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

Dong-Gill Kim[a *], Elisa Grieco[b,c], Antonio Bombelli[b,d], Jonathan E. Hickman[e], Alberto Sanz-Cobena[f, g]

[a] Wondo Genet College of Forestry and Natural Resources, Hawassa University, PO. Box 128, Shashemene, Ethiopia

[b] Foundation Euro-Mediterranean Center on Climate Change (CMCC)—Impacts on Agriculture, Forests and Ecosystem Services Division, 01100, Viterbo, Italy

[c] National Research Council of Italy - Institute of Bio-Economy - CNR – IBE - Via dei Taurini 19- 00185 Roma, Italy

[d]Agenzia Nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (ENEA), Rome, Italy

[e] NASA Goddard Institute for Space Studies, New York, NY 10025, USA

[f] Escuela Técnica Superior de Ingeniería Agronómica, Alimentaria y de Biosistemas, Universidad Politécnica de Madrid, Ciudad Universitaria, 28040 Madrid, Spain.

[g] Research Center for the Management of Environmental and Agricultural Risks (CEIGRAM), Universidad Politécnica de Madrid, Madrid 28040, Spain

*Corresponding author: Dong-Gill Kim, Tel: +251 928 768480, E-mail: donggillkim@gmail.com

Running page title

Food security & greenhouse gas mitigation in sub-Saharan Africa

Funding

Financial support was provided by International Atomic Energy Agency (IAEA) Coordinated Research Project (CRP D1.50.20) 'Developing Climate Smart Agricultural Practices for Mitigation of Greenhouse Gases' and the European Commission through the project ‘Supporting EU-African Cooperation on Research Infrastructures for Food Security and Greenhouse Gas Observations’(SEACRIFOG; project ID 730995).

Availability of data and material

No new data was generated from study.

Author Contributions

D.-G.K. designed and led the study and D.-G.K., E.G., A.B., J.E.H, and A.S.-C. carried out the study and drafted and revised the paper.

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

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).

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 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. 2016 c), 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. 2006). 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/FAO 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 and Byerlee 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. 2016 b; 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 Trincheria Gomez 2018; Karpouzoglou and Barron 2014; Dlie 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; Croppendstedt et al. 2003) and low response rates of crops to fertilizer inputs (Roobroeck et al. 2020; 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 et al. 2013). Ten African governments spend roughly US$1 billion annually on fertilizer subsidy programs (Jayne and Rashid 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.

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. 2016 a; 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; Sánchez-Martín et al. 2012). Increased CO_2 (up to 9000%) and N_2O fluxes (up to 80,000%) within 6 to 24 hours 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. 2014c). 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. 2020; 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. 2014). 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. 2014).

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 et al. 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. 2016 a). 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. 2016 a). 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. 2016 a), 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± 0.26%) were higher than those from rain-fed soils (0.27±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 et al. 2017).

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 a, b) 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. 2014a, b; 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 2017; Sainju 2016; Kim et al. 2016 c; 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. 2014a). 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.

4. 5 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. 2017) and soil fertility management practices (Brown et al. 2018 b; 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. 2018 a; 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 et al. 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 (UNFCC 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. 2018; 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.

Acknowledgement

We are grateful for the numerous researchers and technicians who provided invaluable data. It is impossible to cite all the references due to the limited space allowed and we apologize for the authors whose work has not been cited. The authors are grateful to Lutz Merbold and Maria Vincenza Chiriacò for constructive and valuable comments in the earlier manuscript. Tanya Kreutzer Sayyed edited the final draft of the manuscript and contributed to Fig. 5. Financial support was provided by International Atomic Energy Agency (IAEA) Coordinated Research Project (CRP D15020) 'Developing Climate Smart Agricultural Practices for Mitigation of Greenhouse Gases' and the European Commission through the project ‘Supporting EU-African Cooperation on Research Infrastructures for Food Security and Greenhouse Gas Observations’(SEACRIFOG; project ID 730995).

Conflict of interest

The authors declared that they have no conflict of interest.

References

Aguilera, E., Lassaletta, L., Sanz-Cobena, A., Garnier, J., & Vallejo, A. (2013). The potential of organic fertilizers and water management to reduce N_2O emissions in Mediterranean climate cropping systems. A review. *Agriculture, Ecosystems and Environment*, 164, 32-52. https://doi.org/10.1016/j.agee.2012.09.006

Ajayi, O.C., Akinnifesi, F.K., Sileshi, G., Chakeredza, S., & Mgomba, S. (2009). Integrating Food Security and Agri-environmental Quality in Southern Africa: Implications for Policy. In: Luginaah, I.N. and Yanful, E.K. (Eds.) Environment and Health in Sub- Saharan Africa: Managing an Emerging Crisis, Springer Publishers, Netherlands, pp 39-49. https://doi.org/10.1007/978-1-4020-9382-1_3

Akinnifesi, F.K., Ajayi, O.C., Sileshi, G., Chirwa, P.W., & Chianu, J. (2010). Fertiliser trees for sustainable food security in the maize-based production systems of East and Southern

Africa. A review. *Agronomy for Sustainable Development*, 30, 615-629. https://doi.org/10.1051/agro/2009058

Alexandratos, N., & Bruinsma, J. (2012). World agriculture towards 2030/2050: The 2012 Revision. ESA Working paper No.12-03. Rome, FAO. http://go.nature.com/fM9kF2. Accessed 23 July 2020.

Altchenko, Y., & Villholth, K. G. (2015). Mapping irrigation potential from renewable groundwater in Africa – a quantitative hydrological approach. *Hydrology and Earth System Sciences*, 19(2), 1055-1067, https://doi.org/10.5194/hess-19-1055-2015

Altchenko, Y., & Villholth, K.G. (2015). Mapping irrigation potential from renewable groundwater in Africa-a quantitative hydrological approach. *Hydrology and Earth System Sciences*, 19,1055-1067. https://doi.org/10.5194/hess-19-1055-2015

Araya, T., Nyssen, J., Govaerts, B., Deckers, J., Sommer, R., Bauer, H., Gebrehiwot, K., & Cornelis, W.M. (2016). Seven years resource-conserving agriculture effect on soil quality and crop productivity in the Ethiopian drylands. *Soil Tillage Research*, 163, 99-109. https://doi.org/10.1016/j.still.2016.05.011

Arslan, A., McCarthy, N., Lipper, L., Asfaw, S., & Cattaneo, A. (2014). Adoption and intensity of adoption of conservation farming practices in Zambia. *Agriculture, Ecosystems and Environment*, 187, 72-86. https://doi.org/10.1016/j.agee.2013.08.017

Assefa, B. T., Chamberlin, J., Reidsma, P., Silva, J. V., & van Ittersum, M. K. (2020). Unravelling the variability and causes of smallholder maize yield gaps in Ethiopia. *Food Security*, 12(1), 83-103, https://doi.org/10.1007/s12571-019-00981-4.

Bai, Z.G., Dent, D.L., Olsson, L., & Schaepman, M.E. (2008). Proxy global assessment of land degradation. *Soil Use and Management*, 24, 223-234. https://doi.org/10.1111/j.1475-2743.2008.00169.x

Balasubramanian, V., Sie, M., Hijmans, R. J., & Otsuka, K. (2007). Increasing rice production in sub-Saharan Africa: challenges and opportunities. *Advances in Agronomy*, 94, 55-133. https://doi.org/10.1016/S0065-2113(06)94002-4.

Barrett, C.B., & Bevis, L.E. (2015). The self-reinforcing feedback between low soil fertility and chronic poverty. *Nature Geosciences*, 8, 907. https://doi.org/10.1038/ngeo2591

Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A., & Wood, E.F. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data*, 5, 180214. https://doi.org/10.1038/sdata.2018.214

Bell, M., Cloy, J., Topp, C., Ball, B., Bagnall, A., Rees, R., & Chadwick, D. (2016). Quantifying N_2O emissions from intensive grassland production: the role of synthetic fertilizer type, application rate, timing and nitrification inhibitors. *Journal* of *Agricultural*

Science, 154, 812-827. https://doi.org/10.1017/S0021859615000945

Biazin, B., Sterk, G., Temesgen, M., Abdulkedir, A., & Stroosnijder, L. (2012). Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa-A review. *Physics and Chemistry of the Earth*, 47, 139-151. https://doi.org/10.1016/j.pce.2011.08.015

Birch, H. (1958). The effect of soil drying on humus decomposition and nitrogen availability. *Plant & Soil*, 10, 9-31. https://doi.org/10.1007/BF01343734

Bouwman, A.F. (1996). Direct emission of nitrous oxide from agricultural soils. *Nutrient Cycling Agroecosystems*, 46, 53-70. https://doi.org/10.1007/BF00210224

Branca, G., Lipper, L., McCarthy, N., & Jolejole, M.C. (2013). Food security, climate change, and sustainable land management. A review. *Agronomy and Sustainable Development*, 33, 635-650. https://doi.org/10.1007/s13593-013-0133-1

Brink, A.B., & Eva, H.D. (2009). Monitoring 25 years of land cover change dynamics in Africa: a sample-based remote sensing approach. *Applied Geography*, 29, 501-512. https://doi.org/10.1016/j.apgeog.2008.10.004

Brown, B., Llewellyn, R., & Nuberg, I. (2018 a). Why do information gaps persist in African smallholder agriculture? Perspectives from farmers lacking exposure to conservation agriculture. *The Journal of Agricultural Education and Extension*, 24, 191-208. https://doi.org/10.1080/1389224X.2018.1429283

Brown, B., Nuberg, I., & Llewellyn, R. (2018). Constraints to the utilisation of conservation agriculture in Africa as perceived by agricultural extension service providers. *Land Use Policy*, 73, 331-340. https://doi.org/10.1016/j.landusepol.2018.02.009

Burney, J.A., Davis, S.J., & Lobell, D.B. (2010). Greenhouse gas mitigation by agricultural intensification. *Proceedings of the National Academy of Sciences*, 107, 12052-12057. https://doi.org/10.1073/pnas.0914216107

Burney, J.A., Naylor, R.L., & Postel, S.L. (2013). The case for distributed irrigation as a development priority in sub-Saharan Africa. *Proceedings of the National Academy of Sciences*, 110, 12513-12517. https://doi.org/10.1073/pnas.1203597110

Cassman KG, & Grassini P (2013). Can there be a green revolution in Sub-Saharan Africa without large expansion of irrigated crop production? *Global Food Security*, 2, 203-209. https://doi.org/10.1016/j.gfs.2013.08.004.

Cayuela, M.L., Aguilera, E., Sanz-Cobena, A., Adams, D.C., Abalos, D., Barton, L., Ryals, R., Silver, W.L., Alfaro, M.A., Pappa, V.A., Smith, P., Garnier, J., Billen, G., Bouwman, L., Bondeau, A., & Lassaletta, L. (2017). Direct nitrous oxide emissions in Mediterranean climate cropping systems: Emission factors based on a meta-analysis of available measurement data. *Agriculture, Ecosystems and Environment,* 238, 25-35. https://doi.org/10.1016/j.agee.2016.10.006

Ceesay, M., Reid, W. S., Fernandes, E. C., & Uphoff, N. T. (2006). The effects of repeated soil wetting and drying on lowland rice yield with System of Rice Intensification (SRI) methods. *International Journal of Agricultural Sustainability, 4*(1), 5-14.

CGIAR Research Program on Water, Land and Ecosystems (WLE) (2017). Healthy soils for productive and resilient agricultural landscapes. Colombo, Sri Lanka: International Water Management Institute (IWMI). WLE Towards Sustainable Intensification: Insights and Solutions Brief 2. https://doi.org/10.5337/2017.211

Chamberlin, J., Jayne, T.S., & Heady, D. (2014). Scarcity amidst abundance? Reassessing the potential for cropland expansion in Africa. *Food Policy,* 48, 51-65. https://doi.org/10.1016/j.foodpol.2014.05.002

Charles, A., Rochette, P., Whalen, J.K., Angers, D.A., Chantigny, M.H., & Bertrand, N. (2017). Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis. *Agriculture, Ecosystems and Environment,* 236, 88-98. https://doi.org/10.1016/j.agee.2016.11.021

Chitakira, M., & Torquebiau, E. (2010). Barriers and coping mechanisms relating to agroforestry adoption by smallholder farmers in Zimbabwe. *The Journal of Agricultural Education and Extension,* 16, 147-160. https://doi.org/10.1080/13892241003651407

Chu, G., Wang, Z., Zhang, H., Liu, L., Yang, J., & Zhang, J. (2015). Alternate wetting and moderate drying increases rice yield and reduces methane emission in paddy field with wheat straw residue incorporation. *Food and Energy Security, 4*(3), 238-254.

Cobo, J.G., Dercon, G., & Cadisch, G. (2010). Nutrient balances in African land use systems across different spatial scales: a review of approaches, challenges and progress. *Agriculture, Ecosystems and Environment,* 136, 1-15. https://doi.org/10.1016/j.agee.2009.11.006

Congreves, K., Wagner-Riddle, C., Si, B., & Clough, T. (2018). Nitrous oxide emissions and biogeochemical responses to soil freezing-thawing and drying-wetting. *Soil Biology & Biochemistry,* 117, 5-15. https://doi.org/10.1016/j.soilbio.2017.10.040

Corbeels, M., Cardinael, R., Naudin, K., Guibert, H., & Torquebiau, E. (2019). The 4 per 1000 goal and soil carbon storage under agroforestry and conservation agriculture systems in sub-Saharan Africa. *Soil and Tillage Research,* 188, 16-26. https://doi.org/10.1016/j.still.2018.02.015

Couto, A., Ruiz Padín, A., & Reinoso, B. (2013). Comparative yield and water use efficiency of two maize hybrids differing in maturity under solid set sprinkler and two different lateral spacing drip irrigation systems in León, Spain. *Agricultural Water Management,* 124, 77-84.

https://doi.org/10.1016/j.agwat.2013.03.022

Critchley, W., & Scheierling, S.M. (2012). Water harvesting for crop production in Sub-Saharan Africa: challenges, concepts and practices. In: Critchley, W., Gowing, J. (Eds.), *Water Harvesting in Sub-Saharan Africa*. Routledge, London/New York, pp. 10–32. https://www.taylorfrancis.com/books/e/9781136273063/chapters/10.4324%2F9780203109984-9. Accessed 25 September 2020.

Croppenstedt, A., Demeke, M., & Meschi, M.M. (2003). Technology adoption in the presence of constraints: the case of fertilizer demand in Ethiopia. *Review of Development Economics*, 7, 58-70. https://doi.org/10.1111/1467-9361.00175

Davis KF, Rulli MC, Seveso A, & D'Odorico P (2017). Increased food production and reduced water use through optimized crop distribution. *Nature Geoscience*, 10, 919-924. https://doi.org/10.1038/s41561-017-0004-5

Deepak KR, & Jonathan AF (2013). Increasing global crop harvest frequency: recent trends and future directions. *Environmental Research Letters*, 8, 044041. https://doi.org/10.1088/1748-9326/8/4/044041

DeFries RS, Rudel T, Uriarte M, & Hansen M (2010). Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nature Geoscience,* 3,178-181. https://doi.org/10.1038/ngeo756

Deininger K, Byerlee D, Lindsay J, Norton A, Selod H, & Stickler M (2011). Rising Global Interest in Farmland: Can it Yield Sustainable and Equitable Benefits?. Agriculture and Rural Development. World Bank. https://openknowledge.worldbank.org/bitstream/handle/10986/2263/594630PUB0ID1810Box358282B01PUBLIC1.pdf?sequence=1&isAllowed=y. Accessed 25 September 2020.

Deng J, Guo L, Salas W, Ingraham P, Charrier-Klobas JG, Frolking S, & Li C (2018). Changes in irrigation practices likely mitigate nitrous oxide emissions from California cropland. *Global Biogeochemical Cycles*, 32, https://doi.org/10.1029/2018GB005961

Dick J, Kaya B, Soutoura M, Skiba U, Smith R, Niang A, & Tabo R (2008). The contribution of agricultural practices to nitrous oxide emissions in semi-arid Mali. *Soil Use and Management*, 24, 292-301. https://doi.org/10.1111/j.1475-2743.2008.00163.x

Dile YT, Karlberg L, Temesgen M, & Rockström J (2013). The role of water harvesting to achieve sustainable agricultural intensification and resilience against water related shocks in sub-Saharan Africa. *Agriculture, Ecosystems and Environment*, 181, 69-79. https://doi.org/10.1016/j.agee.2013.09.014

Dobbie K, McTaggart I, & Smith K (1999). Nitrous oxide emissions from intensive agricultural systems: Variations between crops and seasons, key driving variables, and mean emission factors. *Journal of Geophysical Research*, 104, 26891-26899. https://doi.org/10.1029/1999JD900378

Domènech L (2015). Improving irrigation access to combat food insecurity and undernutrition: A review. *Global Food Security*, 6, 24-33. https://doi.org/10.1016/j.gfs.2015.09.001

Don A, Schumacher J, & Freibauer A (2011). Impact of tropical land-use change on soil organic carbon stocks – a meta-analysis. *Global Change Biology*, 17, 1658-1670. https://doi.org/10.1111/j.1365-2486.2010.02336.x

Drechsel P, Gyiele L, Kunze D, & Cofie O (2001). Population density, soil nutrient depletion, and economic growth in sub-Saharan Africa. *Ecological Economics*, 38, 251-258. https://doi.org/10.1016/S0921-8009(01)00167-7

Droppelmann, K. J., Snapp, S. S., & Waddington, S. R. (2017). Sustainable intensification options for smallholder maize-based farming systems in sub-Saharan Africa. *Food Security*, 9, 133-150, https://doi.org/10.1007/s12571-016-0636-0

Duflo E, Kremer M, & Robinson J (2008). How high are rates of return to fertilizer? Evidence from field experiments in Kenya. *American Economic Review*, 98, 482-88. https://doi.org/10.1257/aer.98.2.482

ELD Initiative (2015). Report for policy and decision makers: reaping economic and environmental benefits from sustainable land management. The Economics of Land Degradation, Bonn, Germany. http://www.eld-initiative.org/fileadmin/pdf/ELD-pm-report_05_web_300dpi.pdf. Accessed 25 September 2020.

ELD Initiative and UNEP (2015). The economics of land degradation in Africa: benefits of action outweigh the costs. The Economics of Land Degradation, Bonn, Germany. http://www.eld-initiative.org/fileadmin/pdf/ELD-unep-report_07_spec_72dpi.pdf. Accessed 25 September 2020.

Entry JA, Mills D, Mathee K, Jayachandran K, Sojka R, & Narasimhan G (2008). Influence of irrigated agriculture on soil microbial diversity. *Applied Soil Ecology*, 40, 146-154. https://doi.org/10.1016/j.apsoil.2008.03.012

FAO (2017). Fertilizer trends and outlook to 2020: Summary report. http://www.fao.org/3/a-i6895e.pdf. Accessed 25 September 2020.

FAO (2018). State of Food Security and Nutrition in the World 2017. http://www.fao.org/state-of-food-security-nutrition/en/. Accessed 25 September 2020.

FAOSTAT, Food and agriculture organization of the United Nations, http://www.fao.org/faostat/en/#data/RL. Accessed 25 September 2020.

Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, Mueller ND, O'Connell C, Ray DK, West PC, Balzer C, Bennett EM, Carpenter SR, Hill J, Monfreda C, Polasky S, Rockstrom J, Sheehan J, Siebert S, Tilman D, & Zaks DP (2011). Solutions for a cultivated planet. *Nature*, 478, 337-342. https://doi.org/10.1038/nature10452

Frelat R, Lopez-Ridaura S, Giller KE, Herrero M, Douxchamps S, Djurfeldt AA, Erenstein O, Henderson B, Kassie M, & Paul BK (2016). Drivers of household food availability in sub-Saharan Africa based on big data from small farms. *Proceedings of the National Academy of Sciences of the United States of America*, 113, 458-463. https://doi.org/10.1073/pnas.1518384112

Gentile R, Vanlauwe B, Chivenge P, & Six J (2008). Interactive effects from combining fertilizer and organic residue inputs on nitrogen transformations. *Soil Biology and Biochemistry*, 40, 2375-2384. https://doi.org/10.1016/j.soilbio.2008.05.018

Gibbs HK, Ruesch AS, Achard F, Clayton MK, Holmgren P, Ramankutty N, & Foley JA (2010). Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proceedings of the National Academy of Sciences of the United States of America*, 107, 16732-16737. https://doi.org/10.1073/pnas.0910275107

Giller KE, Corbeels M, Nyamangara J, Triomphe B, Affholder F, Scopel E, & Tittonell P (2011). A research agenda to explore the role of conservation agriculture in African smallholder farming systems. *Field Crops Research*, 124, 468-472. https://doi.org/10.1016/j.fcr.2011.04.010

Githunguri CM, & Esilaba AO (2014). Appropriate integrated nutrient management and field water harvesting options for maize production mitigating drought in the semiarid southern rangelands of eastern Kenya. *International Journal of Agricultural Resources, Governance and Ecology*, 10, 217-226. https://doi.org/10.1504/IJARGE.2014.064000

Gizachew B, Astrup R, Vedeld P, Zahabu EM, & Duguma LA (2017). REDD+ in Africa: contexts and challenges. *Natural Resources Forum*, 41, 92-104. https://doi.org/10.1111/1477-8947.12119

Gnacadja L, & Wiese L (2016). Land degradation neutrality: Will africa achieve it? Institutional solutions to land degradation and restoration in Africa. In: Lal R, Kraybill D, Hansen DO, Singh BR, Mosogoya T, Eik LO (Eds.), *Climate Change and Multi-Dimensional Sustainability in African Agriculture: Climate Change and Sustainability in Agriculture*. Springer International Publishing, Cham, pp. 61-95.

Gonzalez-Sanchez EJ, Veroz-Gonzalez O, Conway G, Moreno-Garcia M, Kassam A, Mkomwa S, Ordoñez-Fernandez R, Triviño-Tarradas P, & Carbonell-Bojollo R (2019). Meta-analysis on carbon sequestration through conservation agriculture in Africa. *Soil and Tillage Research*, 190, 22-30. https://doi.org/10.1016/j.still.2019.02.020

Graham RF, Wortman SE, & Pittelkow CM (2017). Comparison of organic and integrated nutrient management strategies for reducing soil N_2O emissions. *Sustainability*, 9, 510. https://doi.org/10.3390/su9040510

Gram, G., Roobroeck, D., Pypers, P., Six, J., Merckx, R., & Vanlauwe, B. (2020). Combining organic and mineral fertilizers as a climate-smart integrated soil fertility management practice in sub-Saharan Africa: A meta-analysis. *PLoS ONE*, 15(9), e0239552, https://doi.org/10.1371/journal.pone.0239552.

Gregory PJ, & George TS (2011). Feeding nine billion: the challenge to sustainable crop production. *Journal of Experimental Botany*, 62, 5233-5239. https://doi.org/10.1093/jxb/err232

Grewer U, Nash J, Gurwick N, Bockel L, Galford G, Richards M, Junior CC, White J, Pirolli G, & Wollenberg E (2018). Analyzing the greenhouse gas impact potential of smallholder development actions across a global food security program. *Environmental Research Letters*, 13, 044003. https://doi.org/10.1088/1748-9326/aab0b0

Guardia G, Cangani MT, Sanz-Cobena A, Junior JL, & Vallejo A (2017). Management of pig manure to mitigate NO and yield-scaled N_2O emissions in an irrigated Mediterranean crop. *Agriculture, Ecosystems & Environment*, 238, 55-66. https://doi.org/10.1016/j.agee.2016.09.022

Gütlein A, Gerschlauer F, Kikoti I, & Kiese R (2018). Impacts of climate and land use on N_2O and CH_4 fluxes from tropical ecosystems in the Mt. Kilimanjaro region, Tanzania. *Global Change Biology*, 24, 1239-1255. https://doi.org/10.1111/gcb.13944

Hagos F, Jayasinghe G, Awulachew SB, Loulseged M, & Yilma AD (2012). Agricultural water management and poverty in Ethiopia. *Agricultural Economics*, 43, 99-111. https://doi.org/10.1111/j.1574-0862.2012.00623.x

Han P, Zhang W, Wang G, Sun W, & Huang Y (2016). Changes in soil organic carbon in croplands subjected to fertilizer management: a global meta analysis. *Scientific Reports*, 6, 27199. https://doi.org/10.1038/srep27199

Headey DD, & Jayne T (2014). Adaptation to land constraints: Is Africa different? *Food Policy*, 48, 18-33. https://doi.org/10.1016/j.foodpol.2014.05.005

Heady DD (2015). The evolution of global farming land: facts and interpretations. *Agricultural Economics*, 47(S1), 185-196 https://doi.org/10.1111/agec.12313

Hertel, T. W., Baldos, U. L. C., & van der Mensbrugghe, D. (2016). Predicting long-term food demand, cropland use, and prices. *Annual Review of Resource Economics*, 8, 417-441. https://doi.org/10.1146/annurev-resource-100815-095333

Hickman, J. E., Tully, K. L., Groffman, P. M., Diru, W., & Palm, C. A. (2015). A potential tipping point in tropical agriculture: Avoiding rapid increases in nitrous oxide fluxes from agricultural intensification in Kenya. *journal of Geophysical Research: Biogeosciences, 120*(5), 938-951. https://doi.org/10.1002/2015JG002913

Higgins, D., Balint, T., Liversage, H., & Winters, P. (2018). Investigating the impacts of increased rural land tenure security: A systematic review of the evidence. *Journal of rural studies*, 61, 34-62. https://doi.org/10.1016/j.jrurstud.2018.05.001

Hoben, J. P., Gehl, R. J., Millar, N., Grace, P. R., & Robertson, G. P. (2011). Nonlinear nitrous oxide (N_2O) response to nitrogen fertilizer in on- farm corn crops of the US Midwest. *Global Change Biology*, 17(2), 1140-1152. https://doi.org/10.1111/j.1365-2486.2010.02349.x

Holden, S. T., & Otsuka, K. (2014). The roles of land tenure reforms and land markets in the context of population growth and land use intensification in Africa. *Food Policy*, 48, 88-97. https://doi.org/10.1016/j.foodpol.2014.03.005

Ichami, S. M., Shepherd, K. D., Sila, A. M., Stoorvogel, J. J., & Hoffland, E. (2019). Fertilizer response and nitrogen use efficiency in African smallholder maize farms. *Nutrient Cycling in Agroecosystems, 113*(1), 1-19. https://doi.org/10.1007/s10705-018-9958-y

International Finance Corporation (IFC) (2013). *Working with smallholders: a handbook for firms building sustainable supply chains*. The World Bank. https://www.ifc.org/wps/wcm/connect/topics_ext_content/ifc_external_corporate_site/sustainability-at-ifc/publications/handbook_working+with+smallholders. Accessed 28 September 2029.

IPCC – Intergovernmental Panel on Climate Change (2006). Guidelines for National Greenhouse Gas Inventories. Geneva, Switzerland. http://www.ipccnggip. iges.or.jp/public/2006gl/index.html. Accessed 2 July 2020.

Itabari, J. K., Nguluu, S. N., Gichangi, E. M., Karuku, A. M., Njiru, E., Wambua, et al. (2004). Managing land and water resources for sustainable crop production in dry areas: A case study of small-scale farms in semi-arid areas of eastern, central and rift valley provinces of Kenya. In: L. Crissma (Ed.), *Proceedings of Agricultural Research and Development for Sustainable Resource Management and Food Security in Kenya*, 11–12 November 2003, KARI, Nairobi.

Jabro, J. D., Sainju, U., Stevens, W. B., & Evans, R. G. (2008). Carbon dioxide flux as affected by tillage and irrigation in soil converted from perennial forages to annual crops. *Journal of Environmental Management*, 88(4), 1478-1484. https://doi.org/10.1016/j.jenvman.2007.07.012

Jayne, T. S., & Rashid, S. (2013). Input subsidy programs in sub- Saharan Africa: a synthesis of recent evidence. *Agricultural Economics*, 44(6), 547-562. https://doi.org/10.1111/agec.12073

Jayne, T. S., Chamberlin, J., & Headey, D. D. (2014). Land pressures, the evolution of farming systems, and development strategies in Africa: A synthesis. *Food policy*, 48, 1-17. https://doi.org/10.1016/j.foodpol.2014.05.014

Jiang, Y., Carrijo, D., Huang, S., Chen, J., Balaine, N., Zhang, W., et al. (2019). Water management to mitigate the global warming potential of rice systems: A global meta-analysis. *Field Crops Research*, 234, 47-54. https://doi.org/10.1016/j.fcr.2019.02.010

Jose, S., & Bardhan, S. (2012). Agroforestry for biomass production and carbon sequestration: an overview. *Agroforestry Systems*, 86(2), 105-111. https://doi.org/10.1007/s10457-012-9573-x

Kahimba, F., Ishengoma, E. K., & Tarimo, A. K. P. R. (2015). Managing water: low-cost drip irrigation systems for smallholder farmers in Tanzania. International Water Management Institute (IWMI); CGIAR Research Program on Water, Land and Ecosystems (WLE); Global Water Initiative East Africa (GWI EA). https://cgspace.cgiar.org/bitstream/handle/10568/66420/31_WaSA_Ch3.9.pdf?sequence=1. Accessed 21 June 2020.

Karpouzoglou T, & Barron J (2014). A global and regional perspective of rainwater harvesting in sub-Saharan Africa's rainfed farming systems. *Physics and Chemistry of the Earth, Parts A/B/C*, 72-75, 43-53. https://doi.org/10.1016/j.pce.2014.09.009

Kessavalou, A., Doran, J. W., Mosier, A. R., & Drijber, R. A. (1998). Greenhouse gas fluxes following tillage and wetting in a wheat- fallow cropping system. *Journal of Environmental Quality*, 27(5), 1105-1116. https://doi.org/10.2134/jeq1998.00472425002700050016x

Kihara, J., Nziguheba, G., Zingore, S., et al. (2016). Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. *Agriculture, Ecosystems and Environment*, 229, 1-12. https://doi.org/10.1016/j.agee.2016.05.012

Kim, D. -G., & Giltrap, D. (2017). Determining optimum nitrogen input rate and optimum yield-scaled nitrous oxide emissions: Theory, field observations, usage, and limitations. *Agriculture, Ecosystems and Environment*, 247, 371-378. https://doi.org/10.1016/j.agee.2017.07.003

Kim, D. -G., & Kirschbaum, M. U. (2015). The effect of land-use change on the net exchange rates of greenhouse gases: a compilation of estimates. *Agriculture, Ecosystems and Environment*, *208*, 114-126. https://doi.org/10.1016/j.agee.2015.04.026

Kim, D. -G., Hernandez-Ramirez, G., & Giltrap, D. (2013). Linear and nonlinear dependency of direct nitrous oxide emissions on fertilizer nitrogen input: A meta-analysis. *Agriculture, Ecosystems and Environment*, *168*, 53-65. https://doi.org/10.1016/j.agee.2012.02.021

Kim, D. -G., Kirschbaum, M. U., & Beedy, T. L. (2016 a). Carbon sequestration and net emissions of CH_4 and N_2O under agroforestry: Synthesizing available data and suggestions for future studies. *Agriculture, Ecosystems and Environment*, 226, 65-78. https://doi.org/10.1016/j.agee.2016.04.011

Kim, D. -G., Terefe, B., Girma, S., Kedir, H., Morkie, N., & Woldie, T. M. (2016 b). Conversion of home garden agroforestry to crop fields reduced soil carbon and nitrogen stocks in Southern Ethiopia. *Agroforestry systems*, 90(2), 251-264. https://doi.org/10.1007/s10457-015-9851-5

Kim, D. -G., Thomas, A., Pelster, D., Rosenstock, T. S., & Sanz-Cobena, A. (2016 c). Greenhouse gas emissions from natural ecosystems and agricultural lands in sub-Saharan Agrica: synthesis of available data and suggestions for further research. *Biogeosciences*, *13*(16), 4789-4809. https://doi.org/10.5194/bg-13-4789-2016

Kim, D. -G., Vargas, R., Bond-Lamberty, B., & Turetsky, M. R. (2012). Effects of soil rewetting and thawing on soil gas fluxes: a review of current literature and suggestions for future research. *Biogeosciences*, 9(7), 2459. https://doi.org/10.5194/bg-9-2459-2012

Kimaro, A. A., Mpanda, M., Rioux, J., Aynekulu, E., Shaba, S., Thiong'o, M., et al. (2016). Is conservation agriculture 'climate-smart'for maize farmers in the highlands of Tanzania?. *Nutrient Cycling in Agroecosystems*, 105(3), 217-228. https://doi.org/10.1007/s10705-015-9711-8

Kiptot, E., & Franzel, S. (2015). Farmer-to-farmer extension: opportunities for enhancing performance of volunteer farmer trainers in Kenya. *Development in Practice*, 25(4), 503-517. https://doi.org/10.1080/09614524.2015.1029438

Kiptot, E., Franzel, S., Hebinck, P., & Richards, P. (2006). Sharing seed and knowledge: farmer to farmer dissemination of agroforestry technologies in western Kenya. *Agroforestry Systems*, 68(3), 167-179. https://doi.org/10.1007/s10457-006-9007-8

Kochsiek, A. E., Knops, J. M., Walters, D. T., & Arkebauer, T. J. (2009). Impacts of management on decomposition and the litter-carbon balance in irrigated and rainfed no-till agricultural systems. *Agricultural and Forest Meteorology*, 149(11), 1983-1993. https://doi.org/10.1016/j.agrformet.2009.07.004

Koussoubé, E., & Nauges, C. (2017). Returns to fertiliser use: Does it pay enough? Some new evidence from Sub-Saharan Africa. *European Review of Agricultural Economics*, 44(2), 183–210, https://doi.org/10.1093/erae/jbw018

Kritee, K., Nair, D., Zavala-Araiza, D., Proville, J., Rudek, J., Adhya, T. K., et al. (2018). High nitrous oxide fluxes from rice indicate the need to manage water for both long-and short-term climate impacts. *Proceedings of the National Academy of Sciences*, 115(39), 9720-9725. https://doi.org/10.1073/pnas.1809276115

Kudo, Y., Noborio, K., Shimoozono, N., & Kurihara, R. (2014). The effective water management practice for mitigating greenhouse gas emissions and maintaining rice yield in central Japan. *Agriculture, Ecosystems and Environment*, 186, 77-85. https://doi.org/10.1016/j.agee.2014.01.015

Kurgat, B. K., Stöber, S., Mwonga, S., Lotze-Campen, H., & Rosenstock, T. S. (2018). Livelihood and climate trade-offs in Kenyan peri-urban vegetable production. *Agricultural Systems*, 160, 79-86. https://doi.org/10.1016/j.agsy.2017.1010.1003

Kuyah, S., Whitney, C. W., Jonsson, M., Sileshi, G. W., Öborn, I., Muthuri, C. W., et al. (2019). Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis. *Agronomy for Sustainable Development, 39*(5), 47, https://doi.org/10.1007/s13593-019-0589-8.

Lal, R. (2006). Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. *Land Degradation & Development*, 17(2), 197-209. https://doi.org/10.1002/ldr.696

Lambin, E. F., & Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences*, 108(9), 3465-3472. https://doi.org/10.1073/pnas.1100480108

Larson, D. F., Otsuka, K., Matsumoto, T., & Kilic, T. (2014). Should African rural development strategies depend on smallholder farms? An exploration of the inverse-productivity hypothesis. *Agricultural Economics*, 45(3), 355-367. https://doi.org/10.1111/agec.12070

Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., & Garnier, J. (2014). 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. *Environmental Research Letters*, 9(10), 105011. https://doi.org/10.1088/1748-9326/9/10/105011

Le, Q. B., Nkonya, E., & Mirzabaev, A. (2016). Biomass productivity-based mapping of global land degradation hotspots. In: E. Nkonya, A. Mirzabaev, & J. von Braun (Eds.), *Economics of Land Degradation and Improvement–A Global Assessment for Sustainable Development*, 55. Cham: Springer. https://link.springer.com/content/pdf/10.1007%2F978-3-319-19168-3_4.pdf

Leal Filho, W., & de Trincheria Gomez, J. (2018). Preface: Rainwater-Smart Agriculture in Arid and Semi-arid Areas. In W. Leal Filho, & J. de Trincheria Gomez (Eds.), In *Rainwater-Smart Agriculture in Arid and Semi-Arid Areas* (pp. 1-5). Cham: Springer. https://doi.org/10.1007/978-3-319-66239-8_1

Leitner, S., Pelster, D. E., Werner, C., Merbold, L., Baggs, E. M., Mapanda, F., et al. (2020). Closing maize yield gaps in sub-Saharan Africa will boost soil N_2O emissions. *Current Opinion in Environmental Sustainability, 47*, 95-105, https://doi.org/10.1016/j.cosust.2020.08.018.

Levine, U. Y., Teal, T. K., Robertson, G. P., & Schmidt, T. M. (2011). Agriculture's impact on microbial diversity and associated fluxes of carbon dioxide and methane. *The ISME Journal*, *5*(10), 1683-1691. https://doi.org/10.1038/ismej.2011.40

Li, W., Ciais, P., Peng, S., Yue, C., Wang, Y., Thurner, M., et al. (2017). Land-use and land-cover change carbon emissions between 1901 and 2012 constrained by biomass observations. *Biogeosciences*, 14, 5053-5067. https://doi.org/10.5194/bg-14-5053-2017

Linquist, B. A., Anders, M. M., Adviento- Borbe, M. A. A., Chaney, R. L., Nalley, L. L., Da Rosa, E. F., & Van Kessel, C. (2015). Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. *Global Change Biology*, 21(1), 407-417. https://doi.org/10.1111/gcb.12701

Linquist, B. A., Van Groenigen, K. J., Adviento- Borbe, M. A., Pittelkow, C., & Van Kessel, C. (2012). An agronomic assessment of greenhouse gas emissions from major cereal crops. *Global Change Biology*, 18(1), 194-209. https://doi.org/10.1111/j.1365-2486.2011.02502.x

Liu, C., Holst, J., Brüggemann, N., Butterbach-Bahl, K., Yao, Z., Han, S., et al. (2008). Effects of irrigation on nitrous oxide, methane and carbon dioxide fluxes in an Inner Mongolian steppe. *Advances in Atmospheric Sciences*, 25(5), 748-756. https://doi.org/10.1007/s00376-008-0748-3

Liu, J. (2009). A GIS-based tool for modelling large-scale crop-water relations. *Environmental Modelling & Software*, 24(3), 411-422, https://doi.org/10.1016/j.envsoft.2008.08.004.

Livesley, S. J., Dougherty, B. J., Smith, A. J., Navaud, D., Wylie, L. J., & Arndt, S. K. (2010). Soil-atmosphere exchange of carbon dioxide, methane and nitrous oxide in urban garden systems: impact of irrigation, fertiliser and mulch. *Urban Ecosystems*, 13(3), 273-293. https://doi.org/10.1007/s11252-009-0119-6

Long, T. B., Blok, V., & Coninx, I. (2016). Barriers to the adoption and diffusion of technological innovations for climate-smart agriculture in Europe: evidence from the Netherlands, France, Switzerland and Italy. *Journal of Cleaner Production*, 112, 9-21. https://doi.org/10.1016/j.jclepro.2015.06.044

Lowder, S. K., Skoet, J., & Raney, T. (2016). The number, size, and distribution of farms, smallholder farms, and family farms worldwide. *World Development*, 87, 16-29. https://doi.org/10.1016/j.worlddev.2015.10.041

Maman, G., Idriss, S., & Wortmann, C. (2018). Crop yield response to fertilizer relative to soil properties in Sub- Saharan Africa. *Soil Science Society of America Journal*, 82(4), 862-870. https://doi.org/10.2136/sssaj2018.02.0066

Mapanda, F., Wuta, M., Nyamangara, J., & Rees, R. M. (2011). Effects of organic and mineral fertilizer nitrogen on greenhouse gas emissions and plant-captured carbon under maize cropping in Zimbabwe. *Plant and Soil*, 343(1-2), 67-81. https://doi.org/10.1007/s11104-011-0753-7

Mapanda, P., Wuta, M., Nyamangara, J., Rees, R. M., & Kitzler, B. (2012). Greenhouse gas emissions from Savanna (Miombo) woodlands: responses to clearing and cropping. *African Crop Science Journal*, 20, 385-400. https://www.ajol.info/index.php/acsj/article/view/81735/71880

Masso, C., Nziguheba, G., Mutegi, J., Galy-Lacaux, C., Wendt, J., Butterbach-Bahl, K., et al. (2017). Soil fertility management in sub-Saharan Africa. In E. Lichtfouse (Ed.), *Sustainable Agriculture Reviews* (pp. 205-231). Cham: Springer.

Materu, S. T., Shukla, S., Sishodia, R. P., Tarimo, A., & Tumbo, S. D. (2018). Water use and rice productivity for irrigation management alternatives in Tanzania. *Water, 10*(8), 1018. https://doi.org/10.3390/w10081018.

Mati, B. M., De Bock, T., Malesu, M., Khaka, E., Oduor, A., Meshack, M., & Oduor, V. (2006). Mapping the potential of rainwater harvesting technologies in Africa. *A GIS overview on development domains for the continent and ten selected countries. Technical Manual, 6,* 126. Nairobi, Kenya: World Agroforestry Centre (ICRAF), Netherlands Ministry of Foreign Affairs. http://www.rainfoundation.org/wp-content/uploads/2017/10/mapping-the-potential-of-rainwater-harvesting-technologies-in-africa.pdf. Accessed 2 July 2020.

Mati, B. M., Wanjogu, R., Odongo, B., & Home, P. G. (2011). Introduction of the system of rice intensification in Kenya: experiences from Mwea irrigation scheme. *Paddy and Water Environment*, *9*(1), 145-154, https://doi.org/10.1007/s10333-010-0241-3.

Mbilinyi, B. P., Tumbo, S. D., Mahoo, H. F., Senkondo, E. M., & Hatibu, N. (2005). Indigenous knowledge as decision support tool in rainwater harvesting. *Physics and Chemistry of the Earth, Parts A/B/C*, 30(11-16), 792-798. https://doi.org/10.1016/j.pce.2005.08.022

Mbow, C., Smith, P., Skole, D., Duguma, L., & Bustamante, M. (2014). Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. *Current Opinion in Environmental Sustainability*, 6, 8-14. https://doi.org/10.1016/j.cosust.2013.09.002

McLauchlan, K. (2006). The nature and longevity of agricultural impacts on soil carbon and nutrients: a review. *Ecosystems*, 9(8), 1364-1382. https://doi.org/10.1007/s10021-005-0135-1

Meijide, A., Gruening, C., Goded, I., Seufert, G., & Cescatti, A. (2017). Water management reduces greenhouse gas emissions in a Mediterranean rice paddy field. *Agriculture, Ecosystems & Environment*, 238, 168-178. https://doi.org/10.1016/j.agee.2016.08.017

Menyailo, O. V., Hungate, B. A., ABRAHAM, W. R., & Conrad, R. (2008). Changing land use reduces soil CH_4 uptake by altering biomass and activity but not composition of high- affinity methanotrophs. *Global Change Biology*, 14(10), 2405-2419.https://doi.org/10.1111/j.1365-2486.2008.01648.x

Minang, P. A., Duguma, L. A., Bernard, F., Mertz, O., & van Noordwijk, M. (2014). Prospects for agroforestry in REDD+ landscapes in Africa. *Current Opinion in Environmental Sustainability*, 6, 78-82. https://doi.org/10.1016/j.cosust.2013.10.015

Miriti, J. M., Esilaba, A. O., Bationo, A., Cheruiyot, H. K., Kathuku, A. N., & Wakaba, P. (2011). Water Harvesting and Integrated Nutrient Management Options for Maize–Cowpea Production in Semi-arid Eastern Kenya. In A. Bationo, B. Waswa, J. Okeyo, F. Maina, J. Kihara (Eds), *Innovations as Key to the Green Revolution in Africa* (pp. 473-480). Dordrecht: Springer. https://doi.org/10.1007/978-90-481-2543-2_49

Misra, A. K. (2014). Climate change and challenges of water and food security. *International Journal of Sustainable Built Environment*, 3(1), 153-165. https://doi.org/10.1016/j.ijsbe.2014.04.006

Molotoks, A., Stehfest, E., Doelman, J., Albanito, F., Fitton, N., Dawson, T. P., & Smith, P. (2018). Global projections of future cropland expansion to 2050 and direct impacts on biodiversity and carbon storage. *Global Change Biology*, 24(12), 5895-5908. https://doi.org/10.1111/gcb.14459

Muchane, M. N., Sileshi, G. W., Gripenberg, S., Jonsson, M., Pumariño, L., & Barrios, E. (2020). Agroforestry boosts soil health in the humid and sub-humid tropics: A meta-analysis. *Agriculture, Ecosystems & Environment*, *295*, 106899, https://doi.org/10.1016/j.agee.2020.106899.

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., & Foley, J. A. (2012). Closing yield gaps through nutrient and water management. *Nature*, 490(7419), 254-257. https://doi.org/10.1038/nature11420

Murty, D., Kirschbaum, M. U., Mcmurtrie, R. E., & Mcgilvray, H. (2002). Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. *Global Change Biology*, 8(2), 105-123. https://doi.org/10.1046/j.1354-1013.2001.00459.x

Nair, P. R., Nair, V. D., Kumar, B. M., & Showalter, J. M. (2010). Carbon sequestration in agroforestry systems. *Advances in Agronomy*, 108, 237-307. https://doi.org/10.1016/S0065-2113(10)08005-3

Nakawuka, P., Langan, S., Schmitter, P., & Barron, J. (2018). A review of trends, constraints and opportunities of smallholder irrigation in East Africa. *Global Food Security*, *17*, 196-212. https://doi.org/10.1016/j.gfs.2017.10.003

Ngigi, S. N., Savenije, H. H., Rockström, J., & Gachene, C. K. (2005). Hydro-economic evaluation of rainwater harvesting and management technologies: Farmers’ investment options and risks in semi-arid Laikipia district of Kenya. *Physics and Chemistry of the Earth, Parts A/B/C*, 30(11-16), 772-782. https://doi.org/10.1016/j.pce.2005.08.020

Nkonya, E., Johnson, T., Kwon, H. Y., & Kato, E. (2016). Economics of land degradation in sub-Saharan Africa. In E. Nkonya (Ed.), *Economics of land degradation and improvement–a global assessment for sustainable development* (pp. 215-259). Cham: Springer. https://doi.org/10.1007/978-3-319-19168-3_9.

Nyamadzawo, G., Shi, Y., Chirinda, N., Olesen, J. E., Mapanda, F., Wuta, M., et al. (2017). Combining organic and inorganic nitrogen fertilisation reduces N_2O emissions from cereal crops: a comparative analysis of China and Zimbabwe. *Mitigation and Adaptation Strategies for Global Change*, 22(2), 233-245. https://doi.org/10.1007/s11027-014-9560-9

Nyamadzawo, G., Wuta, M., Nyamangara, J., Smith, J. L., & Rees, R. M. (2014). Nitrous oxide and methane emissions from cultivated seasonal wetland (dambo) soils with inorganic, organic and integrated nutrient management. *Nutrient Cycling in Agroecosystems*, 100(2), 161-175. https://doi.org/10.1007/s10705-014-9634-9

OECD/Food and Agriculture Organization of the United Nations (2015). *OECD-FAO Agricultural Outlook 2015*, OECD Publishing, Paris. http://dx.doi.org/10.1787/agr_outlook-2015-en

Ordway, E.M., Asner, G.P., & Lambin, E.F. (2017). Deforestation risk due to commodity crop expansion in sub-Saharan Africa. *Environmental Research Letters*, 12 (4), 044015. https://doi.org/10.1088/1748-9326/aa6509

Ortiz-Gonzalo, D., Vaast, P., Oelofse, M., de Neergaard, A., Albrecht, A., & Rosenstock, T.S. (2017). Farm-scale greenhouse gas balances, hotspots and uncertainties in smallholder crop-livestock systems in Central Kenya. *Agriculture, Ecosystems and Environment*, 248, 58-70. https://doi.org/10.1016/j.agee.2017.06.002

Pavelic, P., Villholth, K.G., Shu,Y., Rebelo, L.M., & Smakhtin, V. (2013). Smallholder groundwater irrigation in Sub-Saharan Africa: country-level estimates of development potential. *Water International*, 38 (4), 392-407. https://doi.org/10.1080/02508060.2013.819601

Pearson, T.R.H., Brown, S., Murray, L., & Sidman, G. (2017). Greenhouse gas emissions from tropical forest degradation: an underestimated source. *Carbon Balance Management*, 12, 3. https://doi.org/10.1186/s13021-017-0072-2 .

Pelster, D., Rufino, M., Rosenstock, T., Mango, J., Saiz, G., Diaz-Pines, E., et al. (2017). Smallholder farms in eastern African tropical highlands have low soil greenhouse gas fluxes. *Biogeosciences*, *14*(1), 187-202, doi:10.5194/bg-14-187-2017. https://doi.org/10.5194/bg-14-187-2017

Peng, X., Peng, Y., Yue, K., & Deng, Y. (2017). Different responses of terrestrial C, N, and P pools and C/N/P ratios to P, NP, and NPK addition: A meta-analysis. *Water, Air, & Soil Pollution*, 228, 197. https://doi.org/10.1007/s11270-017-3383-8

Place, F., Ajayi, O.C., Torquebiau, E., Detlefse, N.G., Gauthier, M., & Buttoud, G. (2012). Improved Policies for Facilitating the Adoption of Agroforestry, in: Kaonga M. (Ed.)., *Agroforestry for Biodiversity and Ecosystem Services - Science and Practice*, InTech.

Powlson, D.S., Stirling, C.M., Thierfelder, C., White, R.P., & Jat, M. (2016). Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? *Agriculture, Ecosystems and Environment*, 220, 164-174. https://doi.org/10.1016/j.agee.2016.01.005

Qiu, L., Wu, Y., Hao, M., Shen, J., Lei, X., Liao, W., & Li, Y. (2018). Simulation of the irrigation requirements for improving carbon sequestration in a rainfed cropping system under long-term fertilization on the Loess Plateau of China. Agriculture, Ecosystems & Environment, 265, 198-208. https://doi.org/10.1016/j.agee.2018.06.015

Raimi, A., Adeleke, R., & Roopnarain, A. (2017). Soil fertility challenges and biofertiliser as a viable alternative for increasing smallholder farmer crop productivity in sub-Saharan Africa. *Cogent Food & Agriculture*, 3, 1400933. https://doi.org/10.1080/23311932.2017.1400933

Riesgo, L., Louhichi, K., Gomez y Paloma, S., Hazell, P., Ricker-Gilbert, J., Wiggins, S., Sahn, D.E., & Mishra, A. (2016). Food and nutrition security and role of smallholder farms: challenges and opportunities - Workshop proceedings. https://doi.org/10.2791/653314

Rioux, J. (2012). Opportunities and challenges of promoting agroforestry for climate change mitigation: a case-study of the Mitigation of Climate Change in Agriculture (MICCA) pilot project in Tanzania. *Nature & Faune*, 26, 63-68. http://www.fao.org/climatechange/36653-0d7b3e802032f0279b368b3536cf5c3ee.pdf

Rochette, P., Tremblay, N., Fallon, E., Angers, D.A., Chantigny, M.H., MacDonald, J.D., et al. (2010). N_2O emissions from an irrigated and non-irrigated organic soil in eastern Canada as influenced by N fertilizer addition. *European Journal of Soil Science*, 61, 186-196. https://doi.org/10.1111/j.1365-2389.2009.01222.x

Rockström, J., & Falkenmark, M. (2015). Agriculture: increase water harvesting in Africa. *Nature*, 519 (7543), 283-285. https://doi.org/10.1038/519283a

Rockström, J., Karlberg, L., Wani, S.P., Barron, J., Hatibu, N., Oweis, et al. (2010). Managing water in rainfed agriculture-The need for a paradigm shift. *Agricultural Water Management*, 97 (4), 543-550. https://doi.org/10.1016/j.agwat.2009.09.009

Roldán, A., Salinas-Garcia, J., Alguacil, M., & Caravaca, F. (2005). Changes in soil enzyme activity, fertility, aggregation and C sequestration mediated by conservation tillage practices and water regime in a maize field. *Applied Soil Ecology*, 30 (1), 11-20. https://doi.org/10.1016/j.apsoil.2005.01.004

Roobroeck, D., Palm, C. A., Nziguheba, G., Weil, R., & Vanlauwe, B. (2021). Assessing and understanding non-responsiveness of maize and soybean to fertilizer applications in African smallholder farms. *Agriculture, Ecosystems & Environment*, 305, 107165, https://doi.org/10.1016/j.agee.2020.107165.

Rosa, L., Chiarelli, D. D., Sangiorgio, M., Beltran-Peña, A. A., Rulli, M. C., D'Odorico, P., et al. (2020). Potential for sustainable irrigation expansion in a 3 °C warmer climate. *Proceedings of the National Academy of Sciences*, 117(47), 29526-29534, https://doi.org/10.1073/pnas.2017796117

Rosenstock, T.S., Rufino, M.C., Butterbach-Bahl, K., & Wollenberg, E. (2013). Toward a protocol for quantifying the greenhouse gas balance and identifying mitigation options in smallholder farming systems. *Environmental Research Letters*, 8 (2), 021003. https://doi.org/10.1088/1748-9326/8/2/021003

Roser, M., & Ritchie, H. (2017). Food per Person. https://ourworldindata.org/food-per-person. Accessed Feb. 15, 2020.

Sainju, U.M. (2016). A global meta-analysis on the impact of management practices on net global warming potential and greenhouse gas intensity from cropland soils. *PloS One*, 11, e0148527. https://doi.org/10.1371/journal.pone.0148527

Sanchez, P.A. (2002). Soil fertility and hunger in Africa. *Science*, 295 (5562), 2019-2020. https://doi.org/10.1126/science.1065256

Sanz-Cobena, A., Lassaletta, L., Aguilera, E., Del Prado, A., Garnier, J., Billen, G., et al. (2017). Strategies for greenhouse gas emissions mitigation in Mediterranean agriculture: A review. *Agriculture, Ecosystems and Environment*, 238, 5-24. https://doi.org/10.1016/j.agee.2016.09.038

Schlecht, E., Buerkert, A., Tielkes, E., & Bationo, A. (2006). A critical analysis of challenges and opportunities for soil fertility restoration in Sudano-Sahelian West Africa. *Nutrient Cycling in Agroecosystems*, 76, 109-136. https://doi.org/10.1007/s10705-005-1670-z

Seck, P.A., Diagne, A., Mohanty, S., & Wopereis, M.C. (2012). Crops that feed the world 7: Rice. *Food Security* 4, 7-24. https://doi.org/10.1007/s12571-012-0168-1

Seebauer, M. (2014). Whole farm quantification of GHG emissions within smallholder farms in developing countries. *Environmental Research Letters* 9, 035006. https://doi.org/10.1088/1748-9326/9/3/035006

Senkondo, E., Msangi, A., Xavery, P., Lazaro, E., & Hatibu, N. (2004). Profitability of rainwater harvesting for agricultural production in selected semi-arid areas of Tanzania. *Journal of Applied Irrigation Science*, 39, 65-81.

Shah, T., Verma, S., & Pavelic, P. (2013). Understanding smallholder irrigation in Sub-Saharan Africa: results of sample survey from nine countries. *Water International*, 38 (6), 809-826. http://dx.doi.org/10.1080/02508060.2013.843843

Sharmasarkar, F.C., Sharmasarkar, S., Miller, S., Vance, G., & Zhang, R. (2001). Assessment of drip and flood irrigation on water and fertilizer use efficiencies for sugarbeets. *Agricultural Water Management*, 46 (3), 241-251. https://doi.org/10.1016/S0378-3774(00)00090-1

Shcherbak, I., Millar, N., & Robertson, G.P. (2014). Global metaanalysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen. *Proceedings of the National Academy of Sciences USA*, 111 (25), 9199-9204. https://doi.org/10.1073/pnas.1322434111

Sheahan, M., & Barrett, C.B. (2014). *Understanding the Agricultural Input Landscape in sub-Saharan Africa. Recent Plot, Household, and Community-Level Evidence*. World Bank Policy Research Working Paper 7014. Washington D.C., USA. http://documents.worldbank.org/curated/en/165341468002108906/Understanding-the-agricultural-input-landscape-in-Sub-Saharan-Africa-recent-plot-household-and-community-level-evidence. Accessed 20 July 2020.

Sheahan, M., & Barrett, C.B. (2017). Ten striking facts about agricultural input use in Sub-Saharan Africa. *Food Policy*, 67, 12-25. https://doi.org/10.1016/j.foodpol.2016.09.010

Shehu, B. M., Merckx, R., Jibrin, J. M., & Rurinda, J. (2018). Quantifying variability in maize yield response to nutrient applications in the northern Nigerian savanna. *Agronomy, 8*(2), 18. https://doi.org/10.3390/agronomy8020018.

Sileshi, G., Akinnifesi, F. K., Ajayi, O. C., & Place, F. (2008). Meta-analysis of maize yield response to woody and herbaceous legumes in sub-Saharan Africa. *Plant and Soil, 307*(1-2), 1-19. https://doi.org/10.1007/s11104-008-9547-y

Simojoki, A., & Jaakkola, A. (2000). Effect of nitrogen fertilization, cropping and irrigation on soil air composition and nitrous oxide emission in a loamy clay. *European Journal of Soil Science*, 51 (3), 413-424. https://doi.org/10.1046/j.1365-2389.2000.00308.x

Singh, B.K., Tate, K.R., Kolipaka, G., Hedley, C.B., Macdonald, C.A., Millard, P., & Murrell, J.C. (2007). Effect of afforestation and reforestation of pastures on the activity and population dynamics of methanotrophic bacteria. *Applied and Environmental Microbiology*, 73, 5153-5161. https://doi.org/10.1128/AEM.00620-07

Singh, B.K., Tate, K.R., Ross, D., Singh, J., Dando, J., Thomas, N., et al. (2009). Soil methane oxidation and methanotroph responses to afforestation of pastures with Pinus radiata stands. *Soil Biology and Biochemistry*, 41 (10), 2196-2205. https://doi.org/10.1016/j.soilbio.2009.08.004

Singh, B.R., Safalaoh, A., Amuri, N.A., Eik, L.O., Sitaula, B.K., & Lal, R. (2020). *Climate impacts on agricultural and natural resource sustainability in Africa*. Springer International Publishing. https://doi.org/10.1007/978-3-030-37537-9

Smith, K. (2010). *Nitrous oxide and climate change*, first ed. Earthscan, UK.

Smith, P., Calvin, K., Nkem, J., Campbell, D., Cherubini, F., Grassi, G., et al. (2019). Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? *Global Change Biology*, 26, 1532-1575 https://doi.org/10.1111/gcb.14878

Svendsen, M., Ewing, M., & Msangi, S. (2009). *Measuring irrigation performance in Africa*, International Food Policy Research Institute (IFPRI), discussion paper 00894. http://www.ifpri.org/publication/measuring-irrigation-performance-africa. Accessed Feb. 25, 2019.

Taffere, G.R., Beyene, A., Vuai, S.A., Gasana, J., & Seleshi, Y. (2016). Reliability analysis of roof rainwater harvesting systems in a semi-arid region of sub-Saharan Africa: Case study of Mekelle, Ethiopia. *Hydrologogical Sciences Journal*, 61 (6), 1135-1140. https://doi.org/10.1080/02626667.2015.1061195

Tate, K.R. (2015). Soil methane oxidation and land-use change- from process to mitigation. *Soil Biology and Biochemistry*, 80, 260-272. https://doi.org/10.1016/j.soilbio.2014.10.010

ten Berge, H.F.M., Hijbeek, R., van Loon, M.P., Rurinda, J., Tesfaye, K., Zingore, S., et al. (2019). Maize crop nutrient input requirements for food security in sub-Saharan Africa. *Global Food Security*, 23, 9-21. https://doi.org/10.1016/j.gfs.2019.02.001

Tenkorang, F., & Lowenberg-DeBoer, J. (2009). Forecasting long-term global fertilizer demand. *Nutrient Cycling in Agroecosystems*, 83, 233-247. https://doi.org/10.1007/s10705-008-9214-y

The Global Economy (2019). Employment in agriculture. https://www.theglobaleconomy.com/rankings/Employment_in_agriculture/. Accessed 22 January 2020.

Thierfelder, C., Chivenge, P., Mupangwa, W., Rosenstock, T.S., Lamanna, C., & Eyre, J.X. (2017). How climate-smart is conservation agriculture (CA)? – its potential to deliver on adaptation, mitigation and productivity on smallholder farms in southern Africa. *Food Security*, 9, 537-560. https://doi.org/10.1007/s12571-017-0665-3

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(50), 20260-20264. https://doi.org/10.1073/pnas.1116437108.

Tittonell, P., & Giller, K.E. (2013). When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. *Field Crops Research,* 143, 76-90. https://doi.org/10.1016/j.fcr.2012.10.007

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Rowe, E.C., Giller, K.E. (2005). Exploring diversity in soil fertility management of smallholder farms in western Kenya: I. Heterogeneity at region and farm scale. *Agriculture, Ecosystems and Environment,* 110 (3-4), 149-165. https://doi.org/10.1016/j.agee.2005.04.001

Tongwane, M.I., & Moeletsi, M.E. (2018). A review of greenhouse gas emissions from the agriculture sector in Africa. *Agricultural Systems,* 166, 124-134. https://doi.org/10.1016/j.agsy.2018.08.011

Trost, B., Ellmer, F., Baumecker, M., Meyer-Aurich, A., Prochnow, A., & Drastig, K. (2014). Effects of irrigation and nitrogen fertilizer on yield, carbon inputs from above ground harvest residues and soil organic carbon contents of a sandy soil in Germany. *Soil Use and Management,* 30, 209-218. https://doi.org/10.1111/sum.12123

Trost, B., Prochnow, A., Drastig, K,. Meyer-Aurich, A., Ellmer, F., & Baumecker, M. (2013). Irrigation, soil organic carbon and N_2O emissions. *Agronomy for Sustainable Development,* 33, 733-749. https://doi.org/10.1007/s13593-013-0134-0

Trost, B., Prochnow, A., Meyer-Aurich, A., Drastig, K., Baumecker, M., & Ellmer, F. (2016). Effects of irrigation and nitrogen fertilization on the greenhouse gas emissions of a cropping system on a sandy soil in northeast Germany. *European Journal of Agronomy,* 81, 117-128. https://doi.org/10.1016/j.eja.2016.09.008

Tubiello, F.N., Salvatore, M., Rossi, S., Ferrara, A., Fitton, N., & Smith, P. (2013). The FAOSTAT database of greenhouse gas emissions from agriculture. *Environmental Research Letters*, 8 (1), 015009. https://doi.org/10.1088/1748-9326/8/1/015009

UNFCCC (2015). Adoption of the Paris Agreement, FCCC/CP/2015/L.9/Rev1, (United Nations Framework Convention on Climate Change), https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf. Accessed 25 January 2020.

United Nations, Department of Economic and Social Affairs, Population Division (2017).World Population Prospects 2017 – Data Booklet (ST/ESA/SER.A/401). https://population.un.org/wpp/Publications/Files/WPP2017_DataBooklet.pdf. Accessed 25 January 2020.

Valentini, R., Arneth, A., Bombelli, A., Castaldi, S., Cazzolla Gatti, R., Chevallier, F., et al. (2014). A full greenhouse gases budget of Africa: synthesis, uncertainties, and vulnerabilities. *Biogeosciences*, 11, 381-407. https://doi.org/10.5194/bg-11-381-2014 van Ittersum, M. K., Van Bussel, L. G., Wolf, J., Grassini, P., Van Wart, J., Guilpart, N., et al. (2016). Can sub-Saharan Africa feed itself? *Proceedings of the National Academy of Sciences the United States of America, 113*(52), 14964-14969. https://doi.org/10.1073/pnas.1610359113.

van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M.A., Linquist, B., van Groenigen, K.J. (2013). Climate, duration, and N placement determine N_2O emissions in reduced tillage systems: a meta-analysis. *Global Change Biology,* 19 (1), 33-44. https://doi.org/10.1111/j.1365-2486.2012.02779.x

van Lent, J., Hergoualc'h, K., & Verchot, L.V. (2015). Reviews and syntheses: Soil N_2O and NO emissions from land use and land-use change in the tropics and subtropics: a meta-analysis. *Biogeosciences,* 12 (23),7299-7313. https://doi.org/10.5194/bg-12-7299-2015

van Loon, M., Hijbeek, R., ten Berge, H.F.M., De Sy, V., ten Broeke, G.A., Solomon, D., et al. (2019). Impacts of intensifying or expanding cereal cropping in sub-Saharan Africa on greenhouse gas emissions and food security. *Global Change Biology,* 25 (11), 3720-3730. https://doi.org/10.1111/gcb.14783

van Oort, P. A. J., & Zwart, S. J. (2018). Impacts of climate change on rice production in Africa and causes of simulated yield changes. *Global Change Biology,* 24(3), 1029-1045, https://doi.org/10.1111/gcb.13967.

Vanlauwe, B., Descheemaeker, K., Giller, K., Huising, J., Merckx, R., Nziguheba, G., et al. (2015). Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. *Soil,* 1, 491-508. https://doi.org/10.5194/soil-1-491-2015

Vlek, P., Le Q, B., & Tamene, L. (2010). Assessment of land degradation, its possible causes and threat to food security in Sub-Saharan Africa, in: Lal, R., Stewart, B.A. (Eds.), *Food security and soil quality*. Boca Raton, Florida, CRC Press, pp. 57–86.

Wang, Z., Zhang, W., Beebout, S. S., Zhang, H., Liu, L., Yang, J., et al. (2016). Grain yield, water and nitrogen use efficiencies of rice as influenced by irrigation regimes and their interaction with nitrogen rates. *Field Crops Research, 193*, 54-69. https://doi.org/10.1016/j.fcr.2016.03.006.

Wanyama I, Pelster D, Arias-Navarro C, Butterbach-Bahl K, Verchot L, & Rufino M (2018). Management intensity controls soil N_2O fluxes in an Afromontane ecosystem. *Science of the Total Environment,* 624, 769-780. https://doi.org/10.1016/j.scitotenv.2017.12.081

Wei, X., Shao, M., Gale, W., & Li, L. (2014). Global pattern of soil carbon losses due to the conversion of forests to agricultural land. *Scientific Reports,* 4, 4062. https://doi.org/10.1038/srep04062

Wheeler, S.A., Zuo, A., Bjornlund, H., Mdemu, M.V., van Rooyen, A., & Munguambe, P. (2017). An overview of extension use in irrigated agriculture and case studies in south-eastern

Africa. *International Journal of Water Resources Development*, 33 (5), 755-769. https://doi.org/10.1080/07900627.2016.1225570

Whitney, C.W., Luedeling, E., Hensel, O., Tabuti, J.R.S., Krawinkel, M., Gebauer, J., et al. (2018). The role of homegardens for food and nutrition security in Uganda. *Human Ecology*, 46, 497-514. https://doi.org/10.1007/s10745-018-0008-9

Wiggins, S. (2009). Can the smallholder model deliver poverty reduction and food security, FAC Working Paper 08, Brighton: Future Agricultures Consortium. http://www.fao.org/tempref/docrep/fao/012/ak982e/ak982e00.pdf. Accessed Feb. 25, 2020.

Wriedt, G., Van der Velde, M., Aloe, A., & Bouraoui, F. (2009). Estimating irrigation water requirements in Europe. *Journal of Hydrology*, 373(3), 527-544, https://doi.org/10.1016/j.jhydrol.2009.05.018.

Wu, W., & Ma, B. (2015). Integrated nutrient management (INM) for sustaining crop productivity and reducing environmental impact: A review. *Science of the Total Environment*, 512, 415-427. https://doi.org/10.1016/j.scitotenv.2014.12.101

Xie, H., You, L., Wielgosz, B., & Ringler, C. (2014). Estimating the potential for expanding smallholder irrigation in Sub-Saharan Africa. *Agricultural Water Management*,131, 183-193. https://doi.org/10.1016/j.agwat.2013.08.011

Yang, J., Zhou, Q., & Zhang, J. (2017). Moderate wetting and drying increases rice yield and reduces water use, grain arsenic level, and methane emission. *The Crop Journal*, *5*(2), 151-158, https://doi.org/10.1016/j.cj.2016.06.002.

You, L., Ringler, C., Wood-Sichra, U., Robertson, R., Wood, S., Zhu, T., et al. (2011). What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach. *Food Policy*, 36 (6), 770-782. https://doi.org/10.1016/j.foodpol.2011.09.001

Yue, K., Peng, Y., Peng, C., Yang, W., Peng, X., & Wu, F. (2016). Stimulation of terrestrial ecosystem carbon storage by nitrogen addition: a meta-analysis. *Scientific Reports*, 6, 19895. https://doi.org/10.1038/srep19895

Zenna, N., Senthilkumar, K., & Sie, M. (2017). Rice Production in Africa, in: Chauhan, B., Jabran, K., and Mahajan, G., (Eds.), *Rice Production Worldwide*. Springer, Cham. pp 117-135. https://doi.org/10.1007/978-3-319-47516-5_5

Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P., & Shen, Y. (2015). Managing nitrogen for sustainable development. *Nature*, 528, 51-59. https://doi.org/10.1038/nature15743

Zingore, S., Murwira, H.K., Delve, R.J., & Giller, K.E. (2007). Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. *Agriculture, Ecosystems and Environment* 119 (1-2), 112-126. https://doi.org/10.1016/j.agee.2006.06.019

Zougmoré, R., Jalloh, A., & Tioro, A. (2014). Climate-smart soil water and nutrient management options in semiarid West Africa: a review of evidence and analysis of stone bunds and zaï techniques. *Agriculture and Food Security*, 3,16. https://doi.org/10.1186/2048-7010-3-16

Figure captions

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).

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.

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.

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).

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).

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).

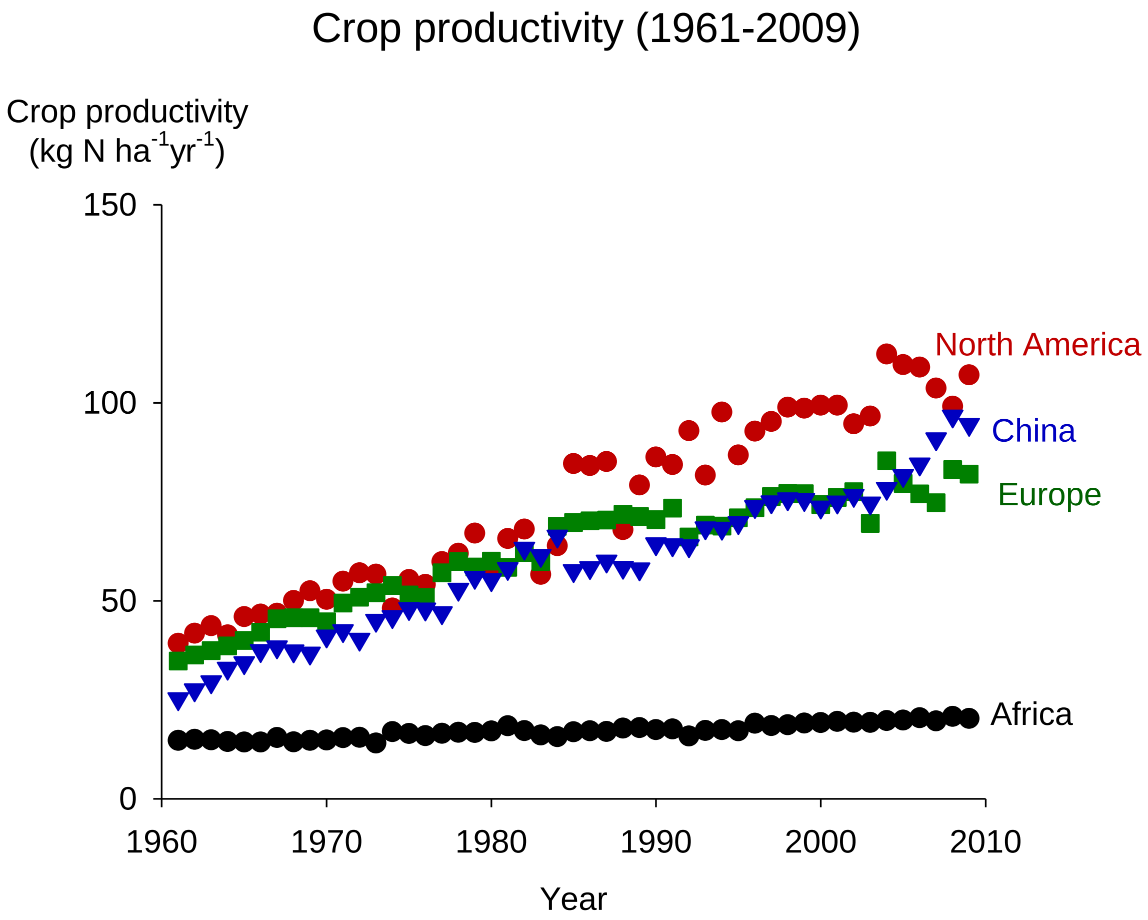


Fig. 2 Changes of crop productivity in Africa, North America, Europe and China in 1961 to 2009 (Data source: FAO STAT). The crop productivity in Africa is very low compared to other regions.

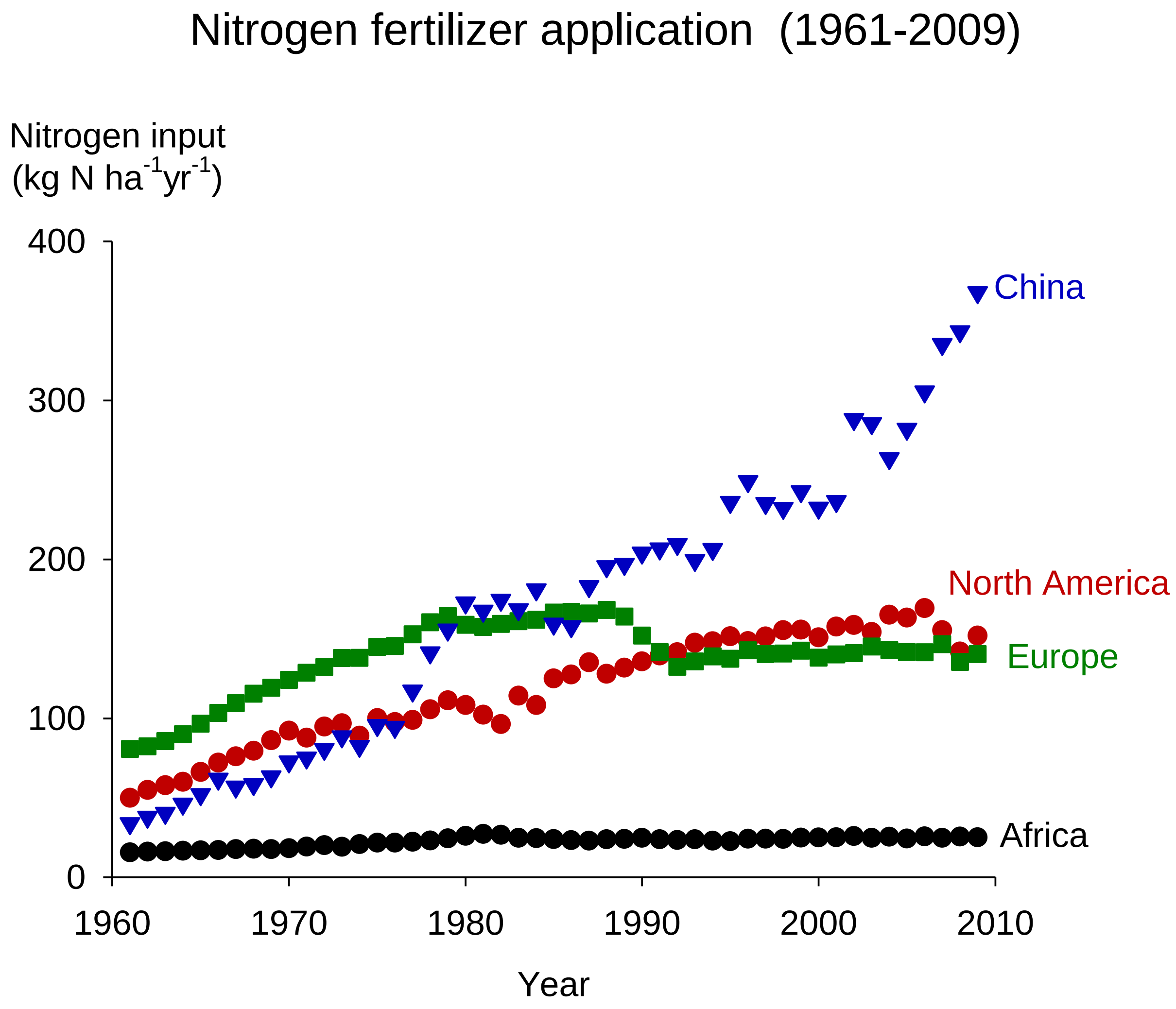


Fig. 3 Changes of nitrogen (N) fertilizer application in Africa, North America, Europe and China in 1961 to 2009 (Data source: FAO STAT). The amount of N fertilizer application in Africa is very low compared to other regions.

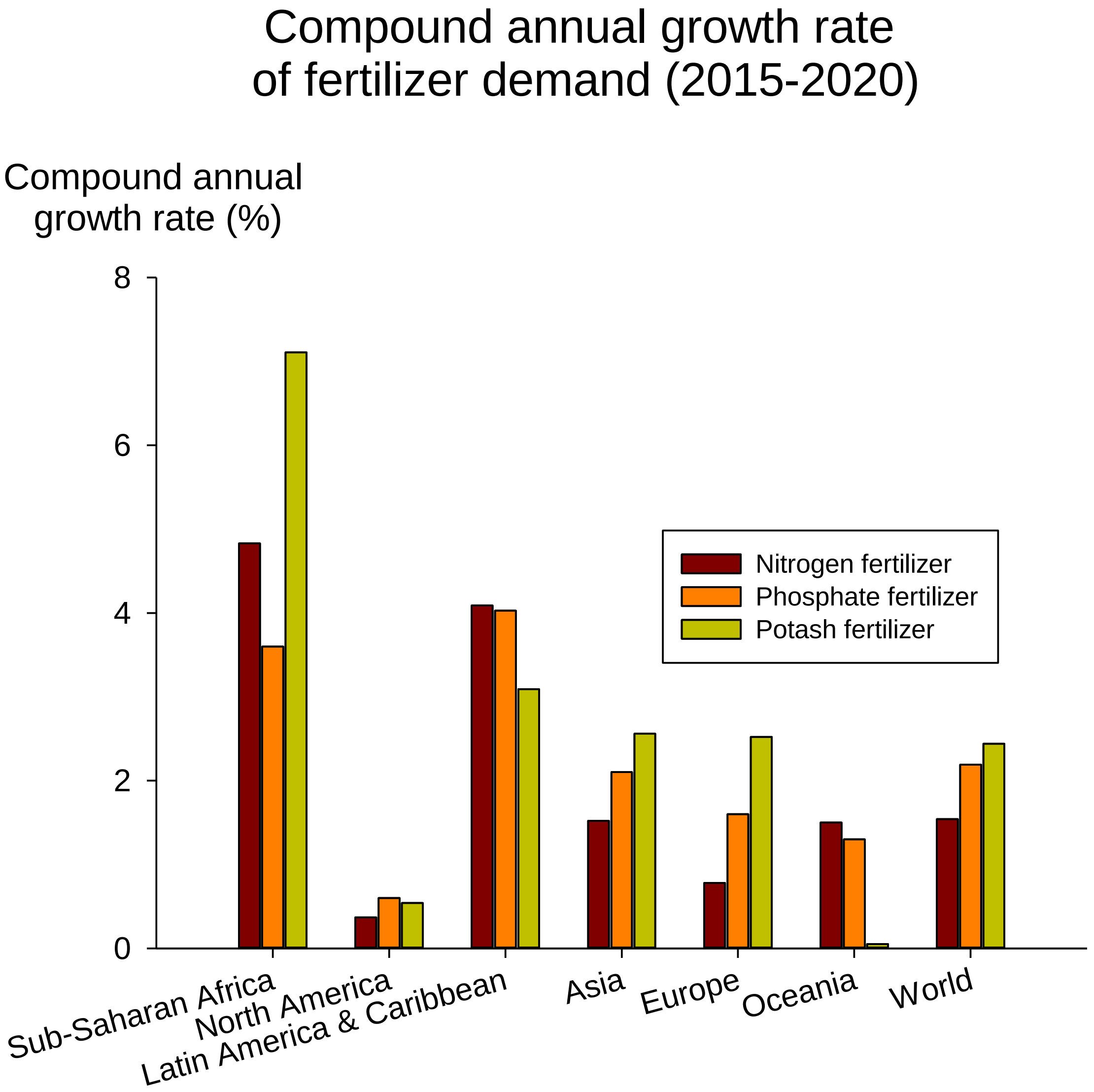


Fig. 4 Annual growth rate from 2015 to 2020 (determined as compound annual growth rate) of synthetic fertilizer (nitrogen, phosphate and potash fertilizers) demand in different regions in 2015 to 2020 (Data source: FAO 2017).

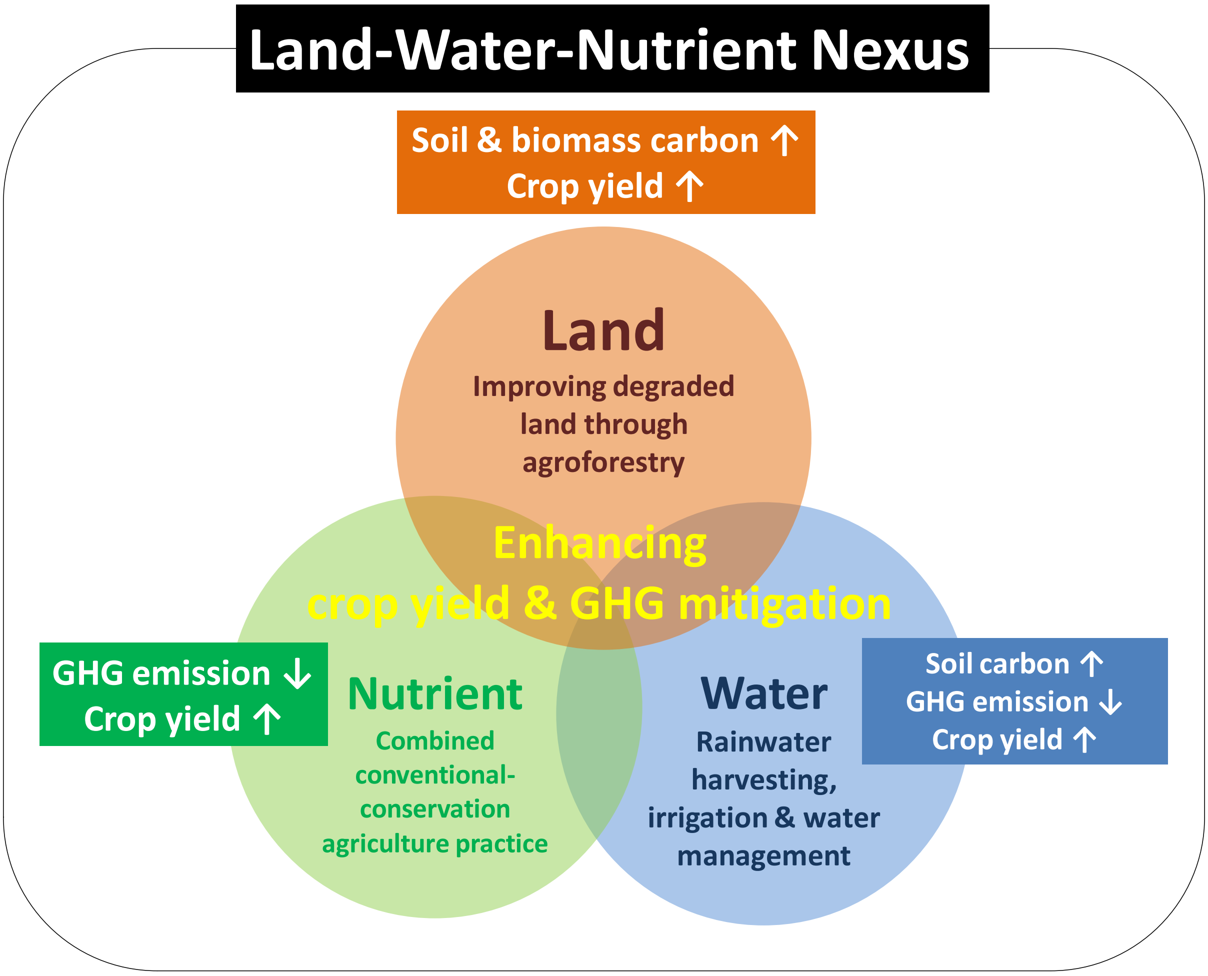


Fig. 5 Land-Water-Nutrient Nexus (LWNN) approach to enhance crop yield and mitigate greenhouse gas (GHG) emission in smallholder crop farming systems in sub-Saharan Africa. ↑: increase and ↓: decrease (Produced by authors).

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

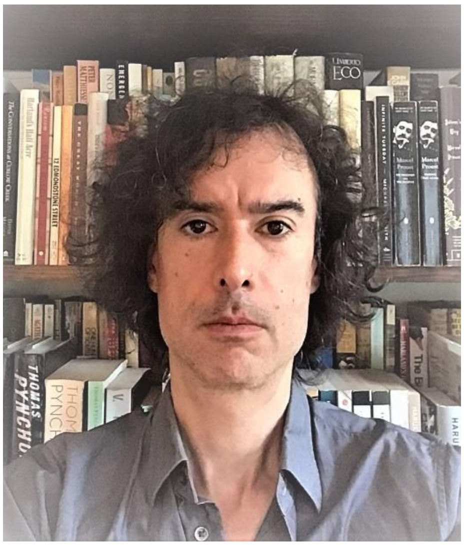
No	Country	Crop type	Conventional practice	CCCA practice	Effects of CCCA	Reference
1	Zimbabwe	Maize (*Zea mays* L.)	N fertilizer (NH_4NO_3-N; 120 kg N ha^{-1})	N fertilizer (NH_4NO_3-N; 60 kg N ha^{-1}) & composted manure (60 kg N ha^{-1})	Yield-scaled N_2O emission mitigation (48 %)	Mapanda et al. 2011
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. 2014a
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. 2014b
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 Phosphate; 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*	N fertilizer (urea, 50 kg	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

		glaucum)	ha^{-1})			

Dong-Gill Kim's research interests are mainly carbon sequestration, greenhouse gas (GHG) mitigation and climate change resilience in agroecosystems. He carried out various GHG research in South-Korea, USA, Ireland and New Zealand and currently works at Hawassa University, Ethiopia. He extensively collaborates with researchers in Africa, Europe, and North and Latin America for enhancing food security and GHG mitigation of smallholder farming systems. He earned his Ph.D. in Environmental Science from Iowa State University, USA.

Elisa Grieco is a research fellow at CNR Institute of Bioeconomy (CNR-IBE) based in Italy and she is currently involved in PPAT&RD project for strengthening communication in support of research and technology transfer in agriculture and rural development in Senegal. She has a PhD in Forest Ecology and her field of experience is focused on land use change and carbon stock dynamics in Africa, climate change adaptation and sustainable development. She worked on H2020 project, SEACRIFOG for supporting EU-Africa cooperation on research infrastructure for food security and GHG observations. She worked at the coordination office of ClimAfrica project and she was also involved in Africa GHG project for deforestation assessment and field data collection to validate LIDAR data. She worked on CARBOAFRICA project for the installation of Eddy Covariance Flux Tower in the Ankasa Conservation Area (Ghana) and she analyzed the dynamic of carbon stock after deforestation and the impact of land use change in the region.

Antonio Bombelli has a degree in Biological Sciences and a PhD in Plant Sciences. He is researcher at ENEA, the Italian National Agency for New Technologies, Energy and Sustainable Economic Development, nominated Seconded Expert at the Italian Ministry of Foreign Affairs. His background concerns Plant Ecophysiology, Agroforestry and Carbon Cycle, particularly with regard to terrestrial ecosystems response to natural and anthropogenic stress, including climate change. He worked on several international research projects in Sub-Saharan Africa (SSA) as project manager and/or workpackage leader, like CarboAfrica (Quantification, understanding and prediction of carbon cycle and GHGs in SSA), ClimAfrica (Climate Change Predictions in SSA: Impacts and Adaptations) and SEACRIFOG (Supporting EU-African Cooperation on Research Infrastructures for Food Security and GHG Observations).



Jonathan E. Hickman is a Senior Fellow in the NASA Postdoctoral Program, based at the NASA Goddard Institute of Space Studies. Jonathan conducts research on gas exchange between the land surface and atmosphere using satellite observations, chemical transport models, Earth system models, and field and laboratory measurements. Much of his work has focused on nitrogen cycling in soils and emissions of GHG and air pollutants, particularly in the context of smallholder farming in sub-Saharan Africa. He earned his Ph.D. in Ecology and Evolution from Stony Brook University, USA.

Alberto Sanz-Cobena, Research Center for the Management of Environmental and Agricultural Risks (CEIGRAM), ETSIAAB, Universidad Politécnica de Madrid). He is Associate Professor at the Technical University of Madrid (UPM) and researcher at the Centre for the Management of Agricultural and Environmental Risks (ETSIAAB, UPM). Beyond quantifying and assessing the impact of crop management on nitrogen (N) dynamics and GHG emissions at plot scale, he also works on a more integrated view of complex problems such as GHG emissions and other nitrogen compounds and their mitigation on the provincial, watershed, national and large (Mediterranean) areas.