer approaches and developing specific policies to address smallholder land tenure issues and motivate long-term investment.

Keywords Sub-Saharan Africa · Smallholder farming systems · Crop production · Greenhouse gas emission · Agricultural land, water harvesting, irrigation, cropping intensity, fertilizer

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1 Introduction

Agriculture in sub-Saharan Africa (SSA) plays an important role in livelihood and economic growth through employing 51.6% of the population and generating 20.5% of the gross domestic product (GDP) of these countries (in 2016) (The Global Economy 2019). Agricultural production systems in SSA are largely based on smallholder farming systems, which are defined by farms covering an area of ≤2 ha (Lowder et al. 2016; Fig. 1). Recent estimates suggest the presence of approximately 33 million smallholder farms in SSA (IFC 2013), which contribute up to 90% of the agricultural production in some SSA countries (Wiggins 2009).

Currently, consumption of self-produced food crops only covers 20% of the food need of SSA households (Frelat et al. 2016). Thus, food security remains difficult to achieve among smallholder farmers and they face a large number of challenges (van Ittersum et al. 2016; Tilman et al. 2011). First, the agricultural sector is underdeveloped and is characterized by over-reliance on primary agriculture, minimal use of external farm inputs, significant pre- and post-harvest food crop loss and minimal value addition and product differentiation (Assefa et al. 2020; van Ittersum et al. 2016; Tilman et al. 2011). All lead to low crop productivity (Singh et al. 2020; Assefa et al. 2020; Frelat et al. 2016; Fig. 2). Second, water availability is highly affected by droughts in the context of regional and global climate variability and change (Misra 2014). Third, severe degradation of agricultural soils negatively affects crop yield (Tittonell and Giller 2013). Fourth, SSA's population is predicted to grow from 1.02 billion in 2017 to 1.4 billion by 2030 and to 2.17 billion by 2050 (United Nations Population Division 2017). Given population expansion, food demand in SSA will substantially increase; while cereal demands will most likely triple, current levels of cereal consumption already depend on substantial imports (van Ittersum et al. 2016).

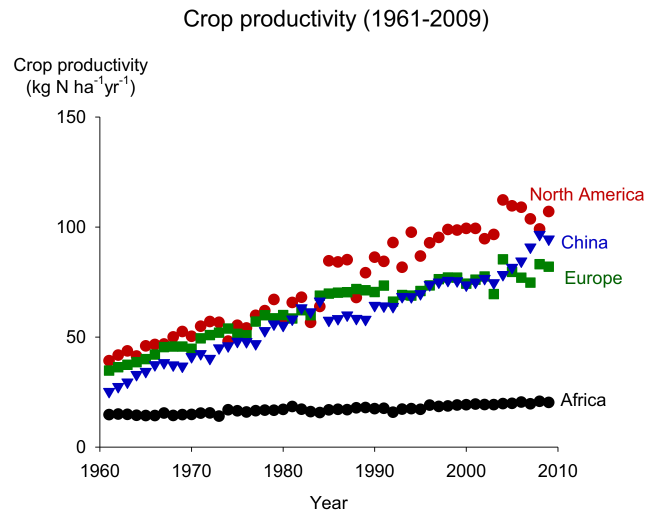

Fig. 2 Changes of crop productivity in Africa, North America, Europe and China in 1961 to 2009 (Data source: FAO STAT). The crop productivity in Africa is very low compared to other regions

In addition, growing concern exists that ongoing practices for increasing crop yield in SSA may cause increasing greenhouse gas (GHG) emissions and further contribute to global climate change (Leitner et al. 2020; van Loon et al. 2019; FAO 2018; Tongwane and Moeletsi 2018). Agricultural land expansion at the expense of forests is expected to continue (Hertel et al. 2016; Lambin and Meyfroidt 2011). Deforestation for agricultural land expansion is a substantial source of GHG emissions (Grewer et al. 2018; Wanyama et al. 2018; Kim and Kirschbaum 2015) and agricultural intensification tends to increase GHG emissions (Grewer et al. 2018; Kim et al. 2013). These increases can be particularly relevant

Fig. 1 Agricultural production systems in sub-Saharan Africa are largely based on smallholder farming systems. Typical example of smallholder farms with small crop fields located nearby homesteads in western Ethiopia (photo courtesy: Dong-Gill Kim)

when inappropriate agricultural practices, such as severe soil disturbance or excessive nitrogen (N) fertilizer use, are adopted (Grewer et al. 2018; Kim et al. 2013). Although emissions of the GHG nitrous oxide (N_2O), per unit area, may be low due to the small amount of N fertilizer applied by most African smallholders (Kim et al. 2016c), N_2O emissions per unit of agricultural production (e.g., yield-scaled N_2O emissions; Kim and Giltrap 2017; Sainju 2016) may be high due to low productivity (Pelster et al. 2017; Seebauer 2014; Kimaro et al. 2016). Overall, agricultural GHG emissions in SSA increased by 1.2–4.7% annually between 1994 and 2014 (Tongwane and Moeletsi 2018), while global agricultural GHG emissions increased by 1.1% annually between 2000 and 2010 (Tubiello et al. 2013). To sustainably improve agricultural production in SSA, efforts are needed to identify and implement measures, which can enhance crop yields while avoiding large increases in GHG emissions (Leitner et al. 2020; van Loon et al. 2019; FAO 2018; Tongwane and Moeletsi 2018).

To enhance crop yields, smallholder farmers in SSA generally adopt a single approach rather than an integration of multiple approaches (Thierfelder et al. 2017; Sheahan and Barrett 2017). However, to enhance crop yield and GHG mitigation simultaneously in smallholder crop farming, it is necessary to comprehensively consider different approaches (Sheahan and Barrett 2017; Zougmoré et al. 2014; Branca et al. 2013), since adopting a single approach cannot properly manage the complexity of crop production and GHG mitigation challenges. The adoption of different approaches can create positive synergetic effects beyond the additive effect of each approach (Sanz-Cobena et al. 2017; Zougmoré et al. 2014; Branca et al. 2013). Even so, due to the lack of on-site data, further efforts including research and field demonstrations identifying optimal combinations of different approaches are urgently needed (Sheahan and Barrett 2017; Thierfelder et al. 2017; Zougmoré et al. 2014; Branca et al. 2013).

This review aims 1) to identify the current status and future potentials of smallholder farming practices for enhancing crop production, 2) to assess how these practices can affect GHG emissions, 3) to identify management practices that can both enhance crop yield and mitigate GHG emissions and 4) to assess the main barriers to their implementation and propose potential solutions in smallholder crop farming systems in SSA.

2 Common practices for increasing crop production of smallholder farms in SSA

Smallholder farmers adopt various practices to increase crop production in SSA. For this review, we selected the most adopted practices by smallholder farmers throughout SSA, of which the magnitudes of adoption were also relatively well quantified: 1) land management, exemplified by the expansion of agricultural lands and the increase of cropping intensity; 2) water management, exemplified by the development of water harvesting and irrigation techniques; and 3) nutrition management, exemplified by the increase of fertilizer use. Current status and future potential of these practices are discussed below.

2.1 Expansion of agricultural lands and increase of cropping intensity

Expanding agricultural lands is one of the most common land management practices to increase crop production in smallholder crop farming in SSA (Nakawuka et al. 2018; Droppelmann et al. 2017; Heady 2015). Agricultural lands in SSA have increased from 86.9×10^7 in 1993 to 92.0×10^7 ha in 2009 with an average increase rate of 3.2×10^6 ha per year (FAOSTAT 2019). Mainly natural lands, such as forests, savannahs and wetlands, have been converted to agricultural lands (Gibbs et al. 2010; Brink and Eva 2009; DeFries et al. 2010). In SSA, natural forest decreased from 65.4×10^7 in 1993 to 59.9×10^7 ha in 2009 with an average deforestation rate of 3.4×10^6 ha per year (FAOSTAT 2019). While overall agricultural lands have increased in SSA, in most of the land-constrained countries, such as Ethiopia, Kenya and Malawi, the farm size of most smallholder farms has been gradually shrinking. Average farm sizes have been reduced by 30–40% since the 1970s, mainly due to rapidly increasing populations (Jayne et al. 2014; Headey and Jayne 2014). Expansion of agricultural lands will likely continue in SSA to meet growing food demand (Molotoks et al. 2018; Hertel et al. 2016; OECD/Food and Agriculture Organization of the United Nations 2015). Alexandratos and Bruinsma (2012) projected that the area used for crop production in Africa will increase to 266×10^6 ha in 2030 and 291×10^6 ha in 2050. Previous studies have shown substantial potential to expand agricultural land in wet savannahs, shrublands and sparse woodlands in SSA (Chamberlin et al. 2014; Alexandratos and Bruinsma 2012; Deininger et al. 2011). However, it was found that many countries in SSA have limited potential for agricultural land expansion while avoiding deforestation (Jayne et al. 2014; Chamberlin et al. 2014; Deininger et al. 2011). Except for a few countries, such as the Democratic Republic of Congo and Angola, most countries in SSA have less than 6% (0.4 to 5.9%) of non-forested unutilized land available (Jayne et al. 2014). Chamberlin et al. (2014) estimated that potentially expandable cropland for smallholder farms is only 80×10^6 ha in SSA if forest conversion is to be avoided.

Intensification has been adopted to enhance crop production in SSA (van Ittersum et al. 2016; Headey and Jayne 2014; Mueller et al. 2012), most notably by increasing cropping intensity−the number of crops grown per a year on the same field (Headey and Jayne 2014). As population pressures cause a gradual shrinking of farm sizes over time (Jayne et al. 2014; Headey and Jayne 2014), smallholder farmers have been practicing cultivating their fields continuously, shortening fallow periods between individual cropping periods and changing the traditional crop types to high-value mono-species cash crops (Kim et al. 2016b; Jayne et al. 2014; Headey and Jayne 2014). Cropping intensity in SSA increased 10.6% and 25.4% in low and high population density countries, respectively, in the period 1977–2007 (Headey and Jayne 2014).

2.2 Development of rainwater harvesting and irrigation

Since more than 90% of cultivated land in SSA is rainfed, crop production in arid, semi-arid and sub-humid areas in SSA is at risk from highly variable rainfall, frequent droughts and low water productivity (Karpouzoglou and Barron 2014; Misra 2014). Rainwater harvesting technologies such as pitting, contouring, terracing, open ponds, and cisterns have been used to enhance crop production in certain regions of SSA (Leal Filho and de Trincheria Gomez 2018; Karpouzoglou and Barron 2014; Dile et al. 2013; Biazin et al. 2012). These technologies have been advanced as essential to achieving water availability and crop production in these areas (Taffere et al. 2016; Rockström et al. 2010). Indigenous rainwater harvesting techniques (e.g. spate irrigation) or those modified from traditional techniques are more common and widely accepted by smallholder farmers compared to introduced ones (Biazin et al. 2012; Mbilinyi et al. 2005). Studies on the economic costs and benefits of rainwater harvesting found significant profits in Ethiopia (Hagos et al. 2012), Tanzania (Senkondo et al. 2004), Kenya (Ngigi et al. 2005) and Burkina Faso (Fox et al. 2005). Due to substantial rain and currently underexploited surface and ground water resources, great potential exists for expanding rainwater harvesting in SSA (Altchenko and Villholth 2015; Cassman and Grassini 2013; Pavelic et al. 2013). In Ethiopia, Kenya, Uganda and Tanzania, rainwater harvesting potential was estimated at over 10,000 to 25,000 m^3 rainwater $person^{-1}$ (Mati et al. 2006).

Irrigation holds the potential to improve crop production and mitigate the impacts of climate stress associated with drought and extreme heat in SSA (Burney et al. 2013). Irrigation has gradually been expanded in SSA (Altchenko and Villholth 2015; Sheahan and Barrett 2014; You et al. 2011). The average rate of expansion of irrigated area over the past 30 years is 2.3% in SSA (You et al. 2011), where the area currently equipped for irrigation is estimated to be slightly more than 13×10^6 ha, making up 6% of the total cultivated area (Cassman and Grassini 2013; You et al. 2011). Around 0.2 to 3.5% of smallholder farms in Ethiopia, Malawi, Niger, Nigeria, Tanzania and Uganda can access irrigation (Sheahan and Barrett 2014). Despite low irrigation development, irrigated agriculture accounts for nearly 38% of the economic value of all agricultural output (Svendsen et al. 2009). A field survey of 1554 smallholder farmers in nine SSA countries showed that gravity-flow, manual-lift and motor-pump irrigation increased the value of agricultural production per farmland size as well as per family worker compared to rain-fed-only farms (Shah et al. 2013).

There is substantial potential for further irrigation development and expansion in SSA (Cassman and Grassini 2013; You et al. 2011). In SSA, average annual renewable groundwater availability for irrigation ranges from 692 to 1644 km^3; therefore, the total area of irrigable cropland with renewable groundwater includes between 20.5 to 48.6% of the continent's cropland (Altchenko and Villholth 2015). Xie et al. (2014) revealed a large potential for profitable smallholder irrigation expansion in SSA, with irrigation technologies benefiting between 113 and 369×10^6 rural people in the region by generating net revenues of US \$14–22 billion yr^{-1} (Xie et al. 2014). Improving rainwater harvesting and irrigation development in SSA will contribute to enhancing crop production in smallholder households.

2.3 Increase of fertilizer use

Research demonstrated that the amount of fertilizer application in SSA was very low compared to other regions (Fig. 3). Mean N application rates in SSA were 16 kg N ha^{-1} in 2009 compared to 169.1 kg N ha^{-1} in the United States in the same year (Lassaletta et al. 2014). The low fertilizer use in SSA has been attributed to low financial capacity of farmers, low availability of input products in local markets, unfavorable fertilizer/crop-price ratios (Duflo et al. 2008; Croppenstedt et al. 2003) and low response rates of crops to fertilizer inputs

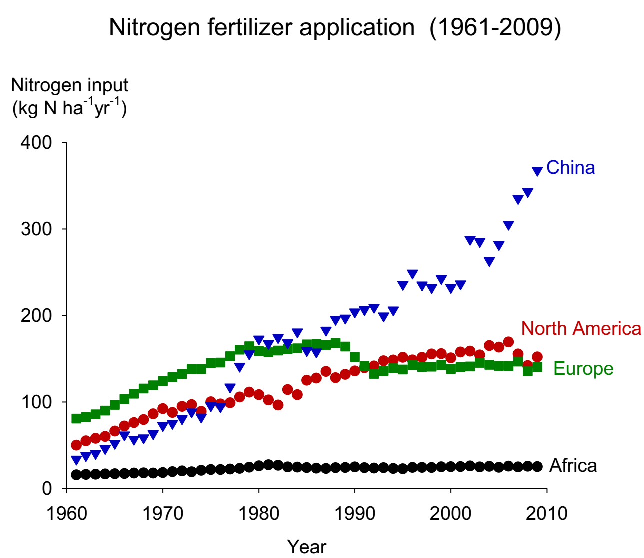

Fig. 3 Changes of nitrogen (N) fertilizer application in Africa, North America, Europe and China in 1961 to 2009 (Data source: FAO STAT). The amount of N fertilizer application in Africa is very low compared to other regions

(Roobroeck et al. 2021; Ichami et al. 2019; Riesgo et al. 2016). Some governments in SSA have introduced fertilizer subsidy programs to increase crop productivity (Koussoubé and Nauges 2017; Jayne and Rashid 2013). Ten African governments spend roughly US$1 billion annually on fertilizer subsidy programs (Jayne et al. 2014). Recent studies found that synthetic fertilizer use among smallholders is far more widespread than commonly assumed (Sheahan and Barrett 2017). Over 75% of all cultivating households in Malawi, 50% in Ethiopia and around 40% in Nigeria use synthetic fertilizer in some amount in the main growing season (Sheahan and Barrett 2017). Maize fields receive more synthetic fertilizer than non-maize-dominated plots (Sheahan and Barrett 2017). Increasing use of synthetic fertilizer is predicted in SSA (Ten Berge et al. 2019; Zhang et al. 2015; Tenkorang and Lowenberg-DeBoer 2009). The annual growth rate of synthetic fertilizer demand (2015–2020) in SSA is predicted to be 3.1, 1.8 and 1.3 times higher than the global average for N, phosphate (P_2O_5) and potash (K_2O) fertilizers, respectively (FAO 2017; Fig. 4). Similarly, N fertilizer use is expected to increase from 0.9 Mt in 2015 to 1.2 Mt in 2030 in SSA (Tenkorang and Lowenberg-DeBoer 2009).

3 Impact of the smallholder farming practices on GHG emissions

Increasing crop production in SSA is an urgent and indubitable necessity. Finding approaches to attaining sustainable crop production requires an understanding of the environmental implications of different pathways of agricultural growth. Here we assess the changes in GHG emissions associated with the management practices detailed in section 2.

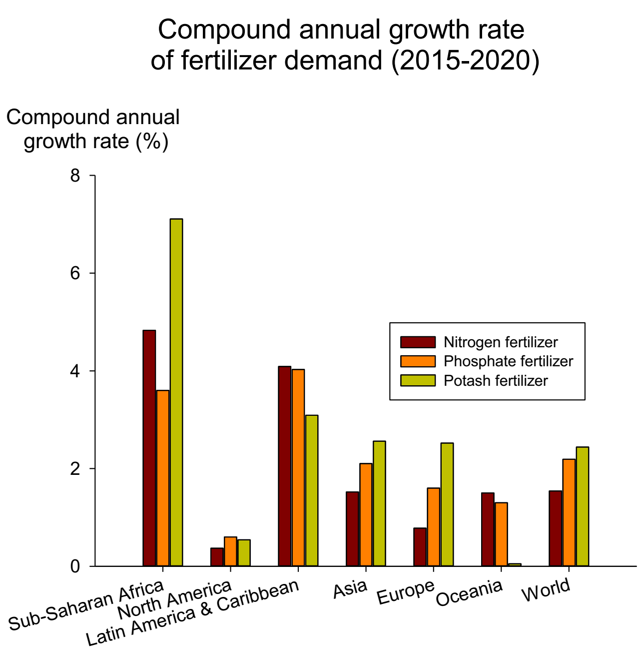

Fig. 4 Annual growth rate from 2015 to 2020 (determined as compound annual growth rate) of synthetic fertilizer (nitrogen, phosphate and potash fertilizers) demand in different regions (Data source: FAO 2017)

3.1 Expansion of agricultural lands and increase of cropping intensity

The conversion of natural forest to agricultural land and increasing cropping intensity affect carbon (C) budgets (Kim and Kirschbaum 2015) due to loss of C stored in standing woody biomass (Pearson et al. 2017) and degraded SOC (Wei et al. 2014; Murty et al. 2002). The changes in SOC and C in vegetation biomass driven by conversion of natural forest to agricultural land are directly related to changes in the CO_2 budget, since any loss of biosphere C stocks increases atmospheric CO_2 (Kim and Kirschbaum 2015). Intensive soil disturbance caused by increasing cropping intensity can enhance the loss of SOC through decomposition of soil organic matter (Kim et al. 2016a; Jayne et al. 2014; Headey and Jayne 2014), resulting in CO_2 emissions.

The conversion of natural forest to agricultural land and increasing cropping intensity also affect fluxes of other GHGs such as methane (CH_4) and N_2O (Tate 2015; Kim and Kirschbaum 2015; van Lent et al. 2015). In a global meta-analysis, Kim and Kirschbaum (2015) found that the conversion of forest to cropland increased net soil CH_4 emissions. This has been associated with changes in the composition (Singh et al. 2007, 2009) and abundance (Menyailo et al. 2008) of the methanotroph communities driven by changed soil properties such as soil moisture, N status, and pH (Tate 2015; Levine et al. 2011). Global meta-analyses found that the conversion of forest to agricultural lands tended to increase soil N_2O emissions (Kim and Kirschbaum 2015; van Lent et al. 2015). In general, the effect of the conversion on N_2O emissions is related to the increase of N input, changed water-filled pore space, changed soil management and microclimatic conditions (Wanyama et al. 2018; van Lent et al. 2015; Smith 2010). Effects of conversion of natural forest to agriculture on soil GHG emissions have been observed in SSA (Wanyama et al. 2018; Gütlein et al. 2018; Mapanda et al. 2012). In Zimbabwe, clearing and converting woodlands to crop lands increased soil emissions of CO_2, CH_4 and N_2O (Mapanda et al. 2012). In Kenya, converted crop lands receiving N input emitted higher N_2O emissions than natural forest (Wanyama et al. 2018).

Overall, conversion from natural forest to crop lands is recognized as the largest source of GHG emissions in SSA, resulting in the release of 0.16×10^9 Mg C yr^{-1} between 1990 and 2009 (Valentini et al. 2014) or a total of 84.2×10^9 Mg CO_2 eq between 1765 and 2005 [emission of 7.3 ± 0.6 Mg CO_2 eq per a converted cropland (ha) per a year; Kim and Kirschbaum 2015]. These emissions contribute to 14.7% of global land use change GHG emissions (Li et al. 2017).

Assuming that agricultural expansion will continue to be associated with deforestation, Molotoks et al. (2018) projected that 11.48×10^9 Mg C will be lost in SSA due to agricultural expansion during 2010 to 2050 (loss of average 0.29×10^9 Mg C yr^{-1}). Results overwhelmingly suggest that expanding agricultural lands to enhance crop production can result in loss of carbon stocks and increasing GHG emissions in SSA.

3.2 Development of rainwater harvesting and irrigation

Rainwater harvesting and irrigation can affect SOC. Increased water supply through water harvesting and irrigation can result in an increased crop biomass and consequently higher input of organic matter into soils through litter and fine root exudates and further decomposition, thus resulting in an increase of SOC (Qiu et al. 2018; Trost et al. 2013; Kochsiek et al. 2009). On the other hand, water harvesting and irrigation can enhance microbial activity, resulting in enhanced degradation of SOC (Trost et al. 2013). A global review by Trost et al. (2013) found that irrigating cropping soils increased soil C stocks by 90–500% in desert climates and 11–35% in semi-arid climates, with the greatest gains in environments with low initial soil carbon, low precipitation and sparse vegetation. But in soils with high initial SOC content, the enhancement of microbial activity can outweigh any increases in biogenic carbon inputs, resulting in the lowering of SOC content (Kochsiek et al. 2009; Jabro et al. 2008; Liu et al. 2008).

Irrigation can also affect other processes leading to GHG emissions from agricultural soils. The effects of irrigation on microbial activity and soil physical properties (e.g. soil moisture, temperature, aeration and oxidation status) can affect methanogenesis, methane oxidation, nitrification, denitrification and other microbial processes involved in regulating CH_4 and N_2O emissions (Trost et al. 2013; Kim et al. 2012; Kessavalou et al. 1998). Some studies found that, especially at high availability of N, certain types of irrigation strategies could enhance the rate of soil microbial processes leading to the production of N_2O emissions following water application (Cayuela et al. 2017; Trost et al. 2014; Aguilera et al. 2013). An abrupt increase of soil moisture in dry soil conditions caused by precipitation or irrigation (often called rewetting) can also affect GHG emissions. This effect was already reported by Birch (1958) and updated by other authors (Congreves et al. 2018; Kim et al. 2012). Increases in CO_2 and N_2O fluxes following rewetting of dry soils have been observed in multiple terrestrial ecosystems and various land-use types including crop land (Guardia et al. 2017; Sanchez 2002). Increased CO_2 (up to 9000%) and N_2O fluxes (up to 80,000%) within 6 to 24 h after rewetting has been well reported (Kim et al. 2012). These results suggest that soil rewetting caused by irrigation can abruptly increase soil CO_2 and N_2O emissions under conditions when soils are permitted to dry. However, some studies found no significant effect of irrigation on N_2O emissions (Trost et al. 2016; Trost et al. 2014). The existence of only limited field data from SSA prevents general conclusions on the effect of expanding rainwater harvesting and irrigation on the amount of GHG emissions (Trost et al. 2013).

3.3 Increase of fertilizer use

Increasing N fertilizer use can affect soil C and GHG emissions. In comparison to unfertilized agricultural fields, increased use of N fertilizer can result in higher plant productivity and increased organic matter input to soil through roots, exudates and crop residues, resulting in enhanced soil carbon sequestration (Peng et al. 2017; Han et al. 2016; Yue et al. 2016). Indeed, a global meta-analysis by Han et al. (2016) found that N fertilizer application increased SOC (10 to 15.4% or 0.9 to 1.7 C g kg^{-1}) in agricultural fields compared to unfertilized agricultural fields. Increasing N fertilizer use can also increase N_2O emissions. Assuming that N fertilizer use will increase from 0.9×10^6 Mg in 2015 to 1.2×10^6 Mg in 2030 in SSA (Tenkorang and Lowenberg-DeBoer 2009) and the IPCC default N_2O emission factor (EF) of 1.0% (IPCC 2006) is applicable in SSA, 78.6×10^6 Mg CO_2 eq would be produced from 2015 to 2030 in SSA. Closing maize yield gaps by 75% through increasing N fertilizer application in SSA will increase N_2O emissions from currently 255 to 1755 Gg N_2O–N $year^{-1}$ (increase of 589%) (Leitner et al. 2020).

Initial models of the relationship between N inputs and N_2O emissions assumed that N_2O emissions were a linear function of N input rate (Dobbie et al. 1999; Bouwman 1996). However, in the last ten years growing evidence suggests that N_2O emissions often increases as an exponential function of N input rate (Bell et al. 2016; Shcherbak et al. 2014; Kim et al. 2013; Hoben et al. 2011), though the relationship is not found universally (Shcherbak et al. 2014). In an exponential response, emissions increase more rapidly once N addition rates exceed the ability of plants and microbes to immobilize it (e.g., >100 kg N ha^{-1}; Bouwman et al. 2002). The resulting soil N surplus is available as a substrate for additional N_2O production (Kim et al. 2013). A study from western Kenya found an exponential relationship between N input and N_2O emissions, with the largest increase in N_2O emissions occurring when N inputs increased from 100 to150 kg N ha^{-1} (Hickman et al. 2015). In addition, low or non- responsive rates of crop productivity to N fertilizer inputs have been reported across SSA, ranging from 11 to 69% of cases in individual farms or field trials (Roobroeck et al. 2021; Ichami et al. 2019; Shehu et al. 2018; Riesgo et al. 2016). In soils that exhibit low fertilizer responses, increasing N fertilizer use may result in soil N surplus and additional N2O production in some regions. The results suggest that increasing N fertilizer use in SSA should be carefully monitored and managed to avoid its excessive use, especially in intensively cultivated cash crop farming (e.g., sugar cane or bioenergy feedstock cultivation). Abruptly increasing N_2O emissions driven by increasing N fertilizer use in SSA will otherwise be a great concern in managing GHG emissions in SSA in the near future.

4 Strategies to enhance crop production and GHG mitigation in smallholder farming systems in SSA

An urgent challenge in SSA is to enhance crop production while avoiding large increases in GHG emissions from cropping systems (Leitner et al. 2020; van Loon et al. 2019; Tongwane and Moeletsi 2018). As potential solutions, approaches based on land, water and nutrient management and a land-water-nutrient nexus (LWNN) are presented and discussed below.

4.1 Land: Improving and utilizing degraded land

The ongoing expansion of agricultural land for enhancing crop production results in deforestation, habitat degradation and GHG emissions (van Loon et al. 2019; Valentini et al. 2014; Gibbs et al. 2010). Smallholder farmers in SSA have limited potential for agricultural land expansion (Jayne et al. 2014; Chamberlin et al. 2014; Deininger et al. 2011). Instead of converting natural land to agricultural lands, it may be sensible to consider restoring, improving and utilizing degraded lands such as abandoned and/or unfertile agricultural land and marginal areas (Foley et al. 2011; Lal 2006). Available estimates suggest that there are 494×10^6 ha of human-induced degraded areas in SSA (Bai et al. 2008). About 40% of grasslands and 12% of croplands have been affected by land degradation in SSA (Le et al. 2016), which may be attributed to various factors including deforestation, expanded agricultural lands in environmentally sensitive areas, low nutrient additions, acidification and improper soil management (CGIAR 2017, Nkonya et al. 2016; Le et al. 2016). The annual costs of land degradation in 2007 were estimated to be US$ 58 billion, which was about 7% of the region's GDP (Nkonya et al. 2016). In contrast, it has been estimated that the benefits of restoring degraded lands in SSA would outweigh the costs by a factor of 7 (ELD Initiative 2015; ELD Initiative and UNEP 2015). Land degradation is expected to increase further in SSA due to expansion of agricultural lands and increase of cropping intensity (Nkonya et al. 2016; Gnacadja and Wiese 2016; Le et al. 2016).

One solution to restore, improve and utilize degraded lands in relatively mesic ecosystems is to practice agroforestry (Nkonya et al. 2016). Agroforestry can be defined as any practice to purposefully grow trees together with crops and/or animals for a variety of benefits and services (Whitney et al. 2018; Jose and Bardhan 2012; Nair et al. 2010). Similarly, another meta-analysis of 94 studies in SSA found that agroforestry increased maize yields by 0.7–2.5 Mg ha^{-1} (or 89–318%) compared to monocropping systems (Sileshi et al. 2008). Another meta-analysis of SSA studies (Kuyah et al. 2019) found that agroforestry increased crop yields in 77 and 68% of all trials conducted on farms and research stations, respectively. In addition to the direct benefits of food production, agroforestry can provide ecosystem services such as improving soil fertility, enhancing carbon sequestration and mitigating GHG emissions (Muchane et al. 2020; Smith et al. 2019; Corbeels et al. 2019; Kim et al. 2016a). A recent global meta-analysis found that soil N stocks under agroforestry were 46% higher than in monocropping (Muchane et al. 2020). Similarly, a meta-analysis of SSA studies found that agroforestry increased soil N by 20% (Kuyah et al. 2019). A review found that the absolute rate of SOC sequestration under agroforestry was up to 14 Mg C ha^{-1} y^{-1} (0–100 cm; Corbeels et al. 2019). Agroforestry may sequester carbon at an equivalent of 27.2 ± 13.5 Mg CO_2 eq ha^{-1} y^{-1} during the early growth stage (up to an average age of 14 years; Kim et al. 2016a). Assuming 20% of the degraded areas in SSA (494×10^6 ha; Bai et al. 2008) could feasibly be converted to agroforestry (Kim et al. 2016a), estimates suggest that doing so could potentially sequester carbon equivalent to 2.7×10^9 Mg CO_2 eq y^{-1}, which is 7.7 times larger than annual GHG emissions caused by recent agricultural expansion (0.35×10^9 Mg CO_2 eq yr^{-1}; Kim and Kirschbaum 2015). Although uncertainty remains in these estimates, the results suggest that converting degraded land to agroforestry could contribute to enhancing soil fertility and crop production and mitigating GHG emissions in SSA. In addition, improving soil fertility and crop productivity of degraded lands through agroforestry could reduce the need to convert additional natural land to agricultural lands, consequently reducing GHG emissions associated with land-use change (van Loon et al. 2019; Branca et al. 2013).

4.2 Water: Appropriate rainwater harvesting, irrigation techniques and water management

The potential for rainwater harvesting and irrigation development in SSA is substantial. Further expansion of rainwater harvesting and irrigation with low cost and appropriate technologies can contribute to enhancing crop production in smallholder farms (Rosa et al. 2020; Leal Filho and Trincheria Gomez 2018; Nakawuka et al. 2018). Evidence from semi-arid environments also suggests that application of appropriate irrigation systems may have some potential to mitigate GHG emissions (Deng et al. 2018; Sanz-Cobena et al. 2017; Cayuela et al. 2017) following two different approaches reviewed below: I. Appropriate rainwater harvesting and irrigation techniques and II. Water management in paddy soils.

4.2.1 Appropriate rainwater harvesting and irrigation techniques

Different types of rainwater harvesting and irrigation technologies have been developed and applied in SSA (Altchenko and Villholth 2015; Karpouzoglou and Barron 2014; Dlie et al. 2013). Results from cropping systems in other regions may be useful to understand the potential effect of these practices on GHG emissions in SSA. Research carried out under semiarid conditions in Mediterranean cropping systems suggests that drip irrigation (both surface and subsurface) can increase the potential to maintain crop yields in the context of frequent droughts and subsequent water scarcity (Deng et al. 2018; Sanz-Cobena et al. 2017; Aguilera et al. 2013). Although N_2O emission factors in drip-irrigated systems ($0.51 \pm 0.26\%$) were higher than those from rain-fed soils ($0.27 \pm 0.21\%$) in Mediterranean ecosystems, drip-irrigated systems have on average 44% lower N_2O emissions than sprinkler systems (Cayuela et al. 2017). Drip-irrigation combined with optimized fertilization (i.e. fertigation) also showed a reduction of up to 50% of direct N_2O emissions compared to sprinkler systems with non-optimal fertilization rates (Sanz-Cobena et al. 2017). The results suggest that the development of rainwater harvesting (Rosa et al. 2020) and low-cost drip and other irrigation technologies (Kahimba et al. 2015) may provide an opportunity for smallholders in SSA to boost crop yield with relatively small additional costs. Although N_2O emissions could increase by a factor of two or more compared to rain-fed Mediterannean systems, the overall emissions per unit area—and especially per unit production—appear likely to remain low in the context of global agriculture. Larger-scale investments in water harvesting and irrigation infrastructure will be important for increasing crop production and limiting C losses - or even facilitating C gains - in agricultural soils. To avoid large indirect GHG emissions associated with irrigation infrastructure and pumping, the location of water bodies and connection with cropping systems, soil characteristics and landscape morphology should be taken into account for development of rainwater harvesting and irrigation technologies.

Significant decreases in crop yields have been reported in semi-arid conditions when irrigation is suppressed (e.g. Wriedt et al. 2009; Liu 2009). For instance, in Europe, large negative impacts on crop yields are expected as water deficit increases (from 4 to 66% decrease for 50 and 150 mm of water deficit, respectively). In cases of no irrigation, compared to an optimum water supply, fall in crop yield could be higher than 80% (Wriedt et al. 2009). In SSA, as crop yields are often damaged by rainfall scarcity and droughts (Karpouzoglou and Barron 2014; Misra 2014), the effect of irrigation on crop yields is expected to be substantial (Altchenko and Villholth 2015; Cassman and Grassini 2013; You et al. 2011). Therefore, although certain irrigation systems could enhance GHG emissions due to increased rates in GHG production processes mainly associated to rewetting events (e.g. sprinkler irrigation), the expected growth in crop yields could lead to an overall decrease in yield-scaled GHG emissions.

4.2.2 Water management in paddy systems

Rice is cultivated in 40 countries in SSA on nearly 10 million ha (Zenna et al. 2017). Rice is also the fastest growing food staple in SSA and the second major source of human calories consumption on the continent (Seck et al. 2012). Water table management in rice paddies may provide great GHG mitigation potential in SSA. Studies have found that water management practices such as flooding, intermittent drainage, midseason drainage and alternate wetting and drying treatment were important factors for rice yield and GHG emissions in paddy fields (Jiang et al. 2019; Meijide et al. 2017; Linquist et al. 2015). For instance, mid-season drainage of the water table of a rice paddy in Northern Italy resulted in lower water use and reduced CH_4 emissions with slightly increased N_2O fluxes (Meijide et al. 2017). Alternate wetting and drying treatments relative to the flooded control treatment in paddies in Arkansas, USA reduced yields by <1–13%, but global warming potential (GWP of CH_4 and N_2O emissions) was also reduced by 45–90% (Linquist et al. 2015). In central Japan, compound treatment with a combination of flooding, midseason drainage and intermittent drainage treatments produced higher rice grain yield and lower total GHG emissions compared to continuous flooding or intermittent drainage treatment (Kudo et al. 2014). Other studies carried out in SSA have shown that improved water management increased rice yields (e.g., Materu et al. 2018; Mati et al. 2011; Balasubramanian et al. 2007). The reason of observed higher yields under certain water management practices was attributed to various mechanisms including altered hormonal levels in rice plants, greater root biomass in deeper soil and higher root oxidation activity, an enhancement in carbon remobilization from vegetative tissues to kernels, and reduction of N loss through nitrification and denitrification in the early vegetative growth stages (Yang et al. 2017; Wang et al. 2016; Chu et al. 2015). However, a study from rice farms in India suggested that N_2O emissions from Indian rice paddies under intermittent flooding might be 30–45 times higher than under continuous flooding due to increased denitrification (Kritee et al. 2018). More studies, combining both GHG and yield measurements, are required, but it appears that careful optimized water management might increase agricultural yields while reducing GHG emissions in SSA paddies, particularly under climate change scenarios (van Oort and Zwart 2018).

4.3 Nutrient: Improved soil fertility management with combined conventional-conservation agriculture (CCCA) practices

Nutrient management should consider two different aspects simultaneously. On the one hand, increasing N fertilizer use is required for resolving problems of depleted soil fertility, low N fertilization levels and thus low crop productivity in most smallholders of SSA (van Loon et al. 2019; Ten Berge et al. 2019; Zhang et al. 2015). On the other hand, abruptly increasing N_2O emissions driven by increasing N fertilizer use in SSA could create new challenges for managing GHG emissions in the near future (Leitner et al. 2020; Tongwane and Moeletsi 2018). Combined practices of conservation agriculture with conventional agriculture (hereafter *combined conventional and conservation agriculture; CCCA*) can provide an appropriate solution for nutrient management. Studies assessing GHG mitigation potentials of CCCA (Table 1) have shown the advantage of combining the high crop yield rate of conventional agriculture with the sustainable soil management of conservation agriculture (Gram et al. 2020; Droppelmann et al. 2017; Wu and Ma 2015). Some global meta-analyses reported GHG mitigation potentials of CCCA (Graham et al. 2017; Charles et al. 2017; Han et al. 2016; Sainju 2016). Nitrous oxide EF of the combined application of composts and synthetic fertilizers (0.37%) and crop residues and fertilizers (0.59%) were lower than N_2O EF of the sole application of synthetic fertilizers (1.34%) and the IPCC default N_2O EF of 1% for synthetic fertilizers (Charles et al. 2017). Inorganic fertilizers with straw application and inorganic fertilizers with manure application increased topsoil organic carbon by 2.0 g kg^{-1} (19.5%) and 3.5 g kg^{-1} (36.2%), respectively (Han et al. 2016). In a separate meta-analysis, GHG intensity (net global warming potential per unit crop yield) was found to be 70 to 87% lower under the improved combined management that included no-till, crop rotation/perennial crop and reduced N rate than under traditional management such as conventional till, monocropping/annual crop and recommended N rate (Sainju 2016). Studies comparing GHG emissions in conventional practices and CCCA in SSA (Kurgat et al. 2018; Kimaro et al. 2016; Nyamadzawo et al. 2014) demonstrated that yield-scaled N_2O emissions were 19 to 88% lower in CCCA practices compared to conventional practices (Table 1). In Mali, pearl millet (*Pennisetum glaucum*) fields treated with both manure and inorganic fertilizer urea emitted significantly less N_2O than plots receiving only urea fertilizer (Dick et al. 2008). The lower N_2O emissions in soils amended with manure were attributed to the initial slow release and immobilization of mineral N and the consequently diminished pool of N available to be lost as N_2O (Nyamadzawo et al. 2014; Mapanda et al. 2011; Dick et al. 2008). The results suggest that CCCA has a greater potential to increase soil fertility while avoiding abruptly increasing N_2O emissions driven by increasing N fertilizer use. In addition, improving soil fertility through CCCA could lead to a consequent increase of crop productivity and decrease of the need to convert additional land to agriculture, thereby reducing associated GHG emissions (van Loon et al. 2019; Branca et al. 2013).

4.4 Land-water-nutrient Nexus (LWNN) approach

To achieve the goal of enhancing crop production while avoiding abruptly increasing GHG emissions in smallholder crop farming in SSA, it is strategic to implement comprehensive approaches resulting in beneficial land, water and nutrient management interactions (Sheahan and Barrett 2017; Thierfelder et al. 2017; Zougmoré et al. 2014; Branca et al. 2013). Research conducted in Kenya and Tanzania found that the combination of water harvesting techniques (ex. tie-ridges) with manure or inorganic fertilizer resulted in higher maize or cowpea yields than when these factors were applied separately (Githunguri and Esilaba 2014; Miriti et al. 2011; Itabari et al. 2004). In semi-arid West Africa, stone bunds, zaï and half-moon techniques combined with the application of organic and/or mineral fertilizers increased agricultural productivity and carbon sequestration (Zougmoré et al. 2014). Differences in the current status of land, water and nutrient depending on the climate and land use history in different regions may exist. Accordingly, different schemes are needed to deal with each of the land, water, and nutrient components and their nexus (Fig. 5).

A simplified hypothetical example of a LWNN approach would be based on applying suitable agroforestry practices combined with CCCA and appropriate rainwater harvesting and irrigation technologies in degraded lands. This approach can restore soil fertility, produce food and enhance carbon sequestration; also improving soil quality, including soil organic matter, a critical factor for increasing yield response to N input in SSA (Maman et al. 2018; Kihara et al. 2016; Jayne and Rashid 2013; Tittonell and Giller 2013). Since irrigation or CCCA practices can increase yields, this approach could also help to limit N_2O emissions due to an increased plant demand and uptake for N, which would reduce its availability for conversion to N_2O (Kim and Giltrap 2017). Therefore, through the LWNN approach, it may be possible to enhance crop production and GHG mitigation.

In order to evaluate co-benefits and trade-offs and identify optimized LWNN schemes, measures accounting for both crop production and GHG mitigation are necessary. In many previous studies, agricultural yield was not well accounted for in GHG budgets and mitigation strategies (Kim and Giltrap 2017; Rosenstock et al. 2013; Linquist et al. 2012). To address the issue, studies use the concept of yield-scaled GHG emissions (GHG emissions per unit agricultural yield) to account for both crop yields and GHG emissions in various regions including SSA (Ortiz-Gonzalo et al. 2017; Kim and Giltrap

Table 1 Summary of comparing conventional agriculture practices and combined conventional-conservation agriculture (CCCA) practice in sub-Saharan Africa

No	Country	Crop type	Conventional practice	CCCA practice	Effects of CCCA	Reference
1	Zimbabwe	Maize (*Zea mays* L.)	N fertilizer (NH_4NO_3-N; 120 kg N ha^{-1})	N fertilizer (NH_4NO_3-N; 60 kg N ha^{-1}) & composted manure (60 kg N ha^{-1})	Yield-scaled N_2O emission mitigation (48%)	Mapanda et al. 2011
2	Zimbabwe	Rape (*Brassica napus*)	N fertilizer (NH_4NO_3-N; 120 kg N ha^{-1})	N fertilizer (NH_4NO_3-N; 60 kg N ha^{-1}) & manure (65 kg N ha^{-1})	Yield-scaled N_2O emission mitigation (88%)	Nyamadzawo et al. 2014
3	Zimbabwe	Maize (*Zea mays* L.)	N fertilizer (NH_4NO_3-N; 120 kg N ha^{-1})	N fertilizer (NH_4NO_3-N; 60 kg N ha^{-1}) & manure (60 kg N ha^{-1})	Yield-scaled N_2O emission mitigation (19%)	Nyamadzawo et al. 2014
4	Zimbabwe	–	N fertilizer (urea, 120 kg N ha^{-1})	N fertilizer (urea, 120 kg N ha^{-1}) & crop residues (Maize, 4 Mg C ha^{-1})	N_2O mitigation (56%)	Gentile et al. 2008
5	Zimbabwe	–	N fertilizer (urea, 120 kg N ha^{-1})	N fertilizer (urea, 120 kg N ha^{-1}) & crop residues (Maize, 4 Mg C ha^{-1})	N_2O mitigation (49%)	Gentile et al. 2008
6	Ghana	–	N fertilizer (urea, 120 kg N ha^{-1})	N fertilizer (urea, 120 kg N ha^{-1}) & crop residues (Maize, 4 Mg C ha^{-1})	N_2O mitigation (103%)	Gentile et al. 2008
7	Kenya	–	N fertilizer (urea, 120 kg N ha^{-1})	N fertilizer (urea, 120 kg N ha^{-1}) & crop residues (Maize, 4 Mg C ha^{-1})	N_2O mitigation (72%)	Gentile et al. 2008
8	Kenya	Vegetables	N fertilizer (diammonium Ph osphate; 40 kg N ha^{-1})	N fertilizer (diammonium Phosphate; 20 kg N ha^{-1}) & manure (15 kg N ha^{-1})	N_2O emissions intensity (N_2OI) mitigation (50%) N_2O emissions economic intensity (N_2OEI) mitigation (45%)	Kurgat et al. 2018
9	Tanzania	Maize (*Zea mays* L.)	Conventional cultivation	Reduced tillage & N fertilizer (urea, 100 kg N ha^{-1})	Yield-scaled global warming potential (GWP) mitigation (62 to 71%)	Kimaro et al. 2016
10	Mali	Pearl millet (*Pennisetum glaucum*)	N fertilizer (urea, 50 kg ha^{-1})	N fertilizer (urea, 50 kg ha^{-1}) & manure (8000 kg dry matter ha^{-1})	Yield-scaled N_2O emission mitigation (52%)	Dick et al. 2008

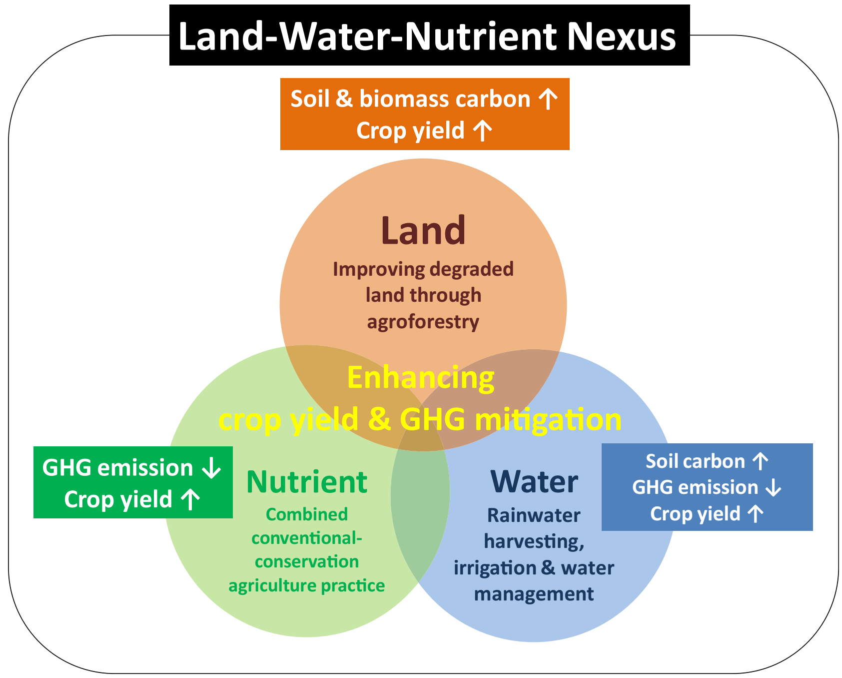

Fig. 5 Land-Water-Nutrient Nexus (LWNN) approach to enhance crop yield and mitigate greenhouse gas (GHG) emission in smallholder crop farming systems in sub-Saharan Africa. ↑: increase and ↓: decrease (Produced by authors)

2017; Sainju 2016; Kim et al. 2016c; Kimaro et al. 2016). For instance, in maize and winter wheat (*Triticum aestivum* L.) fields in Zimbabwe, yield-scaled N_2O emissions was used to compare the application of inorganic fertilizer (ammonium nitrate, NH_4NO_3-N) with manure and sole application of inorganic fertilizer (Nyamadzawo et al. 2014). These studies suggest that yield-scaled GHG emissions may be an alternative means to account for food security and GHG mitigation (Kim and Giltrap 2017; Sainju 2016; van Kessel et al. 2013). Therefore, instead of separately considering agricultural yield and GHG emissions, yield-scaled GHG emissions may identify optimal LWNN schemes.

Barriers and their potential solutions for enhancing crop production and GHG mitigation in smallholder farming systems in SSA.

Inextricably linked, technical, economic and policy barriers to adopting integrated approaches (e.g. LWNN) for enhancing crop production and GHG mitigation may exist. From the technical perspective, the most challenging barrier for smallholder farmers may be the lack of relevant knowledge and experience in applying agroforestry (Mbow et al. 2014; Rioux 2012; Place et al. 2012), rainwater harvesting, irrigation and water management (Leal Filho and Trincheria Gomez 2018; Nakawuka et al. 2018) and soil fertility management practices (Brown et al. 2018b; Masso et al. 2017; Vanlauwe et al. 2015). Technology transfer remains a challenge in the smallholder context. Limited institutional and human capacity or infrastructure supporting extension programs generally exist in SSA (Brown et al. 2018a; Wheeler et al. 2017; Ajayi et al. 2009). From an economic perspective, initial financial and labor investments can be very high, representing a critical barrier to adopting new methods for smallholder farmers. Returns on investment are not immediate since trees may take years to grow and bear benefits (e.g., timber, firewood, fruit, etc.). It also takes time for farmers to realize that after adopting these new approaches, their lands demonstrate improved soil fertility, which in turn brings significant increases to yields (Place et al. 2012; Schlecht et al. 2006). Investment in new technologies and capacity building are costly and need to be addressed by strong policy. From a policy perspective, land tenure questions may introduce an additional challenge, as there may be reduced incentives for farmers to make the necessary investments in labor and finances if they cannot rely on the future returns of their investments (Higgins et al. 2018; Holden and Otsuka 2014). The intersectional nature of integrated practices for enhancing crop production and GHG mitigation may introduce structural challenges to the development of national policies, since intersectional planning and resource sharing are very rare at the national level in SSA (Place et al. 2012). Additionally, with limited resources, governments must juggle multiple priorities including health, education, and the development of clean water and road infrastructure, which may create a particular challenge for introducing practices whose primary purpose is GHG mitigation. Furthermore, GHG mitigation strategies need to be planned by national policies in response to international commitments made by the Intergovernmental Panel on Climate Change, like the Paris Agreement (UNFCCC 2015).

These challenges are far from trivial, but various efforts may improve the chance of smallholder farmers adopting the LWNN approach. Successful technologies will be those with low barriers to entry, reliable returns on investment and appropriate and appealing design and implementation. Taking advantage of locally available knowledge, experience and resources to develop appropriate technologies and disseminating new information and technologies through the farmer to farmer approach may improve rates of adoption and technology transfer (Brown et al. 2018a, b; Kiptot and Franzel 2015; Kiptot et al. 2006). Lessons must be taken from past successes and failures to develop socioeconomic incentives for adoption and maintenance of sustainable agricultural technologies (Long et al. 2016; Arslan et al. 2014). Micro-financing tied to carbon trading schemes such as REDD+ can be used to support investment and development among smallholders (Gizachew et al. 2017; Mbow et al. 2014; Minang et al. 2014). Policy for smallholder farmers to secure land tenure and encourage long-term investment is urgently needed.

5 Conclusion

Smallholder farmers in SSA have commonly practiced expansion of agricultural land, increase of cropping intensity, and development of water harvesting and irrigation to enhance crop production. However, these practices may result in creating trade-offs between enhancing crop production and GHG mitigation. To enhance crop production while avoiding abruptly increasing GHG emissions, interrelated land, water, and nutrient management strategies such as those offered by the LWNN approach require consideration. While technical, economic and policy barriers may hinder implementing the LWNN approach on the ground, these may be overcome by developing appropriate technologies, disseminating information and technologies through the farmer to farmer approach, applying small spatial and long-term temporal scale trials and developing specific policies for smallholder farmers. Throughout this study, serious data gaps were identified in the effects of different land, water and nutrient management strategies on SOC and GHG emissions. The effect of rainwater harvesting and irrigation on SOC and GHG emissions has especially not been well studied and deserves further investigation. The data gaps hinder further in-depth assessments of the trade-offs between enhancing crop production and mitigating GHG emissions caused by smallholder farmers' past and future practices. Further studies are urgently needed for addressing these data gaps and developing viable options for applying the LWNN approach proposed herein.

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Declarations

Conflict of interest The authors declared that they have no conflict of interest.

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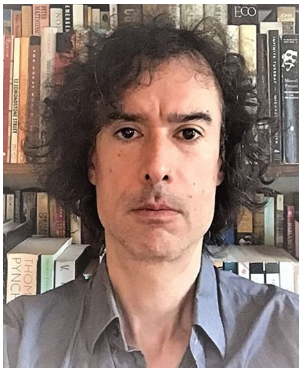

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