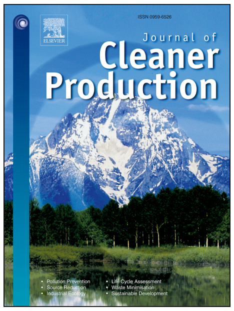

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Combined application of the EM-DEA and EX-ACT approaches for integrated assessment of resource use efficiency, sustainability and carbon footprint of smallholder maize production practices in sub-Saharan Africa

Francis Molua Mwambo [1, 2, *], Christine Fürst [2], Christopher Martius [3], Marcos Jimenez-Martinez [1], Benjamin Kofi Nyarko [4], and Christian Borgemeister [1]

[1] Department of Ecology and Natural Resources Management, Center for Development Research (ZEF), University of Bonn, Genscherallee 3, 53113 Bonn, Germany; marcosjm23@gmail.com; cb@uni-bonn.de
[2] Martin Luther University Halle-Wittenberg, Institute for Geosciences and Geography, Department of Sustainable Landscape Development, Von-Seckendorff-Platz 4, 06120 Halle, Germany; christine.fuerst@geo.uni-halle.de
[3] Center for International Forestry Research (CIFOR) Germany gGmbH, Charles-de-Gaulle-Str. 5, 53113 Bonn, Germany; c.martius@cgiar.org
[4] Department of Geography and Regional Planning, University of Cape Coast, Cape Coast, Ghana; bnyarko@ucc.edu.gh
* Correspondence: mwambof@gmail.com

Abstract: The goal to improve food security in sub-Saharan Africa (SSA) through domestic, resource efficient and low carbon agriculture is importance. Interventions to produce more food could impact the resource-base and lead to increase in greenhouse gas (GHG) emissions from agroecosystems. Unfortunately, existing methods are limited in analyzing small-scale agricultural systems, and this situation is an obstacle to decision making which aims at sustainable agriculture. In this paper, we showcase the recently developed Emergy-Data Envelopment Analysis (EM-DEA) approach to assess the resource use efficiency (RUE) and sustainability in maize production systems in Ghana, SSA. Using the Agricultural Production Systems sIMulator (APSIM), five land use and resource management scenarios were modeled to represent practices as decision making units (DMUs) in small-scale maize systems. The carbon footprint of the systems was assessed using an approach, which we adapted from the FAO Ex-Ante Carbon balance Tool (EX-ACT). The overall trend of the results showed that the yield, total emergy, GHG emissions and carbon footprint all increased with increase in urea application intensity. However, the relationship between the yield and urea input was not always linear. A system that used more renewable or fewer resources to produce a yield equal to that of its peer was considered more efficient and sustainable in relative terms. In particular, the business-as-usual scenario (12 kg/ha/yr NPK input to rainfed maize system, i.e. *Extensive12*) was inefficient when compared to the four contrasting scenarios. The ecological intensive scenario (20 kg/ha/yr urea input to rainfed maize-legume intercropping system, i.e. *Intercrop20*) achieved the greatest marginal yield, better RUE and sustainability. The high input scenario (100 kg/ha/yr urea input plus supplemental irrigation to maize monoculture, i.e. *Intensive100*) produced the greatest yield, but the demand for purchased inputs as well as GHG emissions and carbon footprint were greatest. The no external input scenario (0 kg/ha/yr urea input to rainfed maize system, i.e. *Extensive0*), and the moderate input scenario (50 kg/ha/yr urea input plus supplemental irrigation to maize monoculture, i.e. *Intensive50*) showed the greatest and least yield gaps relative to *Intensive100*, respectively. Based on these results and trade-off analysis, it was evident that *Intercrop20* and *Intensive50* were the two best case scenarios. As such, land use policy that aims at sustainable agriculture could recommend *Intercrop20* and *Intensive50* for implementation in low and high input maize production systems, respectively. Comparison between our results and other existing empirical studies revealed similarities that confirm our results. We conclude that the information derived using the EM-DEA and EX-ACT approaches could be useful when making informed decisions that aim at sustainable agriculture. Despite the limitation caused by scarcity of data, the use of the EM-DEA approach led to inclusive information on RUE and sustainability of the DMUs. Hence, the EM-DEA approach represents a way forward to better assess energy footprint in agricultural land use as a whole.

Keywords: agricultural sustainability; resource use efficiency; greenhouse gas emissions; carbon footprint; maize; sub-Saharan Africa; Emergy-Data Envelopment Analysis.

Combined application of the EM-DEA and EX-ACT approaches for integrated assessment of resource use efficiency, sustainability and carbon footprint of smallholder maize production practices in sub-Saharan Africa

Francis Molua Mwambo [1, 2, *], Christine Fürst [2], Christopher Martius [3], Marcos Jimenez-Martinez [1], Benjamin Kofi Nyarko [4], and Christian Borgemeister [1]

[1] Department of Ecology and Natural Resources Management, Center for Development Research (ZEF), University of Bonn, Genscherallee 3, 53113 Bonn, Germany; marcosjm23@gmail.com; cb@uni-bonn.de

[2] Martin Luther University Halle-Wittenberg, Institute for Geosciences and Geography, Department of Sustainable Landscape Development, Von-Seckendorff-Platz 4, 06120 Halle, Germany; christine.fuerst@geo.uni-halle.de

[3] Center for International Forestry Research (CIFOR) Germany gGmbH, Charles-de-Gaulle-Str. 5, 53113 Bonn, Germany; c.martius@cgiar.org

[4] Department of Geography and Regional Planning, University of Cape Coast, Cape Coast, Ghana; bnyarko@ucc.edu.gh

* Correspondence: mwambof@gmail.com

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Keywords: agricultural sustainability; resource use efficiency; greenhouse gas emissions; carbon footprint; maize; sub-Saharan Africa; Emergy-Data Envelopment Analysis.

1. Introduction

Agriculture has emerged as the only means to produce more food to feed the growing global population (Fróna et al., 2019; Harris and Fuller, 2014). At the global scale, the majority of farms are relatively small, and they are owned as well as managed by families (Lowder et al., 2014; 2016; Graeub et al., 2016). Smallholder farming systems are critical to food security (Lowder et al., 2014; 2016; 2019; Graeub et al., 2016; Arce et al., 2016; United Nations, 2017a; Ricciardi et al., 2018). Nevertheless, they are facing lots of challenges which are still to be solved (Veeck and Shaohua, 2000; Stringer et al., 2008; De Castro et al., 2014).

Once again, agriculture is top on the international development agenda, and food security is still a major challenge. In the quest to achieve food security, perhaps a greater challenge is how to ensure that this goal is achieved using sustainable agricultural practices in smallholder farming systems with grater vulnerability, and in particular those in sub-Saharan Africa (SSA) (FAO et al., 2020; United Nations, 2019a; Fraval et al., Mwambo, 2016; FAO, 2015; Pretty, 2007; Sasson, 2012). Following resolution 72/239 by the General Assembly of the United Nations, which declared 2019-2028 as the United Nations decade of family farming (United Nations, 2017a), a better understanding of smallholder farming systems could guide policy makers' efforts towards achieving a number of Sustainable Development Goals (SDGs) (Lowder et al., 2019; United Nations, 2019b). For example, efforts to solve the global hunger challenge are of great concern as enshrined by the United Nations SDG 2: "to end hunger, achieve food security and improve nutrition and promote sustainable agriculture" (United Nations, 2017b). It adds to the challenge that future agricultural systems are expected to use fewer resources to produce more food, while causing minimal environmental impacts (FAO, 2017a; Godfray and Garnett, 2014). Hence, both SDG 12: "to ensure sustainable consumption and production patterns", and SDG 13: "to take urgent action to combat climate change and its impacts", are equally relevant to this study.

Agriculture in SSA is dominated by smallholder farming systems (Moyo, 2016; Sheahan and Barrett, 2017; Herrero et al., 2017; Shimeles et al., 2018; Gassner et al., 2019). These systems rely mostly on traditional inputs such as land, labor and farm animals (Frisvold and Ingram, 1995). Agricultural production is labor intensive (Dahlin and Rusinamhodzi, 2019), and a significant proportion of the labor force are women (FAO, 2011a; Palacios-Lopez et al., 2017; Rufai et al., 2018). Draft animals are deployed for traction (Starkey and Faye, 1990; Blench, 1997; Hesse, 1997; Fall et al., 1997; Bobobee, 1999). The use of modern external inputs such as mechanization, improved seeds, inorganic fertilizer and irrigation are limited at the continent level, but vary at country level (Sheahan and Barrett, 2017; FAO and AUC, 2018; FAO, 2008; Pingali et al., 1988).

The future food security situation in SSA could be at risk (FAO and ECA, 2018; Rosegrant et al., 2002). Crop and labor productivity show stagnating marginal growth relative to similar systems in other developing regions (Collier and Dercon, 2014). As such, intensification is often proposed as a means to improve on the productivity of small-scale agricultural systems (Tilman, 1999; 2011; Pretty and Bharucha, 2014; FAO, 2017b; Hunter et al., 2017). However, intensification demands for more input resources, and this could adversely impact on the natural resource-base as well as cause other negative externalities (Ibarrola-Rivas, 2015). Alternatively, to meet the demand for food simply by expanding cropland (extensification) poses other threats. Although Africa accounts for only 3-4% of the global carbon emissions (Ritchie and Roser, 2017), but the conversion of natural ecosystems into agroecosystems is happening at a fast pace in Africa, and this is a cause for concern. Studies show that the overall cropland, and in particular the area cultivated with maize (*Zea mays* L.) in Africa is expanding (Andela and van der Werf, 2014; Santpoort, 2020). Given the growing demand for maize-based products (Ekpa et al., 2018; Tesfaye et al., 2015; Nuss and Tanumihardjo, 2010; Pingali, 2001), continuous expansion of cropland could lead to increase in greenhouse gas (GHG) emissions from maize agroecosystems, and ultimately drive climate change and aggravate global warming (Palmer et al., 2019; van Loon et al., 2019; Tongwane and Moeletsi, 2018; Fearnside, 2000; Kim et al., 2016; Canadell et al., 2009; Duxbury, 1994). This could adversely impact on maize productivity, and aggravate the risks of food insecurity in the future (Jones and Thornton, 2003; Lobell et al., 20111; Cairns et al., 2013; Msowoya et al., 2016). This dilemma is further compounded by limited data available as well as insufficient empirical evidence and uncertainties concerning the magnitude of emissions which could be caused by various land use changes (Kim et al., 2016). More so, policies to boost maize production in SSA overlook smallholders (Santpoort, 2020). Under such circumstances, it is difficult to develop sectoral policies that aim at sustainable production of maize which could contribute towards food security.

In the BiomassWeb Project (http://biomassweb.org/), concepts to increase the availability of and access to food in SSA through more and higher-value biomass for food and non-food purposes in the next decades are being developed. Mindful of potential environmental impacts which could follow such intervention, this study assesses the resource use efficiency (RUE), sustainability and carbon footprint of various maize-based land use practices before they could be implement on a large scale. The RUE is the output per unit of input resource. The RUE relates rates of productivity to the amount of resources demanded by a production system (Hodapp et al., 2019), and therefore the sustainability of a system, i.e. how efficient is a given system able to convert inputs into outputs (Van Passel, 2007). The energy use efficiency is as an integral of the RUE (Alluvione et al., 2011), and in particular input resources that are used up during production will energize processes to eventually yield biomass output (Odum, 1957; 1984; De Wit, 1979; 1992). As such, different agricultural practices could use resources differently while causing varying environmental impacts, i.e. varying sustainability (Reinhard, 1999). On that note, the RUE is a connotation of the technical efficiency (TE), which is the ability of a decision making unit (DMU) to produce maximum output given a set of inputs and technology (Thiam et al., 2001; Battese, 1992).

From the environmental sustainability standpoint, the carbon footprint of an agricultural system should be quantified (Hillier et al., 2009; Dubey and Lal, 2009; Smith et al., 2013, Niggli et al., 2009; FAO, 2017c; Duxbury, 1994). The carbon footprint is defined as "a measure of the total amount of GHG emissions of a defined population, system or activity, considering all relevant sources, sinks and storage within a given spatial and temporal boundary of a population, system or activity of interest, and calculated in carbon dioxide equivalent (CO_2 e) using the relevant 100-year global warming potential" (Wright et al., 2011). As such, agricultural practices which could lead to efficient use of resources and minimal amount of GHG emissions are indispensable for future agriculture, because global agriculture is already causing significant environmental impacts (Ritchie and Roser, 2020; Poore and Nemecek, 2018; Tilman, 1999; Woods et al., 2010; Smith et al., 2013; Hillier et al., 2009). For example, about 70% of fresh water use and 37% of the global land surface area are devoted to agriculture (Searchinger et al., 2013), while 12% out of the 37% is cropland, respectively (Wood et al., 2000). The agri-food sector currently consumes 30% of the global energy use which is about 95 EJ per year (FAO, 2011b), while causing about 13.7 Gton of the GHG emissions (Poore and Nemecek, 2018). Global food production was the second main source of GHG emissions, accounting for 26% of GHG emissions in 2018. Besides, non-food agriculture and other deforestation factors are responsible for an additional 2.8 Gton, which is equivalent to 5% of GHG emissions (Poore and Nemecek, 2018). As such, achieving SDG 2 under these constraints, it might be reasonable for policy making to be based on reliable methods which could be used to better assess agricultural land use systems as a whole.

Challengingly, existing methods are limited in assessing the RUE including sustainability of agricultural production systems (Jones, 1989; FAO, 1995; Schindler et al., 2015). This situation is an obstacle to decision making that aims at sustainable agriculture (Siebrecht, 2020). There are various methods for quantifying environmental impacts. However, none is flexible enough to account for multiple inputs of diverse types from various sources, while doing a peer comparison of multiple production systems, and lead to comprehensive information which is based on a common metric. The relevant question to this study was: what information could be obtained using the newly developed Emergy-Data Envelopment Analysis approach to assess the environmental impacts of small-scale maize-based systems in SSA?.

The objective of this paper was to showcase the recently developed Emergy-Data Envelopment Analysis (EM-DEA) approach (Mwambo and Fürst, 2019), to assess the RUE and sustainability of small-scale maize production practices in Ghana, SSA. The primary data were collected using semi-structured questionnaire, and this was upscaled using data from published secondary sources. The Agricultural Production Systems sIMulator (APSIM) (Keating et al., 2003), was used to model five land use and resource management scenarios to represent practices in small-scale maize production systems. The RUE values which were derived using the EM-DEA approach were validated by comparing our results to an empirical assessment of the technical efficiency (TE) of small-scale maize producers in the northern Sudan and Guinea savanna in Ghana (Wongnaa, 2016). Furthermore, three empirical studies were sourced from online and this study was also included in order to constitute a sample of four studies. The Z-score of the measured efficiency values of the sample studies was calculated. The Z-score was considered as the proxy for the uncertainty of our results. The 95% confidence interval of the sample was calculated, and it was considered as the proxy for the reliability of our results. The carbon footprint of the practices was assessed by adaptively applying the Ex-Ante Carbon balance Tool (EX-ACT), which was developed by the Food and Agriculture Organization (Bernoux et al., 2010; Bockel et al., 2013; Grewer et al., 2013). The carbon footprint was quantified using the following metrics: (i) the carbon balance per unit of farmland, and (ii) the carbon balance associated with per tonne of grain produced. Our results on carbon footprint were validated by comparing the trend of index of sustainability based on our results and the typical trend which is observed for farms with an increasing intensity of input fertilizer (Lal, 2004).

This paper is divided into 5 sections and is structured as follows. In section 1, the introduction is presented. In section 2, the study area, materials and methods are described in detail. In section 3, the results are presented. In section 4, the results are discussed and compared with other empirical studies. The trade-off analysis among the various land use and resource management options is elaborated, and the empirical evidence drawn. Finally in section 5, the main findings are summarized in the conclusions, and an application of the EM-DEA approach in future works is proposed in the outlook.

2. Materials and Methods

2.1. Study area

The study area is Bolgatanga and Bongo Districts located in the Upper East Region, Ghana, SSA[1] (Figure 1). The area is about 1217 km^2, situated within latitudes 10° and 11° N, and longitudes 0° and 1° W. The natural vegetation is a mosaic of Sudan and Guinea savanna woodland, characterized by scanty stunted trees which form an open canopy over grasses as the understorey (Bagamsah, 2005). The area is drained by the Volta River, and the climate is sub-arid. The rainfall ranges between 800 and 1100 mm (Callo-Concha et al., 2013; GSS, 2014), while the annual mean rainfall is about 1044 mm (Badmos et al., 2015). The annual mean temperature is 29°C (Badmos et al., 2015), maximum is 34°C, and minimum is 15°C (Faulkner et al., 2008). The annual rainy season lasts between April/May and September/October, and the distribution is unimodal. The length of the growing period is between 90 and 165 days (Mdemu, 2008). Small-scale agriculture is the major economic activity in this area. The fertility of the soil is low, except alluvial plains (Mdemu, 2008). The area is impacted by climatic and environmental stress factors (Amikuzino and Donkoh, 2012; Issahaku et al., 2016). This situation is exacerbated by pressure from agro-pastoral activities which are carried out by a growing population (Akolgo, 2011). The complex combination of these natural and man-made constraints contribute in land degradation (Callo-Concha et al., 2013), and this

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[1] The Sub-Saharan African region is defined by the United Nations Statistical Division and is used to indicate all of Africa, except Northern Africa, with Sudan included in Sub-Saharan Africa. Regional aggregations are available at *http://unstats.un.org/unsd/methods/m49/m49regin.htm.*

situation aggravates the cycle of poverty (GSS, 2015; Cooke et al., 2015) as well as the risks of food insecurity (Abane, 2015; Alhassan, 2015). Considering that smallholder farmers in semi-arid Africa are in an increasingly vulnerable situation due to the direct and indirect effects of climate change, demographic pressure and resource degradation (Tittonell et al., 2012), as well as a likely increase in the demand for cereals in the Sudano-Sahelian zone in the coming decades (Ringler et al., 2010), this area represents a typical situation in the Sudan savanna zone.

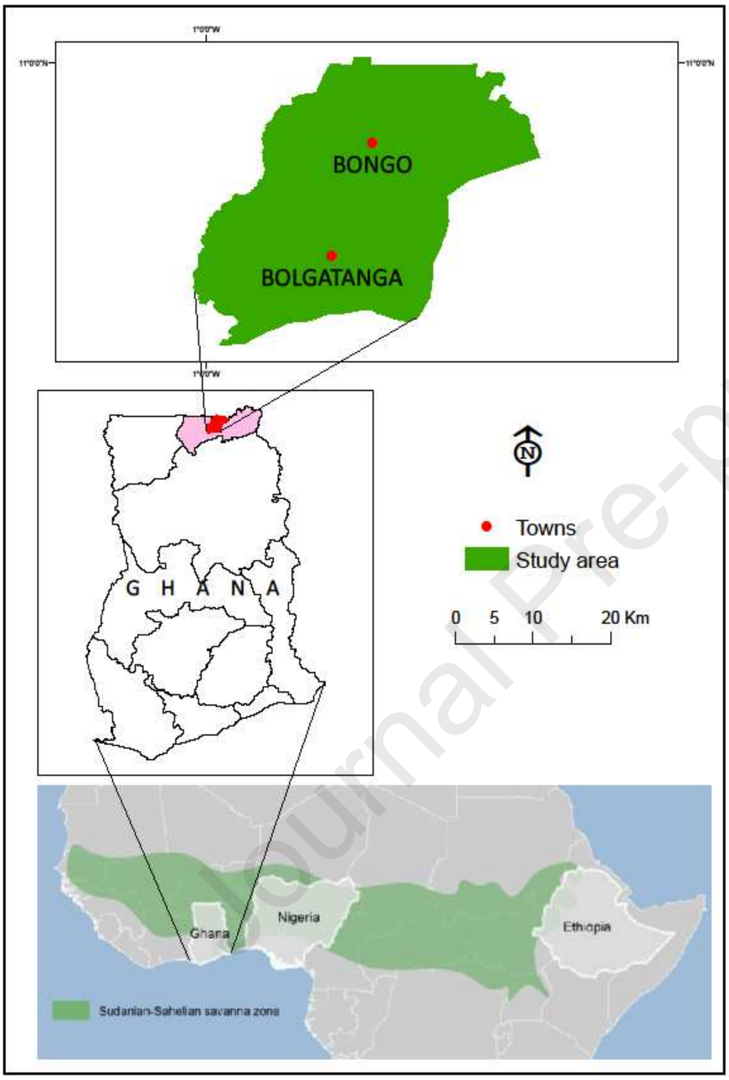

Figure 1. Study area

2.2. *Data Sources and Data Processing*

The data for this study were derived from primary and secondary sources. The primary data focused on farmers' practices including agricultural land use and resource management in small-scale maize systems. Using the snowball sampling method, in total n=56 personal interviews of small-scale maize farmers were conducted in Bolgatanga and Bongo Districts in 2015. The data were collected using semi-structured questionnaire. Local varieties were the most cultivated. The farm labor (L) inputs were as follows: land preparation, sowing, fertilizer/ manure application, weeding, harvesting, and threshing. The following services (S) were considered: cost of purchased inputs (seeds, NPK/urea fertilizer, solar powered pump for irrigation, draft animal, animal feed, stable, phytosanitary care, and a shadow price for farm labor). The data were processed using standard statistical tools in Microsoft Excel 2007. The data are presented in

Table 1.

Table 1. Primary data

Variable	**Minimum**	**Maximum**	**Mean**
Farmer's experience (years of practicing farming)	1	45	13.4
Farm size (ha)	0.04	2.07	1.5
NPK (15 15 15) fertilizer application (kg/ha)	0	27	12
Seeds (kg/ha)	14	22	16
Human labor (man days/ha)*			
Land preparation (plowing with draft animal)	3.5	7	6
Sowing	8.5	10.5	9.5
Application of fertilizer	6	8.5	7
Application of manure	0	11	9
Manual weeding (2 cycles per crop season)	32	48	46
Harvesting	10	13	11.5
Threshing	14	19.5	17
Draft animal labor (plowing) (animal days/ha)**	5.5	9	7.5
Grain Yield (ton/ha)	0.23	2.71	1.06

Source: Field survey in Bolgatanga & Bongo Districts, 2015. *1 man day = 6 hours, **1 animal day = 4hours.

The majority of the interviewees could not present farm records during the interview survey, and hence the primary data were based on estimates. The representativeness of the primary data was checked using statistical comparison between the mean yield (

Table 1) and the mean yield based on production data for Bolgatanga and Bongo Districts during the period 2003-2011 (Ghanaian Ministry of Food and Agriculture, MoFA) (Appendix E). The statistical difference between both means was small. The primary data (

Table 1) was enhanced further by substituting the mean yield which was based on estimates (

Table 1) with the mean yield which was based on recorded production data (Table 17).

The Agricultural Production Systems sIMulator (APSIM) (Keating et al., 2003) was used to simulate the maize yield response to 0, 20, 50, and 100 kg/ha/yr urea input, while considering the following cropping systems: irrigated maize monoculture, rainfed maize-other cereal, and maize-legume intercropping. The maize residue (stover and cob) was calculated as stated in *Eq*. (1), which is based on experimentation (Lang, 2002). The conversion of the residue from customary units (ton/acre) to metric units (ton/ha) was done using *Eq*. (2). The primary data (

Table 1) were supplemented with the simulated data, and complemented with biophysical data from reliable and published secondary sources (

Table 2). These consolidated datasets were used to model five land use and resource management scenarios to represent practices in smallholder maize systems in Ghana, SSA. The scenarios were synthesized by combining land use and resource management options (Table 3). The scenarios were the decision making units (DMUs). The data on GHG emissions and carbon stocks in maize systems were derived from reliable and published secondary sources (Table 4).

$$Estimated\ residue, i.e. stover\ (ton/acre) = Grain\ yield\ (bushel/acre) *\ 56/2000, \quad (1)$$

Note: $Eq.$ (2) was derived from $Eq.$ (1) by conversion of customary units to metric units

$$Estimated\ residue\ (ton/ha)\ = [(Grain\ yiled * 14.86 * \frac{56}{2000} * 2.25], \qquad (2)$$

Table 2. Biophysical data

Data	**Value**	**Reference**
Grain yield	1.2 ton/ha	[Table 17] *
Rainfall in study area during 2003–2011	0.911 m/yr	(MoFA, 2012)
Manure input	29.25 kg/ha	(Dadson et al., 2016)
Moisture content in manure	0.70	(Sonko et al., 2016)
Solar insolation	1.20E+21 J/m^2/yr	(CEP, 2012)
Albedo	0.15	(Arku, 2011)
Subsurface heat	42 mW/m^2	(Beck and Mustonen, 1972)
Wind speed	2.6 m/s	(World Weather Online)
Fraction of evapotranspiration water	0.73	(Nurudeen, 2011)
Soil erosion	0.1291 ton/ha/yr	(Badmos et al., 2015)
Soil organic matter (OM) content	0.0129%	(Amegashie, 2009)
Moisture content in OM	0.012%	(Dawidson and Nilsson, 2000)
Cost of NPK (15 15 15) fertilizer urea N fertilizer	2.30 Gh¢/kg 2.10 Gh¢/kg	(MoFA, 2016)
Cost of maize seeds	1.00 Gh¢/kg	(Ghana Business News 2013)
Cost of solar pump (1.5hp) for irrigation	800 Gh¢/yr	(Dey and Avumegah, 2016)
Capital cost of 1 draft animal Maintenance cost of 1 draft animal	728 Gh¢ 730 Gh¢/yr	(Houssou et al., 2013)

* Source: Statistics, Research and Information Directorate (SRID), Ministry of Food and Agriculture (MoFA), Ghana.

Table 3. Land use and resource management practices

Scenario	**Description**	**External inputs**	**Biomass output**
Extensive0	Zero external input to maize system. Maize and other non-leguminous crops could be grown in an intercropping system.	Water as rain, 0 kg/ha/yr urea fertilizer, ± 29.25 kg manure.	1.17 t/ha (grain, wet matter)^{o} 0.93 t/ha (grain, dry matter) 0.93 t/ha (residue, wet matter) 0.88 t/ha (residue, dry matter)

Extensive12	Low external input to maize systems. Maize and other non-leguminous crops could be grown in an intercropping system.	Water as rain, 12 kg/ha/yr NPK (15 15 15), ± 29.25 kg manure.	1.2 t/ha (grain, wet matter)§ 0.96 t/ha (grain, dry matter) 0.96 t/ha (residue, wet matter) 0.90 t/ha (residue, dry matter)
Intercrop20	Maize-legume (cowpea -*Vagna unguiculata,* ground nuts -*Arachis hypogaea* or soybean – *Glycine max*) intercropping system. Modest external input to maize system.	Water as rain, 20 kg/ha/yr urea fertilizer, ± 29.25 kg manure.	1.88 t/ha (grain, wet matter)º 1.5 t/ha (grain, dry matter) 1.41 t/ha (residue, wet matter) 1.17 t/ha (residue, dry matter)
Intensive50	Moderate external input to maize system. Maize is grown in a monoculture system.	Water as rain including supplemental irrigation from a surface source (0.18m/ha/yr), 50 kg/ha/yr urea fertilizer.	2.75 t/ha (grain, wet matter)º 2.20 t/ha (grain, dry matter) 2.20 t/ha (residue, wet matter) 2.06 t/ha (residue, dry matter)
Intensive100	High external input to maize systems. Maize is grown in a monoculture system.	Water as rain including supplemental irrigation from a surface source (0.18m/ha/yr), 100 kg/ha/yr urea fertilizer.	2.81 t/ha (grain, wet matter)º 2.25 t/ha (grain, dry matter) 2.25 t/ha (residue, wet matter) 2.11 t/ha (residue, dry matter)

Source: § = interview survey and MoFA. º = simulated using Agricultural Productivity SIMulator (APSIM)

Table 4. Data for carbon emissions and stocks

Type	Description	Conversion factors /units	Reference
Emission	Emission factor for industrial production of NPK (15 15 15), and when applied as nutrient	1.61 (production), 10.71 (application) kg CO_2 e/kg	[a]
Emission	Emission factor for industrial production of Urea mineral, and when applied as nutrient	5.15 (production), 11.19 (application) kg CO_2 e/kg	[a]
Emission	Shipment of NPK (15 15 15) Assumption: NPK (15 15 15) was imported (from Agadir, Morocco to Takoradi, Ghana)[b]	2389 nautical mile (nm) [c] ≈ 4424.43 km 8 g CO2 e/ton-km	[b], [c] (ECTA and Cefic, 2011)
Emission	Shipment of urea mineral Assumption: urea mineral was imported (from Ambarli, Turkey to Takoradi, Ghana) [b]	4569 nautical miles (nm) [c] ≈ 8461.79 km 8 g CO2 e/ton-km	[b], [c] (ECTA and Cefic, 2011)
Emission	Transportation of NPK/urea by road from Takoradi to study area	832.9 km 62 g CO_2	[d] (ECTA and Cefic, 2011)
Emission	Emission from compost manure (production & application)	368.4 ± 18.5 kg CO_2/Mg manure	(Hao et al., 2004)
Emission	Soil Organic Carbon (SOC) loss during plowing	4 ± 1.9 kg C e/ha	(Lal, 2004)

Emission	Emission caused by human labor	12.1 - 14.4 MJ/day 0.36 kg CO_2/MJ	(Bleiberg et al., 1980; Brun et al., 1981; Houshyar et al., 2015)
Stock	Carbon content in the above ground biomass	43.6% of above ground biomass (dry matter)	(Latshaw and Miller, 1924)

[a] https://www.fertilizerseurope.com/fileadmin/user_upload/publications/agriculture_publications/carbon_footprint_web_V4.pdf

[b] https://www.infoafrica.it/wp-content/uploads/2018/02/Ghana-Fertilizer-Statistics-Overview-2016.pdf,

[c] https://sea-distances.org/,

[d] https://www.google.com/maps/dir/Sekondi-Takoradi,+Ghana/Bolgatanga,

2.3. Assessment methods

The assessment methodology is composed of the application of the Emergy-Data Envelopment Analysis (EM-DEA) and Ex-Ante Carbon balance Tool (EX-ACT) approaches. The methodological framework is shown in Figure 2. First, the EM-DEA approach was applied to assess the resource use efficiency (RUE) and sustainability of the various maize systems (Table 3). The EM-DEA approach is a coupling of Emergy Accounting (EMA) and Data Envelopment Analysis (DEA) as well as the integration of the concept of eco-efficiency. Second, the carbon footprint was assessed using an approach, which we adapted from the EX-ACT. The detailed methodology is as follows.

2.3.1. Explanation of the Emergy Accounting (EMA)

The concept of energy memory (Emergy) is useful for environmental accounting, i.e. to evaluate resources on the basis of the environmental work required to generate and make resources available (Bonilla et al., 2016). Emergy is "the energy of one type previously used up directly and indirectly to make a product or deliver a service" (Odum, 1996), and it is measured in solar emjoule (*sej*). The concept of emergy provides flexibility when accounting the available energy (exergy) of diverse resource types on the basis of their embodied energy (Scienceman, 1987; Brown and Herendeen, 1996). This method is based on thermodynamics and systems theory, and hence enables accounting of all natural and socio-economic inputs on a common metric (Bonilla et al., 2016). Emergy Accounting (EMA) provides a means to account for resources such as nature, materials, energy, resource generation time, labor, economic and societal infrastructures including other resources whose market value are ambiguous to monetized (Odum, 1984; 1996; Odum and Odum, 1983; Brown and Ulgiati, 2004). The emergy of a given resource is calculated as the product of the exergy and Unit Emergy Value (UEV) as stated in *Eq*. (3). In this paper, EMA was applied to account for the basic input resources that were used in the production of maize (Table 12), and EMA was implemented using the EM-DEA approach (Mwambo and Fürst, 2019). The emergy baseline was 12.0E+24 *sej*/yr (Brown and Ulgiati, 2016a).

$$Emergy_{resource} = exergy_{resource} * \tau_{resource}, \tag{3}$$

where,

$Emergy_{resource} = emergy\ of\ a\ given\ resource\ (measured\ in\ sej)$

$exergy_{resource} = the\ available\ energy\ of\ a\ resource\ (measured\ in\ J)$

$\tau_{resource} = transformity\ (measured\ in\ sej/J)\ or\ UEV\ of\ a\ resource\ (measured\ in\ sej/unit)$

2.3.2. Explanation of the Data Envelopment Analysis (DEA)

Data Envelopment Analysis (DEA) is a nonparametric linear programming based technique for estimating the relative efficiency of similar entities (also referred to as decision making units

-DMUs) (Toloo and Nalchigar, 2009; Wen, 2015). The modeled scenarios (Table 3) were herein the DMUs. DEA was applied principally to estimate the productive efficiency of the various DMUs. Maize production is a multiple-inputs and multiple-outputs agroecological system. Efficiency is the ratio of output to the observed input. As such, the productive efficiency (E_P) was calculated as the ratio of the weighted sum of outputs to the weighted sum of inputs. The linear programming function in DEA reduces the ratio of weight sum of outputs to inputs into a single virtual output as the numerator and a single virtual input as denominator as stated in *Eq*. (4). The ratio of the single virtual output to the single virtual input for each DMU relative to that of the most performing DMU leads to the relative technical efficiency (rTE) scores (Hartwich and Kyi, 1999), and this was considered as the proxy for expressing the relative sustainability of the various DMUs. In this paper, DEA was implemented using the EM-DEA approach (Mwambo and Fürst, 2019).

$$E_p = \frac{u_1 y_1 + u_2\, y_2 + u_3 y_3 + u_4 y_4 + u_m y_m}{v_1 x_1 + v_2 x_2 + v_3 x_3 + v_4 x_4 + v_n x_n} = \frac{\sum_{o=1}^{m} u_{o1} y_{o1}}{\sum_{i=1}^{n} v_{i1} x_{i1}}, \tag{4}$$

where,

E_P = *productive efficiency of a DMU*

$\mu_0 = weight\ allocated\ to\ output\ o$

$v_i = weight\ allocated\ to\ input\ i$

$y_o = amount\ of\ output\ o\ from\ a\ DMU$

$x_i = amount\ of\ input\ i\ allocated\ to\ a\ DMU$

2.3.3. Application of the Emergy-Data Envelopment Analysis (EM-DEA) approach

The EM-DEA approach is an assessment framework that aggregates EMA and DEA (Mwambo and Fürst, 2014), and the concept of eco-efficiency is integrated to assess the RUE and sustainability of agricultural production systems as a whole (Mwambo and Fürst, 2019). This approach was applied as follows.

The five scenarios representing the DMUs in small-scale maize production practices in SSA (Table 3), were visually sketched using emergy systems diagrams (Figure 8, Figure 9 and Figure 10), because visualization facilitates the process of accounting resource use. Standard statistical tools in Microsoft Excel 2007 were used to manage the data as follows. The annual input resources as well as outputs (grain yield and residue) were itemized and quantified in standard units of measurement (SI units). The exergy of each input resource as well as output was calculated using an appropriate formula. The emergies of the resources were calculated using *Eq*. (3). The detailed calculation of emergies is presented in Appendix B, and the basic sources are summarized in Table 12, respectively. To avoid double counting, the refined approach for emergy calculation was applied (Brown and Ulgiati, 2016b), and the calculated emergies were summed up in categories defined as follows: renewable sources denoted by R, non-renewable sources denoted by N, imported sources denoted by F, yield denoted by Y, labor and services denoted by L&S, respectively (Table 13). This led to retainment of emergy values of selected inputs and outputs (Table 11) from the basic sources (Table 12). Subsequently, the retained emergy values were used to evaluate the RUE and sustainability as follows.

2.3.3.1 Mathematical evaluation of the relative Sustainability

The DMUs (names), emergy values of the retained output, i.e. grain yield (dry matter) and emergy values of the retained input resources were concatenated using Microsoft Excel, and the file saved in comma delimited (*.csv*). This was imported into an Open Source Data Envelopment Analysis (OSDEA)[2] model. The Charnes Cooper Rhodes input (CCR_I) oriented model of DEA (Charnes et al., 1978) was applied for calculating the relative Technical Efficiency (rTE) scores. The optimization function in DEA assumes the multiple ordinary least square regression as stated in *Eq*. (5) (Kuosmanen and Johnson, 2010), and applies Pareto efficiency to select the weights for the imported data. DEA model uses the imported data and applies *Eq*. (4) to calculate the rTE scores (Table 15).

$$\gamma_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7 + \mu_i\,, \tag{5}$$

where,

$\gamma_i = yield\ or\ output\ produced\ by\ the\ i^{th} practice$
$\beta_0 = coefficient\ of\ the\ intercept$
$\beta_1, \ldots \beta_7 = slopes\ or\ coefficients\ of\ selected\ input\ resources, i.e.\ x_1, \ldots x_7$
$x_1 = evapotranspired\ water$
$x_2 = topsoil\ loss$
$x_3 = NPK\ or\ urea\ application\ intensity$
$x_4 = draft\ animal\ labor\ (plowing)$
$x_5 = maize\ seeds$
$x_6 = human\ labor$
$x_7 = services$
$\mu_i = slacks\ (residuals) of\ the\ i^{th} practice$
$Note: x_1, \ldots x_7\ were\ the\ selected\ input\ resources, (see\ also, Table\ 11)$

The performance of a production system is described using the Technical Efficiency (TE) (Farrell, 1957). The TE is the degree to which the actual output of a production unit approaches its maximum (Fare and Lovell, 1978). By analogy, the rTE is a scalar indicator to express the performance of peer DMUs on a relative basis. Hence, the rTE score that is estimated using the DEA was the proxy for expressing the relative RUE and sustainability of the peer DMUs (De Koeijer et al., 2002).

2.3.3.2 Mathematical evaluation of the Resource Use Efficiency (RUE)

The absolute RUE was evaluated by applying the concept of eco-efficiency (Kortelainen and Kuosmanen, 2004; Pang et al., 2016). The Unit Emergy Value (UEV) of the output was equated to the eco-efficiency as stated in *Eq*. (6). The eco-efficiency was further sub-divided as follows: (i) UEV in terms of Resource use (UEV_R), and (ii) UEV in terms of Exergy use (UEV_E). The UEV_R and UEV_E were further evaluated based on the input materials from nature ($UEV_{R(without\ L\&S)}$ and $UEV_{E(without\ L\&S)}$), as well as based on the input materials from nature including labor and services from the human economy ($UEV_{R(with\ L\&S)}$ and $UEV_{E(with\ L\&S)}$), respectively. This distinction is important to better appreciate the impacts of a production systems on: (i) natural resources, and (ii) whole economy. The evaluation schemes are stated in *Eqs*. (7) - (10), respectively.

$$Eco - efficieincy = \frac{Environmental\ impact}{Economic\ value} = \frac{Total\ emergy\ U}{yielded\ product} = UEV_{(product)}\,, \tag{6}$$

$$UEV_{R(without\ L\&S)} = \frac{U_{(without\ L\&S)}}{yielded\ product} = \frac{R + N + F}{grain\ yield_{\ dry\ mass\ (g)}}\,, \tag{7}$$

$$UEV_{R(with\ L\&S)} = \frac{U_{(with\ L\&S)}}{yielded\ product} = \frac{R + N + F + L + S}{grain\ yield_{\ dry\ mass\ (g)}}\,, \tag{8}$$

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[2] http://opensourcedea.org/ (accessed in 2017)

$$UEV_{E(without\ L\&S)} = \frac{U_{(without\ L\&S)}}{exergy\ of\ yielded\ product_{(J)}} = \frac{R+N+F}{grain\ yield_{\ dry\ mass\ (g)} * LHV}\,, \tag{9}$$

$$UEV_{E(with\ L\&S)} = \frac{U_{(with\ L\&S)}}{exergy\ of\ yielded\ product_{(J)}} = \frac{R+N+F+L+S}{grain\ yield_{\ dry\ mass\ (g)} * LHV}\,, \tag{10}$$

where,

F = *Imported resources*
N = *Non-renewable resources*
R = *Renewable resources*
U = *Total emergy of a system*
L&S = *Labor and Services*
g = *mass of dried grain yield measured in grams*
J = *available energy content of dried grain yield measured in Joule*
LHV = *lower heating value of dried grain yield*

Note: *Details on F, N, R, U, L, S, g, J, & LHV are stated in Table 12.*

2.3.3.3 Mathematical evaluation of absolute Sustainability

The absolute sustainability was evaluated by applying the following emergy-based indicators: Total emergy (U), Percentage Renewability (%REN), Emergy Yield Ratio (EYR), Environmental Loading Ratio (ELR), and Emergy Sustainability Index (ESI) (Brown and Ulgiati, 2004; Ulgiati et al., 2011; Dong et al., 2014; Viglia et al., 2017). The indicators were evaluated based on the input materials from nature as stated in *Eqs*. (11) - (15), as well as based on raw material from nature including labor and services from the human economy as stated in *Eqs*. (16) - (20), respectively.

$$Total\ emergy\ (U) = R + N + F\,, \tag{11}$$

$$EYR = \frac{(R+N+F)}{F}\,, \tag{12}$$

$$ELR = \frac{(N+F)}{R}\,, \tag{13}$$

$$ESI = \frac{EYR}{ELR}\,, \tag{14}$$

$$\%REN = \frac{1}{(1+ELR)}\,, \tag{15}$$

$$Total\ emergy\ (U) = R + N + F + L + S\,, \tag{16}$$

$$EYR = \frac{(R+N+F+L+S)}{(F+L+S)}\,, \tag{17}$$

$$ELR = \frac{(N+F+L+S)}{R}\,, \tag{18}$$

$$ESI = \frac{EYR}{ELR}\,, \tag{19}$$

$$\%REN = \frac{1}{(1 + ELR)}, \qquad (20)$$

where,

F = *Imported resources*
N = *Non-renewable resources*
R = *Renewable resources*
U = *Total emergy of a system*
$L\&S$ = *Labor and Services*

Note: *Details of F, N, R, U, L, S, g, J, & LHV are stated in Table 12.*

2.3.4. Application of the EX-ACT to evaluate the Carbon Footprint

The Ex-Ante Carbon balance Tool (EX-ACT) is a land-based accounting method which was developed by the Food and Agriculture Organization, to appraise ex-ante carbon-balance of agricultural and forestry projects. The carbon-balance is the net balance from all GHGs expressed in CO_2 e that were emitted or sequestered due to a project implementation as compared to a business-as-usual scenario (Bernoux et al., 2010; Bockel et al., 2013; Grewer et al., 2013).

On that note, the EX-ACT was adaptively applied to assess the carbon footprint of the various scenarios representing the DMUs in small-scale maize systems in Ghana, SSA as follows. The emergy systems diagrams (Figure 8, Figure 9 and Figure 10) were used to define the system boundaries. By considering intensification as a strategy for improving productivity in small-scale maize systems, it was assumed that *Intensive100* was the reference scenario against which the following farm scenarios: *Extensive0*, *Extensive12, Intercrop20*, and *Intensive50* were compared (see also the trade-off analysis, Table 8). The carbon emissions and stocks were quantified in ton CO_2 e/ha/yr. The following sources of GHG emissions were quantified: industrial production of NPK and urea fertilizer as well as the transportation, on-farm application of NPK and urea fertilizer or organic manure, loss of soil carbon during plowing, and emissions by human during farm labor. The GHG emissions were calculated using *Eq*. (21). Maize crop was the carbon sink, and the carbon stock was calculated using *Eq*. (22). The annual carbon balance was the difference between the sum of GHG emissions and sum of carbon stocks, and this was calculated using *Eq*. (23). This net emissions value per unit of farmland was considered as the carbon balance, i.e. net carbon emissions per hectare (ton CO_2 e/ha/yr). This being the metric which was used to quantify the net GHG emissions in crop production while focusing on environmental health. Using *Eq*. (24), the carbon balance associated with per tonne of grain produced, i.e. carbon balance per tonne grain (ton CO_2 e/ton grain) was quantified. This being the metric which was used to emphasize both emissions during the production of a crop as well as the products (grain yield) associated with per unit of emission.

$$GHG\ emissions = activity\ data * GHG\ emission\ factor\ , \qquad (21)$$

$$carbon\ stock = above\ ground\ biomass * carbon\ stock\ exchange\ factor\ , \qquad (22)$$

$$carbon\ balance = \left(\sum GHG\ emissions\right) - \left(\sum carbon\ stocks\right), \qquad (23)$$

$$carbon\ balance\ per\ unit\ product = \frac{(\sum GHG\ emissions) - (\sum carbon\ stock)}{grain\ yield\ in\ ton_{(dry\ mass)}}\ , \qquad (24)$$

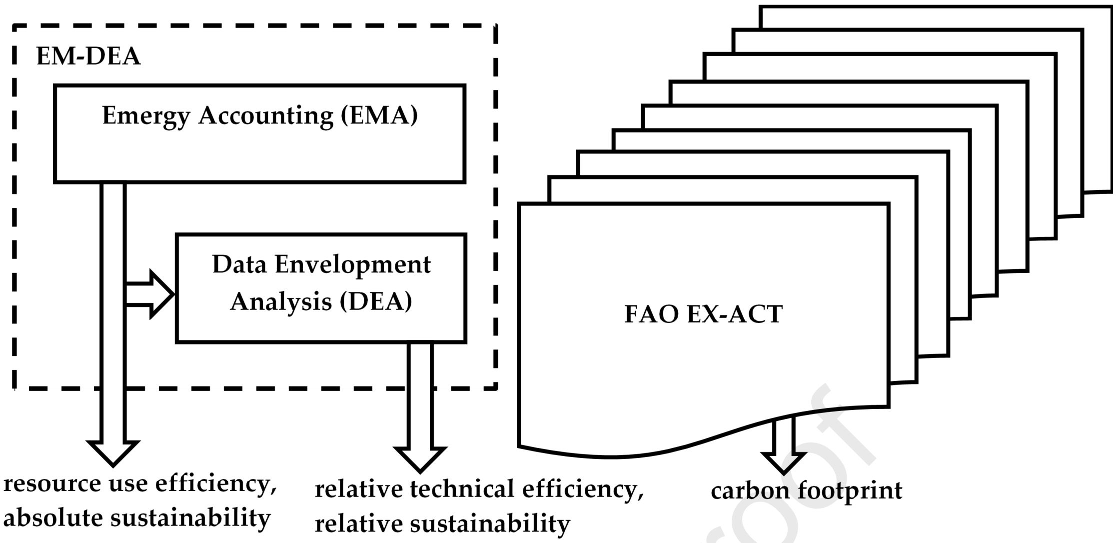


Figure 2. Methodological framework

2.4 Validation methods

First, the results which were obtained using the EM-DEA approach were validated as follows. *Extensive12* was considered as the "business-as-usual" scenario (*Extensive12*), because it was based on production data from primary source (interviews during the field survey). The relative Technical Efficiency (rTE) score of *Extensive12* was compared to the Technical Efficiency (TE) of small-scale maize farmers in the northern Sudanian and Guinea savanna, Ghana (Wongnaa, 2016). The TE was obtained using the stochastic frontier production function (SFPF) (Aigner et al., 1977; Meeusen and van den Broeck, 1977). The SFPF is a standard method for analyzing economic and technical efficiency. The evaluation of TE using SFPF is on the basis of the ratio of the maximum amount of output which is obtainable from given input bundles with fixed technology, i.e. the observed output to the frontier output given the quantity of resources that are used to obtain a given output (Aigner et al., 1977).

Second, the result which were obtained using the applied EX-ACT were validated as follows. The index of sustainability (I_s) trend was compared to the characteristic trend which is observed for farm operations when the intensity of input resources vary. The I_s is the ratio of carbon output to carbon input measured in CO_2 e during a time frame (t) as stated in *Eq*. (25) (Lal, 2004).

$$Index\ of\ sustainability\ (I_s) = \left(\frac{C_o}{C_i}\right) t\ , \qquad (25)$$

where,

C_o = *carbon output, i.e. ∑carbon stocks in sinks measured in* CO_2 *e*
C_i = *carbon input, i.e. ∑GHG emissions from sources measured in* CO_2 *e*
t = *time measured in year, and usually as multiples of 25 years (in this study, t = 1, because usually emergy-based accounting is for a 1 year period)*

3. Results

Agricultural production uses input resources which include raw materials from nature as well as labor (L) and services (S) from the human economy. As such, the assessment results on RUE and sustainability are presented in two clusters as follows:

(i) assessment based on input materials from nature excluding labor and services, and
(ii) assessment based on material inputs from nature including labor and services from the human economy.

These clusters focus on quantifying the impacts of production on the natural resource-base and whole economy, respectively. The assessment results were as follows.

3.1 RUE and absolute sustainability based on the raw materials from nature

The analysis of input raw materials is shown in Figure 3. The assessment results (Table 5), showed that when resource use efficiency was evaluated based on input raw materials excluding labor and services ($\text{RUE}_{\text{(without L\&S)}}$), the total emergy (U) increased with increase in the dosage of inputs. The U is the total size of a system in terms of demand for environmental support from the biosphere, i.e. the environmental support which is provided by the biosphere to sustain production in a given system. The sequence of the scenarios in terms of the U, from low to high was as follows: *Extensive0*, *Intercrop20*, *Extensive12*, *Intensive50*, and *Intensive100*. The U required by *Extensive0* was very small, slightly greater for *Intercrop20* and *Extensive12,* about twice as much for *Intensive50*, and much greater for *Intensive100* when compared to *Extensive0*, respectively. The smaller the value of the U, the more competitive a system could be. For example, *Extensive0* demanded the least amount of inputs and hence this system was the most competitive, meanwhile *Intensive100* demanded the greatest amount of inputs, and this makes *Intensive100* the least competitive.

The various scenarios showed similar trends based on the Unit Emergy Value in terms of Resources use ($\text{UEV}_{\text{R(without L\&S)}}$) and Unit Emergy Value in terms of Exergy use ($\text{UEV}_{\text{E(without L\&S)}}$). The scenarios were ranked as follows, from low to high: *Intercrop20*, *Intensive50*, *Extensive0*, *Intensive100*, and *Extensive12*. The UEV_{R} is the ratio of the environmental impact to economic value added in terms of resource use, while the UEV_{E} is the ratio of the environmental impact to economic value added in terms of exergy use. The smaller the value of both indicators, the more efficient a given system could be. In relative terms, *Intercrop20* was the most efficient while *Extensive12* was the least efficient, respectively.

Considering the emergy-based indicators which were used to assess the absolute sustainability, the Emergy Yield Ratio (EYR) provides information on a system's reliance on local resources. A high EYR implies that a system relies more on local resources, while a low EYR implies that a system relies on resources which are imported from outside a given system. A system which relies on local resources is more adapted to the local environment, and overall it would be more resilient when compared to a system which relies on imported resources. Based on the EYR, the scenarios were ranked as follows, from high to low: *Extensive0*, *Intercrop20*, *Extensive12*, *Intensive50*, and *Intensive100*. Hence, *Extensive0* relies on local resources. The reliance of *Intercrop20* and *Extensive12* was intermediate. *Intensive50* shows moderate reliance on imported resources, while *Intensive100* shows a strong reliance on imported resources, and this makes *Intensive100* least resilient when compared to the various scenarios.

Furthermore, the trend of assessment result based on the Environmental Loading Ratio (ELR) was similar to that of the EYR. The ELR is the measurement of distance from equilibrium, i.e. excess pressure from outside the system. The sequence of the various scenarios was as follows: *Extensive0* was closest to the equilibrium, while *Intensive100* was furthest from the equilibrium. *Intercrop20*, *Extensive12* and *Intensive50* were situated between *Extensive0* and *Intensive100*, at an increasing distance from the equilibrium, respectively. The closer a system is to the equilibrium, the more stable it could be, which implies the more sustainable the system could be as compared to a system which is further away from the equilibrium. In relative terms, *Extensive0* was the most sustainable, while *Intensive100* was the least sustainable in term of ELR.

The Emergy Sustainability Index (ESI) is a connotation of environmental sustainability, i.e. higher yield per unit of environmental loading. The greater the ESI, the better is the sustainability of a given system. Based on the ESI, the various scenarios were ranked as follows, from high to low: *Extensive0*, *Intercrop20*, *Extensive12*, *Intensive50*, and *Intensive100*. As such, *Extensive0* achieved the greatest ESI and was the most environmentally stable scenario, while *Intensive100* was the least stable in relative terms, respectively. The ESI of *Intercrop20*, *Extensive12*, *Intensive50*, and *Intensive100* were very small, and the difference between the various scenarios was marginal.

The Percentage Renewability (% REN) is the fraction of renewability of the product, i.e. the fraction of the product (yielded grain delivered at the farm-gate) that originated from renewable input resources. The greater the %REN, implies that the product was produced using more renewable resources, and hence the more sustainable the given system is. The sequence of the scenarios based on the % REN, from high to low was as follows: *Extensive0*, *Intercrop20*, *Extensive12*, *Intensive50* and *Intensive100*. *Extensive0* achieved the greatest fraction of renewability of product by using more renewable input resources, while *Intensive100* achieved the least fraction of renewability of the product by using more non-renewable input resources. For instance, the 0.93 ton of grain yielded by *Extensive0* was produced using 85% of renewable input resources, while *Intensive100* used 30% of renewable input resources to yield 2.25 ton of grain, respectively. The difference in the magnitude of the %REN between *Extensive12* and *Intercrop20* was marginal.

3.2 RUE and absolute sustainability based on the iputs from the whole economy

The analysis of the input materials as well as labor and services is shown in Figure 4. The assessment results (Table 5), showed that when resource use efficiency was evaluated based on inputs from the whole economy ($\mathrm{RUE}_{(\text{with L\&S})}$), the trend was similar to the one which was observed for the assessment cluster $\mathrm{RUE}_{(\text{without L\&S})}$. However, the absolute values of the U, $\mathrm{UEV}_{\mathrm{R}}$, and $\mathrm{UEV}_{\mathrm{E}}$ increased, while the absolute values of the EYR, ESI and %REN decreased when compared to the values that were observed for the assessment cluster $\mathrm{RUE}_{(\text{without L\&S})}$, respectively. The overall performance of *Intercrop20* was better when compared to the performance that was observed for the assessment cluster $\mathrm{RUE}_{(\text{without L\&S})}$.

3.3 Relative sustainability

The relative Technical Efficiency (rTE) score (Table 15), was the proxy indicator for assessing the relative sustainability, i.e. the ability of a DMU to transform inputs into outputs relative to the peers DMUs. The assessment results (Table 5), showed that *Extensive12* scored 64.7%, while *Extensive0*, *Intercrop20*, *Intensive50*, and *Intensive100* all scored 100%. This implies that the ability of *Extensive12* to transform inputs into outputs was 64.7% when compared to *Extensive0*, *Intercrop20*, *Intensive50*, and *Intensive100*, respectively. Thus, *Extensive12* was less sustainable relative to *Extensive0*, *Intercrop20*, *Intensive50*, and *Intensive100*.

3.3 Carbon footprint

The GHG emissions increased with increase in the intensity of NPK or urea input. Both the carbon balance per unit of farmland and carbon balance per unit of product (grain yield) showed similar trends (Figure 6 and Figure 7). The assessment results (Table 6), showed that the field-to-farm gate carbon balance ranged between -0.680 and 0.114 ton CO_2 e/ha/yr, while the carbon balance per tonne grain ranged between -0.563 and 0.015 ton CO_2 e/ton grain, respectively. The impact of the various scenarios based on the carbon balance per unit of farmland, from low to high were as follows: *Intensive50*, *Intercrop20*, *Extensive0*, *Extensive12*, and *Intensive100*. When the carbon balance per unit of product was considered, the impact caused by the various systems, from low to high were as follows: *Extensive0*, *Intercrop20*, *Extensive12*, *Intensive50*, and *Intensive100*. In both metrics, the impacts caused by Intensive100 were greatest when compared to the peer systems. The source attributed with the greatest emission was industrial production of NPK and urea fertilizer. The detailed analysis of the carbon footprint of the various scenarios are presented in Appendix D.

3.4 Holistic view of the aggregated results

The overall trend of the assessment results (Table 5 and Table 6), showed that the yield, GHG emissions and carbon footprint all increased with increase in intensity of NPK or urea input. However, the relationship between the yield and urea intensity was not always linear. A system that used more renewable or fewer resources to produce a yield equal to that of its peer was considered more efficient and sustainable in relative terms. The incremental input in NPK/urea contributed to improve the yield. Hence, the various scenarios showed improved yield from 0.93 ton/ha/yr for *Extensive0* with 0 kg/ha/yr urea input through 2.25 kg/ha/yr ton/ha for *Intensive100* with 100 kg/ha/yr urea input, respectively. More so, increase in synthetic N also increased the GHG emissions and carbon footprint. Although urea input in *Intensive100* was twice and 5 times as much when compared to *Intensive50* and *Intercrop20*, the marginal yield was greatest in *Intercrop20*, while the marginal yield in *Intensive50* was greater when compared to *Intensive100*, respectively. Meanwhile the amount of GHG emissions and carbon footprint of *Intercrop20* were lesser when compared to the emissions and carbon footprint of *Intensive50. Intensive100* emitted the greatest amount of GHG emissions and carbon footprint. The total amount of GHG emissions were negatively correlated with the intensity of urea input.

The RUE and sustainability were positively correlated. More so, the triangulation among the yield, RUE and carbon footprint (Figure 5, Table 5, and Table 6), showed convergence with the trade-off analysis among yield gap, resource and carbon saving (Table 8). The ranking of the various scenarios based of the carbon footprint, from low to high emitter were as follows: *Extensive0*, *Intercrop20*, *Extensive12*, *Intensive50*, and *Intensive100*. On the one hand, when the assessment of RUE and absolute sustainability was based on input materials only, the scenarios from best to worst case were as follows: *Intercrop20, Extensive0, Intensive50, Intensive100,* and *Extensive12.* On the other hand, when the assessment of RUE and absolute sustainability was based on input materials including labor and services, the scenarios from best to worst case were as follows: *Intercrop20, Intensive50, Intensive100, Extensive0,* and *Extensive12.* This difference in the sequence of the various scenarios based on their performances when different input resources were taken into account, demonstrates that existing methods which do not account for input labor by human and draft animals, including services and other environmental externalities such as erosion (topsoil loss), could be limited in analyzing small-scale agricultural production systems as a whole.

Table 5. Analysis of RUE and sustainability

Indicator	***Extensive0***		***Extensive12***		***Intercrop20***		***Intensive50***		***Intensive100***	
	without L&S	*with L&S*	*without L&S*	*with L&S*	*without L&S*	*with L&S*	*without L&S*	*With L&S*	*without L&S*	*with L&S*
Total emergy U (E+15 *sej*/ha yr)	0.273	5.35	0.396	5.87	0.385	4.64	0.611	8.85	0.904	9.55
UEV_R (E+9 *sej/g* d.m.)	0.292	5.72	0.412	6.12	0.256	3.09	0.278	4.02	0.402	4.25
UEV_E (E+5 ***sej/J***)	0.195	3.81	0.275	4.08	0.171	2.06	0.185	2.68	0.268	2.83
EYR	6.60	1.05	2.42	1.05	2.49	1.05	1.83	1.03	1.44	1.03
ELR	0.19	22.27	0.72	24.54	0.67	19.19	1.22	31.18	2.28	33.73

ESI	34.97	0.05	3.35	0.04	3.70	0.05	1.50	0.03	0.63	0.03
%REN	84	4	58	4	60	5	45	3	30	3
rTE	100		64.7		100		100		100	
UEV_{currency} (E+12 sej/Gh¢)	1.30		1.30		1.30		1.30		1.30	

Table 6. Field-to-farm gate analysis of GHG emissions and carbon footprint

Indicator	*Extensive0*	*Extensive12*	*Intercrop20*	*Intensive50*	*Intensive100*
GHG emission (ton CO_2e/ha/yr)	0.266	0.436	0.546	1.177	2.015
Carbon stock (ton CO_2 e/ha/yr)	0.789	0.811	1.164	1.857	1.901
Carbon balance (ton CO_2 e/ha/yr)	- 0.523	- 0.374	- 0.618	-0.680	0.114
Carbon balance/ton grain (ton CO_2 e/ton grain)	- 0.563	- 0.390	- 0.412	-0.309	0.051
Index of sustainability (*Is*)	2.97	1.86	2.13	1.57	0.94

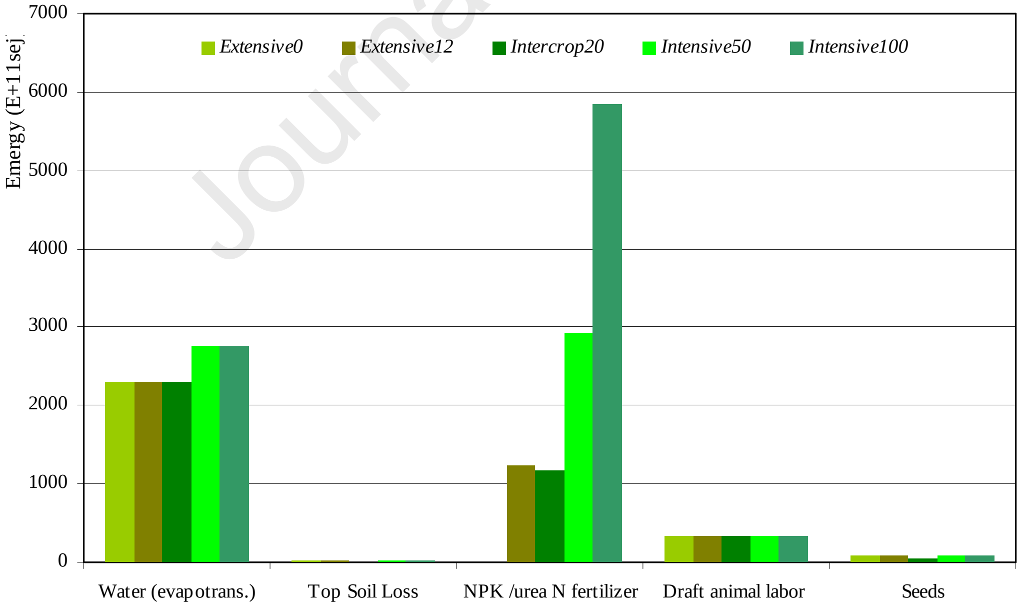


Figure 3: Input raw materials per hectare

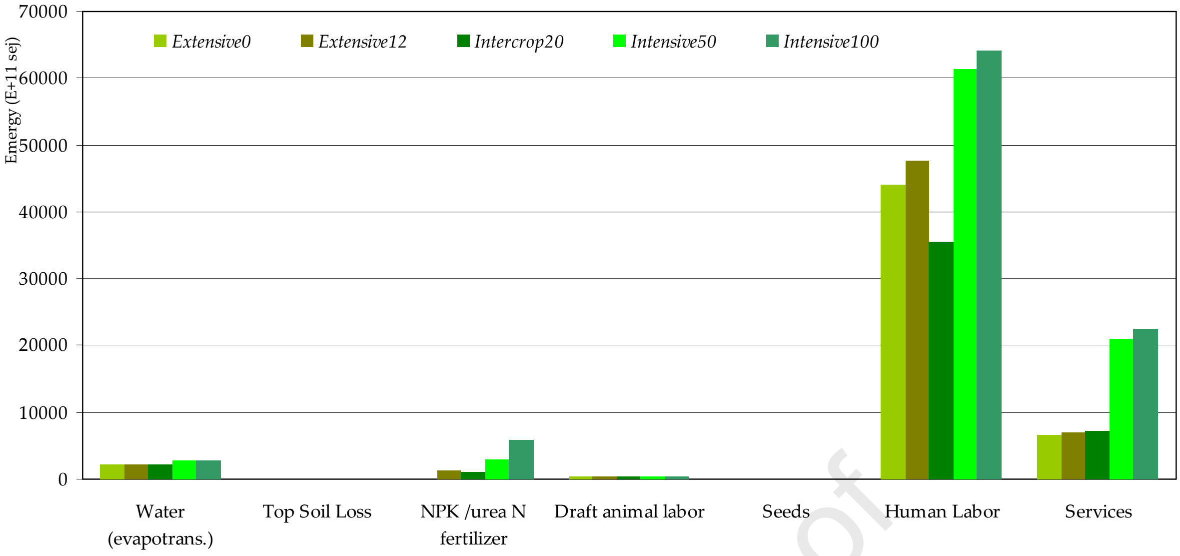


Figure 4. Input raw materials including labor and service per hectare

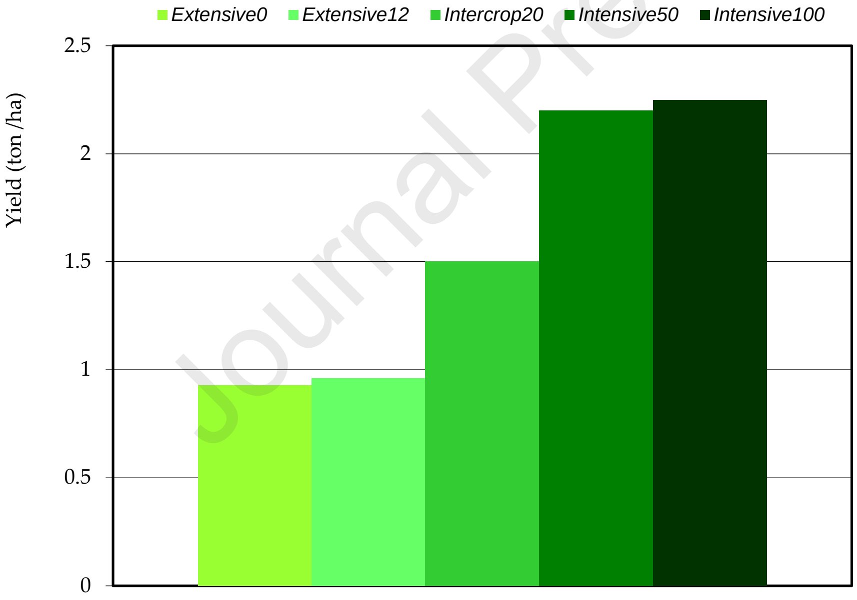


Figure 5. Dry matter yield

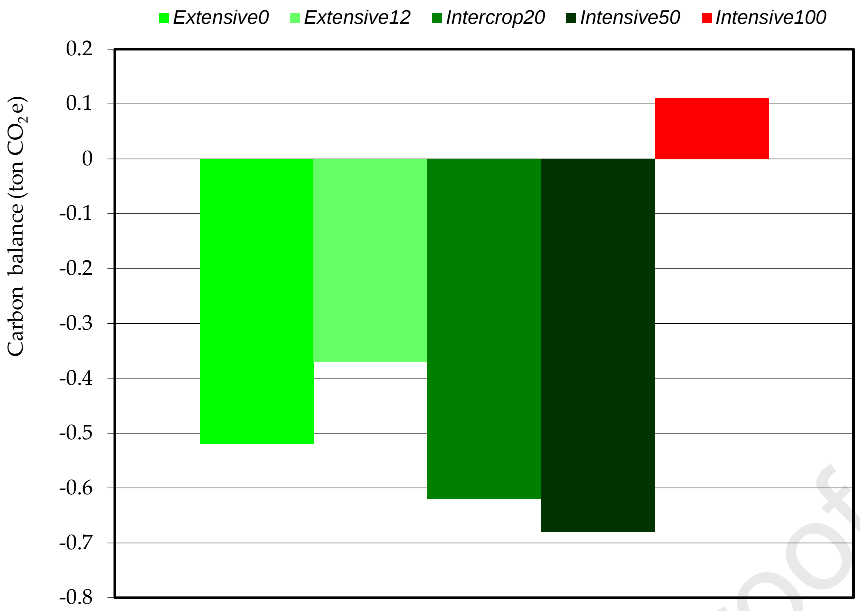


Figure 6. Carbon balance per unit of farmland

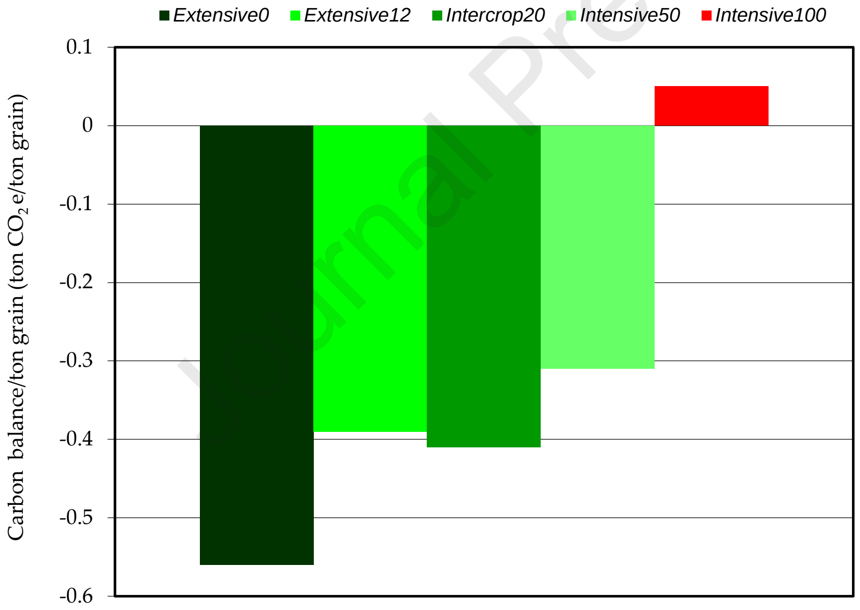


Figure 7. Carbon balance per tonne grain

4. Discussion

4.1. Validation of the results for RUE

The validation was by comparing our results for the RUE to the results of another empirical study that was assessed using another method. In this study, *Extensive12* was the "business-as-usual" scenario, because it was based on primary data. While *Extensive0, Intercrop20, Intensive50,* and *Intensive100* were the contrasting scenarios, because they were based on simulations (Table 3). The use of the EM-DEA approach in this study showed that the relative Technical

Efficiency (rTE) score for *Extensive12* was 64.7% (Table 5). This value was compared to the Technical Efficiency (TE) of small-scale maize farmers in the Sudanian and Guinea savanna, Ghana (Wongnaa, 2016). The TE was assessed using the stochastic frontier production function (Aigner et al., 1977; Meeusen and van den Broeck, 1977). The observed TE was 61.2% (Wongnaa, 2016). This value is statistically comparable to 64.7%, which was derived using the EM-DEA approach in this study. The comparability between both values which were derived using different methods as applied to assess the efficiency in similar production systems located in an identical agroecological zone, demonstrates the validity of our results for RUE.

4.2 Uncertainty of the results for RUE

The uncertainty of the results for the RUE was evaluated using the Z-score as the proxy (Farrance and Frenkel, 2012). Three empirical studies (excluding the one that was used for the validation) were sourced from online. The three empirical studies and this study were amalgamated into a sample of four studies (Table 7). The standard deviation (SD) of the efficiency values reported by the sample of studies was calculated using *Eq*. (26). The variance between the rTE for *Extensive12* (this study) and the TE reported by the three empirical studies was calculated. The Z-score was used to calculate the number of SDs of the rTE value for *Extensive12* from the mean TE value reported by the three empirical studies as stated in *Eq*. (27).

The calculated Z-score was about -0.21, and this implies that the rTE value for *Extensive12* was 0.21 times below the mean efficiency value reported by the sample of studies (

Table **7**). To further confirm that the uncertainty was statistically small, the difference between the mean efficiency values reported by the sample of studies (including and excluding this study) was calculated. The difference was 0.76, which is statistically small. Thus, the uncertainty of the rTE value which was derived using the EM-DEA approach was small and allowable. The following assumptions were applied: (i) the efficiency values of the sample of studies formed a normal distribution (

Table **7**), (ii) the values of the TE reported by the three empirical studies were representative of the TE of small-scale maize production systems in Ghana, SSA, (iii) the mean efficiency value reported by the sample of studies approximated to the true mean efficiency value for small-scale maize production systems in Ghana, SSA.

4.3 Relaibility of the results for RUE

The reliability of the results for the RUE was evaluated using the confidence interval (CI) as the proxy (Oosterwijk et al., 2017). Considering the sample of studies (Table 7), the 95% CI of the efficiency values that were reported by these studies was calculated using *Eq*. (28). The calculated 95% CI was between 56.12 and 77.88%. As such, the rTE value for *Extensive12* being 64.7% (this study) implies that it lies between 56.12 and 77.88%, and this is an indication that our results for the RUE were reliable.

To further confirm that this interval was statistically true, the calculated 95% CI was compared to the TE values for small-scale maize production systems in Africa. The reported mean TE value for small-scale maize systems in east Africa, southern Africa, west Africa and overall TE are as follows: 57, 72, 82, and 70%, respectively (Kibirige et al., 2014). These mean values lie between the calculated 95% CI. Hence, our results for the RUE derived using the EM-DEA method were valid and reliable. The uncertainty was statistically small and allowable.

$$SD = \sqrt{\frac{\sum(X-\bar{X})^2}{n-1}}\,, \tag{26}$$

$$Z - score = \frac{X - \bar{X}}{SD}\,, \tag{27}$$

$$95\%CI = \bar{X} - \pm Z\frac{SD}{\sqrt{n}}\,, \tag{28}$$

where,

$SD = standard\ deviation$

$X = TE\ value\ reported\ by\ an\ empirical\ study$

$\bar{X} = mean\ of\ the\ TE\ values$

$n = sample\ studies$

$Z - score = number\ of\ SDs\ of\ the\ rTE\ value\ for\ Extensive12\ from\ mean\ TE\ value\ of\ sample\ studies$

$CI = confidence\ interval\ (distribution\ of\ efficiency\ values)\ evaluated\ at\ 95\%$

$Z = the\ standardized\ value\ used\ for\ the\ 95\%CI\ was\ 1.96$

Table 7: Sample of studies used for evaluating uncertainty and reliability of RUE results

Sample study/ Method of assessment	**Technical Efficiency (%)**
(Addai and Owusu, 2014) Translog Stochastic Production Frontier Function was used in estimating the TE of small-scale maize farmers in Forest, Transitional, and Savanna Zones in Ghana. The sample size *n* = 453. The results of the TE were as follows: 79.9, 60.5, and ***52.3***%, respectively. The mean was 64.1%. Note: In this cited study, only the TE for the Savanna Zone was considered for its close similarities to the mix Guinea and Sudanian savannas in northern Ghana.	52.3
(This study) The EM-DEA method was used for measuring the rTE of five practices for cultivating maize in small-scale systems in the mix Sudanian and Guinea savannas in northern Ghana. The sample size consists of interview with 56 farmers, simulations using APSIM and extensive secondary data sources.	64.7
(Abdulai et al., 2013) The Stochastic Frontier Approach (SFA) was used in estimating the TE of maize farmers in northern Ghana (Northern-, Upper East-, and Upper West- Regions). The sample size *n* = 360.	74
(Abdulai et al., 2013) Data Envelopment Analysis (DEA) was used in estimating the TE of maize farmers in northern Ghana (Northern-, Upper East-, and Upper West- Regions). The sample size *n* = 360.	77
Mean efficiency of sample studies (excluding this study)	*67.76*
Mean efficiency of sample studies (including this study)	*67*
Difference between the calculated means of efficiency values (with and without this study)	*0.76*
Standard deviation (SD) of efficiency distribution of the given sample studies	*11.1*
Number of SDs of rTE for Extensive12 from the mean efficiency value of the sample studies	*-0.21*
95% Confidence Interval	*56.12 – 77.88*

4.4 Validation of the results for carbon footprint

The results for the carbon footprint were validated by comparing the index of sustainability (I_s), i.e. the ratio of total carbon stocks to total carbon emissions for this study to the typical inverse I_s which is observed for agricultural operations with increasing intensity of fertilizer input (Lal, 2004). The relationship between the I_s and urea application intensity was an inverse one. As such, the I_s and input intensity of NPK/urea (kg/ha) were as follows: 2.97, 0 (*Extensive0*), 1.86, 12 (*Extensive12*), 2.13, 20 (*Intercrop20*), 1.57, 50 (*Intensive50*), and 0.94, 100 (*Intensive100*), respectively. This trend was similar to the characteristic trend which is observed for agricultural production when the input fertilizer dosage increases (Lal, 2004). That is, the I_s decreases as the dosage of input resources increases. Hence, the results for the carbon footprint derived using the adapted EX-ACT approach was valid.

To further confirm that our assessment for total GHG emissions were realistic, we compared the mean total GHG emissions for this study with the results of another empirical study on the carbon emissions from maize systems in South Africa. The mean total GHG emissions by the various scenarios was 0.89 ton CO_2 e/ha/yr (Appendix D). This value is statistically comparable to 0.57 ton CO_2 e/h as the carbon emission from maize production in South Africa, which was assessed using the Agriculture and Land Use National Greenhouse Gas Inventory Software, and on the is based on the Intergovernmental Panel on Climate Change Guidelines for National GHG Inventory (Tongwane et al., 2016). The minor difference between 0.89 (our assessment) and 0.57 (empirical assessment) could be attributed to the fact that our assessment was more inclusive on the various carbon sources and sinks when compared to the empirical study. The detailed calculation on the carbon footprint is presented in Appendix D.

4.5. Comparison of results to other existing empirical studies

First, this study was compared to an empirical study on maize yield response to fertilizer input in Guinea savanna zone, Nigeria, SSA. The results of the empirical study showed that intensive land use systems treated with 100 kg/ha urea N as the base intensity, produced a yield that was suboptimal relative to systems that were treated with input fertilizer intensities that were less than 100 kg/ha urea N. The greatest yield was observed in fields that were treated with an input fertilizer intensity that ranged between 50 and 100 kg/ha urea N (Adediran and Banjoko, 1995). The results of the empirical study are similar to the results of this study. For instance, *Intensive100* was treated with 100 kg/ha/yr urea input, and the marginal yield was suboptimal when compared with the marginal yield that was observed in *Intercrop20* and *Intensive50*, which were treated with 20 and 50 kg/ha/yr urea input, respectively (Table 3). Thus, the input fertilizer intensity that produced optimum yield in both studies were within the same range. This similarity confirms that our simulated yield response was accurate and comparable to the response that one would observe in a field experimentation with maize systems in the Sudan and Guinea savanna, SSA.

Second, this study was compared to an empirical study on the relationship between the net energy yield and carbon footprint of maize systems cultivated using various nitrogen fertilizer application intensities (0, 75, 150, 225 and 300 kg/ha N) in North China Plain. The results of the empirical study showed that the grain yield, input energy, GHG emission, and carbon footprint all increased with increase in N fertilizer intensity. More so, the treatment with 225 kg/ha N produced the optimum yield and lesser carbon footprint when compared with the treatment using 300 kg/ha N (Wang et al., 2015). The reported results are similar to the results of this study. For instance, the yield, total emergy, GHG emission, and carbon footprint all increased with increase in urea application intensity. In particular, *Intercrop20* achieved the greatest marginal yield, better RUE, sustainability, while the carbon footprint was lesser when compared to *Intensive100*. To a lesser extent, the performance of *Intensive50* was similar to that of *Intercrop20*. (Table 5 and Table 6).

Third, this study was compared to an empirical study on the carbon footprint of maize production as affected by synthetic nitrogen input intensity (100, 200 kg/ha N) to continuous monoculture and maize-legume (alfalfa -*Medicago sativa*, red clover -*Trifolium pratense*, or soyabean

-*Glycine max*) rotation systems in North America. The results of the reported field experiment showed that high application of N increased both the GHG emissions and carbon footprint across all rotation systems. Although the GHG emissions were high in the rotation systems, however, the carbon footprint was lesser due to the improved yield in the maize that follows the legume crop cycle. More so, the GHG emissions and carbon footprint of the maize-legume rotation systems were lesser when compared to the emissions and footprint of the monoculture systems (Ma et al., 2012). The results of the reported experiment are similar to the results of this study. For instance, the GHG emissions and carbon footprint of *Intercrop20* was lesser relative to the GHG emissions and carbon footprint of *Intensive50* and *Intensive100*. More so, although the total GHG emissions emitted by *Intercrop20* was greater than the total GHG emissions emitted by *Extensive12,* however, the carbon footprint (carbon balance per tonne grain) of *Intercrop20* was lesser relative to the carbon footprint (carbon balance per unit tonne grain) of *Extensive12* (Appendix D). The similarities between our results and the results obtained by Wang et al., (2015), and Ma et al., (2012), confirm that our results conform to trends that have been observed in systems with cropping pattern and input resources in other regions.

4.6 Trade-off analysis

The total emergy (U), carbon balance per tonne grain, and grain yield were the proxies for analyzing the trade-offs among resource saving, carbon saving and yield gap, respectively. In this trade-off analysis, it was assumed that *Intensive100* was the "reference scenario", while *Extensive0*, *Extensive12*, *Intercrop20* and *Intensive50* were the "farm scenarios", respectively. *Extensive0* and *Extensive12* demanded for fewer resources and the productivities were lower relative to the other scenarios. The yield gap was much wider when compared with *Intensive100* (Table 8). More so, food provision by *Extensive0* and *Extensive12* was lower (Mwambo et al., 2020). As such, the risk of converting more naturally occurring ecosystems into farmland in order to grow more food could likely occur in *Extensive0* than in the other systems, and this could lead to increase in GHG emissions (

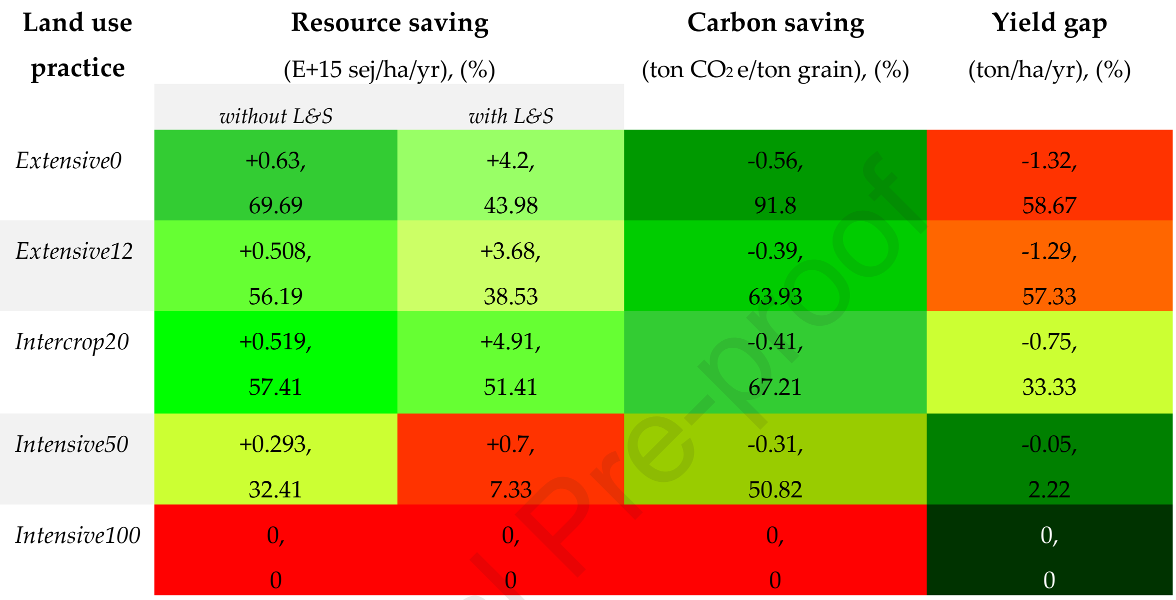
Table 9). Hence, *Extensive0* and *Extensive12* were less attractive, because of the wider yield gap. *Intensive100* produced the greatest yield, but the input urea and GHG emissions were also greatest. Although the yield gap was null, however, the resources and carbon saving were least relative to the various scenarios. As such, *Intensive100* was not a preferable practice, because of the environmental impacts (Table 8).

Intercrop20 showed modest demand for urea, and the marginal yield was greatest relative to the various scenarios. The resource and carbon saving were greater than 50% when compared to *Intensive100*, while the yield gap was narrower when compared to *Extensive0* and *Extensive12,* respectively (Table 8). Hence, *Intercrop20* could be implemented to better adapt low input systems such as *Extensive0* and *Extensive12* to improve the productivity while causing fewer environmental impacts (Table 8 and Table 9).

Alternatively, *Intensive50* showed moderate demand for urea, and the yield gap was negligible relative to *Intensive100*. The input urea intensity was 50% less, and the yield gap was less than 3%, while the GHG emissions were fewer when compared to *Intensive100* (Table 8 and Table 9). *Intensive50* could the implement to better adapt high input systems such as *Intensive100* to maintain high productivity, while the demand for resources and GHG emissions are substantially reduced. The trade-off analyses are summarized in Table 8 and

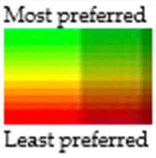
Table 9. The detailed calculations of the trade-off are presented in Appendix F.

Table 8. Trade-off between yield gap, resource and carbon saving.



Land use practice	**Resource saving** (E+15 sej/ha/yr), (%)		**Carbon saving** (ton CO_2 e/ton grain), (%)	**Yield gap** (ton/ha/yr), (%)
	without L&S	*with L&S*		
Extensive0	+0.63, 69.69	+4.2, 43.98	-0.56, 91.8	-1.32, 58.67
Extensive12	+0.508, 56.19	+3.68, 38.53	-0.39, 63.93	-1.29, 57.33
Intercrop20	+0.519, 57.41	+4.91, 51.41	-0.41, 67.21	-0.75, 33.33
Intensive50	+0.293, 32.41	+0.7, 7.33	-0.31, 50.82	-0.05, 2.22
Intensive100	0, 0	0, 0	0, 0	0, 0

Legend:	*Cell value*	*Color ramp*
	The absolute difference relative to *Intensive100*, The difference in percentage relative to *Intensive100*	Most preferred Least preferred



Assumption: *Intensive100* was the "reference scenario", and the yield was the "maximum attainable yield". Meanwhile *Intensive50*, *Intercrop20*, *Extensive12*, and *Extensive0* were the "farm scenarios" and the yields were the "attainable yield", respectively. The readings in a cell represent the difference between the reference and farm scenarios for a given indicator, expressed as an absolute value and a percentage.

Table 9. Trade-off between area cultivated, carbon emission and grain yield

Strategy	**Scenario**	**Yield,** dry matter (ton/ha)	**Cultivated area** (ha)	**C emission** (ton CO_2 e)
Extensification	*Extensive0*	0.93	1.0	0.266
		1.5 P	1.6 P	0.419 P
		2.25 P	2.4 P	0.623 P
	Extensive12	0.96	1.0	0.436
	Intercrop20	1.5	1.0	0.546
	Intensive50	2.20	1.0	1.177
Intensification	*Intensive100*	2.25	1.0	2.015

[P] projection using the data for *Extensive0*

4.7 Emperical evidence and policy recommendations

1) Supplemental irrigation as a means to adapt to climate change and improve yield.

The majority of small-scale maize production systems in SSA are rainfed (Edreira et al., 2018). Water (evapotranspiration) was the most demanded input from nature (Figure 3). Water is a scarce resource. Climate change is aggravating water scarcity (Oyebande and Odunuga, 2010; Kabo-Bah, et al., 2016; Mancosu et al., 2015; Amisigo et al., 2015), and this could affect future maize yield (Jones and Thornton, 2003; Lobell et al., 20111; Cairns et al., 2013). As such, supplemental irrigation could become relevant to boost productivity in small-scale maize systems in SSA (Rosegrant et al., 2002).

The results and trade-off analyses (Table 5, Table 6, Table 8 and Table 9), showed that *Intercrop20* and *Intensive50* were the two best case scenarios. *Intercrop20* was a rainfed maize-legume intercropping scenario, while *Intensive50* was an irrigation scenario (Table 3). Both scenarios could be implemented alternatively. The feasibility of both scenarios could be justified using an empirical study that was conducted in northern Ghana. The study demonstrated that improved irrigation management could save between 0.13 and 1.325 m of water when compared to traditional irrigation practice. Water that was saved using improved irrigation in the cultivation of vegetables during the dry season could be used for supplemental irrigation of maize during the rainy season. The water requirements for maize in the experimental irrigation scheme was 0.107–0.126 m and 0.088–0.105 m during weather conditions of low rainfall with frequent dry spells and high rainfall with rare dry spells, respectively (Sekyi-Annan et al., 2018).

2) A rational mix of extensive and intensive land use practices could contribute towards sustainable intensification.

Table 9 demonstrates the trade-off among yield, cultivated area and GHG emissions. Meanwhile cropland expansion (extensification) demands for fewer purchased input resources at the expense of land sparing, intensification favors land sparing over purchased input resources. The compromises made by both land use strategies could lead to increase in GHG emissions from agriculture and threaten biodiversity (Zabel et al., 2019; Pellegrini and Fernández, 2018). As such, practicing solely extensification or intensification to produce more maize in the coming decades would be limiting as far as sustainability is concern (Pingali, 2001). Hence, neither extensification nor intensification alone seem to offer a reliable pathway which could sustainably boost crop production.

Based on the results and trade-off analysis (Table 5, Table 6, Table 8 and Table 9), *Intercrop20* and *Intensive50* emerged as the best case scenarios. On the one hand, *Intercrop20* achieved the optimal economic yield using a low input strategy, i.e. rainfed maize-legume intercropping system. On the other hand, *Intensive50* achieved high yield using a de-intensification strategy, i.e. by using 50% less urea relative to *Intensive100*. This combination of *Intercrop20* and *Intensive50* represent a rational mix of extensive and intensive land use practices, which could be suitable for implementation in small-scale systems on arable and high input systems on marginal land, respectively. This evidence is in conformity with the results of other empirical studies (Struik and Kuyper, 2017; Tilman, 1999).

3) Maize-legume intercropping and de-intensification as cost effective strategies for boosting the efficiency and sustainability.

To improve the yield, while reducing the cost of production and GHG emissions are factors to consider when planning to boost the resource use efficiency and sustainability in an agroecosystem (De Wit, 1979; Ma et al., 2012). Assuming that the minimum threshold yield required for a small-scale maize system in Ghana, SSA, to be economic and sustainably contribute towards household food security is 1.5 ton/ha (Scheiterle and Birner, 2018), *Intercrop20* and *Intensive50* fulfilled these criteria. For instance, manual weeding in small-scale maize systems was responsible for the spiking demand for labor that was required (Figure 4). High input of labor or intensity of urea implies high cost of production. Maize-legume intercropping substantially reduced the input labor by increasing the percentage cover, which in turn suppressed weeds and minimized the cost of labor. More so, increase in percentage cover also minimized soil erosion, while biological nitrogen fixation by the leguminous intercrop adds to soil nitrogen. Together, these contributed to increase the yield and ultimately the overall efficiency and sustainability of *Intercrop20* (Table 5). This evidence is in conformity with other empirical studies (Kermah et al., 2017; Stagnari et al., 2017). More so, using 50% less urea in *Intensive50* led to a reduction in the cost of production, GHG emissions and carbon footprint relative to *Intensive100*. This contributed in making *Intensive50* more efficient and sustainable when compared to *Intensive100*. This evidence is similar to the results of a field experiment (Ma et al., 2012).

4.8 Strengths and weaknesses of the assessment approaches

Until now, the EMA and DEA methods were applied separately to assess resource use and relative performance of systems, respectively (Odum, 1996; Bastianoni et al., 2001; Lefroy and Rydberg, 2003; Brown and Ulgiati, 2004; Cavalett et al., 2006; Chen et al., 2006; Martin et al., 2006; Ulgiati et al., 2011; Rótolo et al., 2015; Chauhan et al., 2006; Malana et al., 2006; Toma et al., 2017; Pang et al., 2016). The novelty of combining both methods leading to the EM-DEA approach (Mwambo and Fürst, 2019), has demonstrated that it is possible to use minimal data to achieve comprehensive analysis in non-mechanized agricultural systems, and in particular to account for human and draft animal labor inputs, which before now was difficult to assess (FAO, 1995).

Given that the carbon footprint as an indicator may not always reflect the environmental sustainability of a production system (Laurent et al., 2012), the application of EMA using the EM-DEA approach as demonstrated in this paper, strengthens the applied EX-ACT approach which we used to assess the carbon footprint of maize production in the various scenarios. In particular, the emergy-based indicators which we used to assess the environmental burden, provided additional information on the environmental sustainability of the various practices.

A weakness with the EM-DEA approach is that comparison of the results derived using the DEA is limited to peer systems of the same batch. As such, the results on RUE and sustainability are to be interpreted with caution. The results in this paper were achieved under conditions of data scarcity. However, the inclusiveness as well as comparability of our results with other existing empirical studies demonstrate that the results derived using the EM-DEA approach are reliable. Our results could be improved using a larger sample size as well as substituting the simulated data with empirical data.

5. Conclusions and outlook

This paper showcases the combined application of the EM-DEA and EX-ACT approaches to assess RUE, sustainability and carbon footprint of small-scale maize production practices in Ghana, SSA. The results which were derived using the EM-DEA approach showed that when the assessment was based on input materials only, *Extensive0* demanded the least amount of input resources while *Intercrop20* was the most resource efficient and sustainable practice. Alternatively, when the assessment was based on input materials including labor and services, *Intercrop20* was the most resource efficient and sustainable practice, and to a lesser extent *Intensive50*. *Intensive100* produced the greatest yield, but the demand for purchased inputs was greatest. The results which were derived using the EX-ACT approach showed that, the carbon footprint increased with increase in urea application intensity. *Intensive100* emitted the greatest amount of total GHG emission and carbon footprint. The overall results showed that grain yield, total emergy, GHG emissions and carbon footprint all increased with increase in urea application intensity. However, the relationship between marginal yield and urea application intensity was not always linear. *Intercrop20* and *Intensive50* emerged as the two best case scenarios. Hence, *Intercrop20* and *Intensive50* could be promoted by policy as recommendable maize-based land use practices for implementation in low input and high input systems, respectively.

The inclusiveness of the results which were derived using the EM-DEA approach demonstrates that this approach is useful for achieving comprehensive assessment of small-scale agricultural land use systems as a whole. Such detailed information could be useful when making informed decisions that aim at sustainable agriculture. Based on the inclusiveness of the information which was derived using the EM-DEA and EX-ACT approaches in this study, we will apply these approaches in future works to develop assessment schemes which could be used for certification of small-scale agricultural systems in developing countries. Such schemes could be used for promoting sustainable agriculture, i.e. a responsible approach to agriculture that could align environmentalism and food security goals, as well as ensure the socio-economic wellbeing of small-scale farmers, end consumers and other stakeholders along the agri-food value chain.

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Appendix A: Emergy diagrams

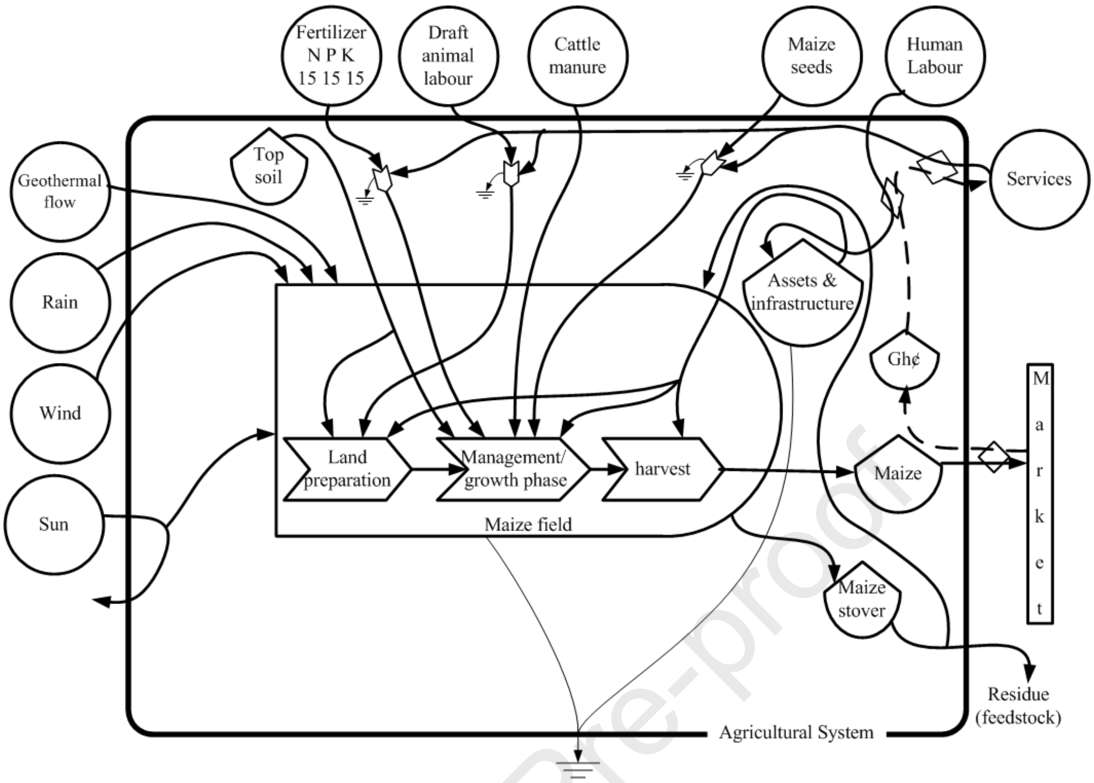


Figure 8. A simplified emergy diagram of *Extensive12* and *Extensive0*

Note: Manure is provided for free or produced locally, and therefore no service is associated.
Source: Adapted from Zucaro et al. (2013).

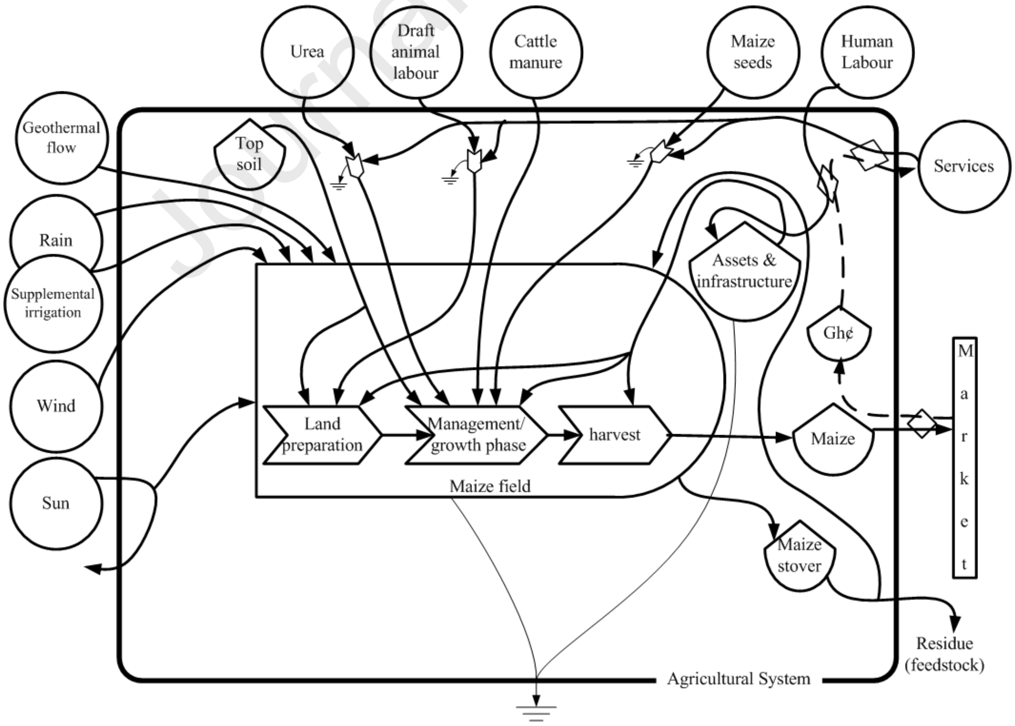


Figure 9. A simplified emergy diagram of *Intensive50* and *Intensive100*

Note: Manure is provided for free or produced locally, and therefore no service is associated.
Source: Adapted from Zucaro et al., (2013).

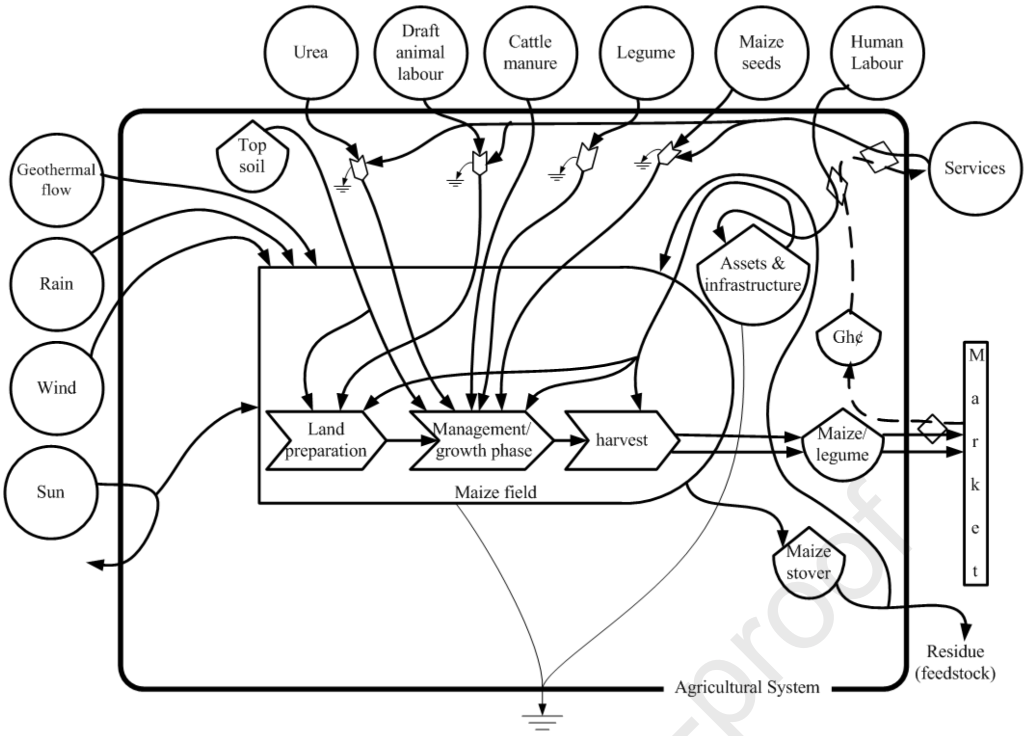
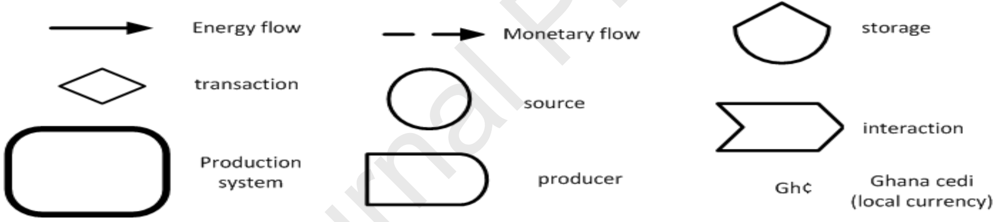


Figure 10. A simplified emergy diagram of *Intercrop20*

Note: Manure is provided for free or produced locally, and therefore no service is associated.
Source: Adapted from Zucaro et al. (2013).



Source: Energy systems symbols from Odum (1996).

Table 10. Distinction between emergy diagrams

Diagrams	Practice	Characteristic features
Fig. 8	*Extensive0* and *Extensive12*	no irrigation, no legume
Fig. 9	*Intensive50* and *Intensive100*	supplemental irrigation
Fig. 10	*Intercrop20*	legume as an intercrop

Appendix B: Emergy data and accounting

Table 11. Emergetic data of selected resource inputs and outputs for import into DEA model

DMUs	Grain yield (d.m.) (kg/ha/yr)	Residue (stover) (d.m.) (kg/ha/yr)	Evap. Water (sej/ha/yr)	Topsoil loss (sej/ha/yr)	NPK/urea (sej/ha/yr)	Animal labor (sej/ha/yr)	Seeds sej/ha/yr)	Human labor (sej/ha/yr)	Services (sej/ha/yr)
Extensive0	936	876	2.30E+14	1.96E+12	0.00E+00	3.32E+13	8.19E+12	4.41E+15	6.67E+14
Extensive12	960	899	2.30E+14	1.96E+12	1.22E+14	3.32E+13	8.19E+12	4.77E+15	7.03E+14
Intercrop20	1500	1410	2.30E+14	4.89E+11	1.17E+14	3.32E+13	4.10E+12	3.55E+15	7.11E+14
Intensive50	2200	2250	2.75E+14	1.96E+12	2.93E+14	3.32E+13	8.19E+12	6.14E+15	2.10E+15
Intensive100	2250	2110	2.75E+14	1.96E+12	5.85E+14	3.32E+13	8.19E+12	6.41E+15	2.24E+15

Table 12. Emergy evaluation of annual inputs and outputs normalized at 1ha of land

Note	**Item**	**Unit**	**Raw amount for Extensive 0**	**UEV (sej/unit)**	**Emergy flow for Extensive 0** (sej/ha/yr)	**Raw amount for Extensive12**	**Emergy flow for Extensive12** (sej/ha/yr)	**Raw amount for Intercrop20**	**Emergy flow for Inter. 20** (sej/ha/yr)	**Raw amount for Intensive50**	**Emergy flow for Inten.50** (sej/ha/yr)	**Raw amount for Intensive 100**	**Emergy flow for Inten.100** (sej/ha/yr)	**Ref. of UEV**
	Renewable inputs (locally available)													
1	Sun	J	4.43E+13	1.00E+00	4.43E+13	4.43E+13	4.43E+13	4.43E+13	4.43E+13	4.43E+13	4.43E+13	4.43E+13	4.43E+13	[a]
2	Deep Heat	J	1.32E+10	4.90E+03	6.49E+13	1.32E+10	6.49E+13	1.32E+10	6.49E+13	1.32E+10	6.49E+13	1.32E+10	6.49E+13	[b]
3	Gravitational potential	J	0.00E+00	3.09E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	[c]
	Sum of primary sources				1.09E+14		1.09E+14		1.09E+14		1.09E+14		1.09E+14	
	Secondary Renewable Sources													
4	Wind	J	5.87E+10	7.90E+02	4.64E+13	5.87E+10	4.64E+13	5.86E+10	4.63E+13	5.86E+10	4.63E+13	5.86E+10	4.63E+13	[d]
5	Evapotranspired water	J	3.29E+10	7.00E+03	2.30E+14	3.29E+10	2.30E+14	3.29E+10	2.30E+14	3.93E+10	2.75E+14	3.93E+10	2.75E+14	[e]
	Maxi. of secondary sources				2.30E+14		2.30E+14		2.30E+14		2.75E+14		2.75E+14	
	Maximum of primary sources (R)				2.30E+14		2.30E+14		2.30E+14		2.75E+14		2.75E+14	
	Nonrenewable sources (locally available) (N)													
6	Topsoil loss	J	3.49E+07	5.61E+04	1.96E+12	3.49E+07	1.96E+12	8.71E+06	4.89E+11	3.49E+07	1.96E+12	3.49E+07	1.96E+12	[f]
	Imported inputs (F)													
7	Fertilizer NPK (15 15 15) / Urea	G	0.00E+00 (urea)	1.02E+10 /5.85E+09	0.00E+00	1.20E+04 (NPK)	1.22E+14	2.00E+04 (urea)	1.17E+14	5.00E+04 (urea)	2.93E+14	1.00E+05 (urea)	5.85E+14	[g] [h]
8	Draft animal labor	Hr	2.40E+01	1.39E+12	3.32E+13	2.40E+01	3.32E+13	2.40E+01	3.32E+13	2.40E+01	3.32E+13	2.40E+01	3.32E+13	[i]
9	Cattle manure	G	2.93E+04	4.96E+08	1.45E+13	2.93E+04	1.45E+13	2.93E+04	1.45E+13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	[j]
10	Maize seeds	G	1.60E+04	5.12E+08	8.19E+12	1.60E+04	8.19E+12	8.00E+03	4.10E+12	1.60E+04	8.19E+12	1.60E+04	8.19E+12	[k]
	Labor & Services (L & S)													
11	Human labor (L)	Gh¢	3.40E+03	1.30E+12	4.41E+15	3.68E+03	4.77E+15	2.73E+03	3.55E+15	4.73E+03	6.14E+15	4.94E+03	6.41E+15	[l]
12	Services (S)	Gh¢	5.14E+02	1.30E+12	6.67E+14	5.41E+02	7.03E+14	5.48E+02	7.11E+14	1.62E+03	2.10E+15	1.72E+03	2.24E+15	[m]
	Total Input emergy (without L&S)				2.73E+14		3.96E+14		3.85E+14		6.11E+14		9.04E+14	
	Total Input emergy (with L&S)				5.35E+15		5.87E+15		4.64E+15		8.85E+15		9.55E+15	
	Yield			***UEV***			***UEV***		***UEV***		***UEV***		***UEV***	
13	Grains (without L&S)	g	9.36E+05	2.92E+08		9.60E+05	4.12E+08	1.50E+06	2.56E+08	2.20E+06	2.78E+08	2.25E+06	4.02E+08	[n]
	Grains (without L&S)	J	1.40E+10	1.95E+04		1.44E+10	2.75E+04	2.26E+10	1.71E+04	3.30E+10	1.85E+04	3.37E+10	2.68E+04	[n]
14	Stover (without L&S)	g	8.76E+05	3.12E+08		8.99E+05	4.40E+08	1.41E+06	2.73E+08	2.06E+06	2.97E+08	2.10E+06	4.29E+08	[o]
	Stover (without L&S)	J	1.31E+10	2.08E+04		1.35E+10	2.94E+04	2.11E+10	1.82E+04	3.09E+10	1.98E+04	3.16E+10	2.86E+04	[o]
13	Grains (with L&S)	g	9.36E+05	5.72E+09		9.60E+05	6.12E+09	1.50E+06	3.09E+09	2.20E+06	4.02E+09	2.25E+06	4.25E+09	[n]
	Grains (with L&S)	J	1.40E+10	3.81E+05		1.44E+10	4.08E+05	2.26E+10	2.06E+05	3.30E+10	2.68E+05	3.37E+10	2.83E+05	[n]
14	Stover (with L&S)	g	8.76E+05	6.11E+09		8.99E+05	6.54E+09	1.41E+06	3.30E+09	2.06E+06	4.30E+09	2.10E+06	4.54E+09	[o]
	Stover (with L&S)	J	1.31E+10	4.07E+05		1.35E+10	4.36E+05	2.11E+10	2.06E+05	3.09E+10	2.87E+05	3.16E+10	3.03E+05	[o]

Footnotes: [a] By definition; [b] Brown & Ulgiati, (2016); [c] Brown & Ulgiati, (2016); [d] Brown & Ulgiati, (2016); [e] Brown & Ulgiati, (2016); [f] https://cep.ees.ufl.edu/nead/data.php#; [g] Odum, (1996); [h] Odum, (1996); [i] This study; [j] This study; [k] Rotolo et al. (2015); [l] This study; [m] This study, [http://www.cep.ees.ufl.edu/emergy/nead.shtml]; [n] This study; [o] This study.

Table 13: **D**efinition of sources

Abbreviation	Unit	Description
R	sej	Renewable sources are resources that are being replaced faster than they are extracted. The standard procedure is to list all major renewable flows as line items, but to use only the largest value for Total Renewable Flow (R), thereby avoiding double-counting of the flows from the three external biospheric inputs: gravitational energy, deep heat flow energy, and solar energy (Odum, 1996). In recent practice, both the chemical potential of rain (or evapotranspiration) and the geopotential of runoff have been listed as separate line items, though summing them is not considered double-counting, and they may be used together as the largest renewable flow (Odum, 1996).
N	sej	Nonrenewable sources are resources that are extracted and used faster than they are being replaced.
F	sej	Fraction of used emergy purchased from outside the system.
L&S	sej	These are human endeavor and purchased resources to enable production.
Y	sej	The yield is the output resources. Most agricultural production systems are capable to produce multiple output resources. The grain was considered as the main yield.

1. **Solar energy**:

Total area of Ghana = 2.30E+07ha =2.30E+11m^2

Area under maize cultivation within the study area (2011) = 3310ha (MoFA 2012)

Analysis area = 1ha = 1.00E+04 m^2 (analysis normalized to 1ha)

Average insolation foe Ghana = 1.20E+21 J m^{-2} y^{-1} (http://www.cep.ees.ufl.edu/nead/data.php?country=74&year=247#)

Albedo = 15.00 (% of insolation) (Arku, 2011)

Energy (J) = (av. insolation)* (area)*(1-albedo)

= [(1.20E+21 J m^{-2} y^{-1})/(2.30E+11m^2)](1.00E+04 m^2)(1-0.15) = 4.43E+13 J y^{-1} (*Extensive0*)

= [(1.20E+21 J m^{-2} y^{-1})/(2.30E+11m^2)](1.00E+04 m^2)(1-0.15) = 4.43E+13 J y^{-1} (*Extensive12*)

= [(1.20E+21 J m^{-2} y^{-1})/(2.30E+11m^2)](1.00E+04 m^2)(1-0.15) = 4.43E+13 J y^{-1} (*Intercrop20*)

= [(1.20E+21 J m^{-2} y^{-1})/(2.30E+11m^2)](1.00E+04 m^2)(1-0.15) = 4.43E+13 J y^{-1} (*Intensive50*)

= [(1.20E+21 J m^{-2} y^{-1})/(2.30E+11m^2)](1.00E+04 m^2)(1-0.15) = 4.43E+13 J y^{-1} (*Intensive100*)

UEV = 1.00 sej J^{-1} (by definition)

2. **Deep heat**:

Area = 1.00E+04 m^2 (normalized to 1ha)

Heat flow = 4.20E+01 mWm^2 y^{-1} (Beck & Mustonen, 1972)

Heat flow per unit area = 1.32E+06 Jm^{-2}y^{-1}

Energy (J) = (land area, m^2) (heat flow per area, Jm-^{2}y^{-1})

= (1.00E+04) (1.32E+06) = 1.32E+10Jy-1 (*Extensive0*)

= (1.00E+04) (1.32E+06) = 1.32E+10Jy-1 (*Extensive12*)

= (1.00E+04) (1.32E+06) = 1.32E+10Jy-1 (*Intercrop20*)

= (1.00E+04) (1.32E+06) = 1.32E+10Jy-1 (*Intensive50*)

= (1.00E+04) (1.32E+06) = 1.32E+10Jy-1 (*Intensive100*)

UEV = 4.90E+03 sej J^{-1}

3. **Wind energy**:

Area = 1.00E+04 m^2 (normalized to 1ha)

Density of air = 1.15E+00 kg m^{-3}

Land wind velocity = 2.6E+00 m s^{-1} (estimate for 2015, worldweatheronline.com)

Geostrophic wind = 4.00E+00 m s^{-1} (estimate)

Drag coeff. = 2.50E−03 (estimate)

Time frame = 3.15E+07s y^{-1}

Energy (J) = (air density, kg/m³)(drag coeff.)(geostrophic wind velo ., m/s)³(area, m²)(s y^{-1})

= (1.15E+00)(2.50E−03)(4.00E+00)(1.00E+04)(3.15E+07) = 5.80E+10J y^{-1} (*Extensive0*)

= (1.15E+00)(2.50E−03)(4.00E+00)(1.00E+04)(3.15E+07) = 5.80E+10J y^{-1} (*Extensive12*)

= (1.15E+00)(2.50E−03)(4.00E+00)(1.00E+04)(3.15E+07) = 5.80E+10J y^{-1} (*Intercrop20*)

= (1.15E+00)(2.50E−03)(4.00E+00)(1.00E+04)(3.15E+07) = 5.80E+10J y^{-1} (*Intensive50*)

= (1.15E+00)(2.50E−03)(4.00E+00)(1.00E+04)(3.15E+07) = 5.80E+10J y^{-1} (*Intensive100*)

UEV = 8.00E+02 sej J^{-1}

4. **Rain, chemical potential energy**:

Area = 1.00E+04 m^2 (normalized to 1ha)

Rainfall (estimate) = 0.911 m y^{-1} (MoFA, 2012)

Density of rain water = 1.00E+06 g m^{-3}

Mass of rain water = 9.11E+09 g y^{-1}

Evapotranspiration rate = 73% (Nurudeen, 2011)

Evapotranspired rain water = 0.665 m y^{-1} (*Extensive12*)

Mass of evapotranspired rain water = 6.65E+09 g y^{-1} (*Extensive12*)

Evapotranspired rain water = 0.665 m y^{-1} (*Extensive0*)

Mass of evapotranspired rain water = 6.65E+09 g y^{-1} (*Extensive0*)

Evapotranspired rain water = 0.7957 m y^{-1} (*Intensive50*)

Mass of evapotranspired rain water = 7.96E+09 g y^{-1} (*Intensive50*)

Evapotranspired rain water = 0.7957 m y^{-1} (Intensive100)

Mass of evapotranspired rain water = 7.96E+09 g y^{-1} (*Intensive100*)

Evapotranspired rain water = 0.665 m y^{-1} (*Intercrop20*)

Mass of evapotranspired rain water = 6.65E+09 g y^{-1} (*Intercrop20*)

Free energy of water = (Evapotranspired water, g/ha/yr) (Gibbs free energy per gram of water, J/g)

Gibbs free energy of water = 4.94 J g^{-1} (Odum, 1996)

Energy of evapotranspired water = (6.65E+09)(4.94) = 3.29E+10 J ha^{-1} y^{-1} (*Extensive0*)

= (6.65E+09)(4.94) = 3.29E+10 J ha^{-1} y^{-1} (*Extensive12*)

= (6.65E+09)(4.94) = 3.29E+10 J ha^{-1} y^{-1} (*Intercrop20*)

= (7.96E+09)(4.94) = 3.93E+10 J ha^{-1} y^{-1} (*Intensive50*)

= (7.96E+09)(4.94) = 3.93E+10 J ha^{-1} y^{-1} (*Intensive100*)

UEV = 7.00E+03 sej J^{-1}

5 **Topsoil, soil erosion**:

Area = 1.00E+04 m^2 (normalized to 1ha)

Rate of erosion = 1.29E+01 g m^{-2} y^{-1} (Badmos et al., 2015)

Net loss of topsoil = (farmed area)(rate of erosion)

= (1.00E+04)(1.29E+01) = 1.29E+05g m^{-2} y^{-1} (*Extensive0*)

= (1.00E+04)(1.29E+01) = 1.29E+05g m^{-2} y^{-1} (*Extensive12*)

= (1.00E+04)(6.45E+00) = 6.45E+04g m^{-2} y^{-1} (*Intercrop20*)

= (1.00E+04)(1.29E+01) = 1.29E+05g m^{-2} y^{-1} (*Intensive50*)

= (1.00E+04)(1.29E+01) = 1.29E+05g m^{-2} y^{-1} (*Intensive100*)

Average % of organic matter in soil (w.m.) = 0.0129 (Amegashie, 2009)

Organic matter in topsoil used up = (total mass of eroded topsoil)(% of organic matter)

= (1.29E+05)(0.0129) = 1.66E+03 g ha^{-1} y^{-1} (*Extensive0*)

= (1.29E+05)(0.0129) = 1.66E+03 g ha^{-1} y^{-1} (*Extensive12*)

= (6.45E+04)(0.0129) = 8.30E+02 g ha^{-1} y^{-1} (*Intercrop20*)

= (1.29E+05)(0.0129) = 1.66E+03 g ha^{-1} y^{-1} (*Intensive50*)

= (1.29E+05)(0.0129) = 1.66E+03 g ha^{-1} y^{-1} (*Intensive100*)

Water content in organic matter = 4.00E-05 (Dawidson & Nilsson, 2000)

Dry organic matter lost in the erosion (d.m.) = 1.66E+03 g ha^{-1} y^{-1} (*Extensive0*)

= 1.66E+03 g ha^{-1} y^{-1} (*Extensive12*)

= 8.30E+02 g ha^{-1} y^{-1} (*Intercrop20*)

= 1.66E+03 g ha^{-1} y^{-1} (*Intensive50*)

= 1.66E+03 g ha^{-1} y^{-1} (*Intensive100*)

Energy content of dry organic matter = 5.00 kcal/g d.m.

Energy loss due to erosion = (loss of dry organic matter)(5kcal)(4186J/kcal)

= (1.66E+03)(5)(4186J) = 3.49E+07 J (*Extensive0*)

= (1.66E+03)(5)(4186J) = 3.49E+07 J (*Extensive12*)

= (8.30E+02)(5)(4186J) = 1.74E+07 J (*Intercrop20*)

= (1.66E+03)(5)(4186J) = 3.49E+07 J (*Intensive50*)

= (1.66E+03)(5)(4186J) = 3.49E+07 J (*Intensive100*)

UEV = 5.61E+04 sej J^{-1}

6 **NPK/urea**:

Area = 1.00E+04 m^{2} (normalized to 1ha)

Quantity of NPK / urea applied = 0kg ha^{-1} y^{-1} = 0.00E+00 g ha^{-1} y^{-1} (*Extensive0*)

= 12 kg ha^{-1} y^{-1} = 1.20E+04 g ha^{-1} y^{-1} (*Extensive12*)

= 20 kg ha^{-1} y^{-1} = 2.00E+04 g ha^{-1} y^{-1} (*Intercrop20*)

= 50 kg ha^{-1} y^{-1} = 5.00E+04 g ha^{-1} y^{-1} (*Intensive50*)

= 100 kg ha^{-1} y^{-1} = 1.00E+05 g ha^{-1} y^{-1} (*Intensive100*)

Unit price of urea fertilizer = 2.10E+00 Gh¢/kg

Unit price of NPK fertilizer = 2.30E+00 Gh¢/kg

Cost of NPK/urea = 0 (2.10E+00) = 0 Gh¢/yr (*Extensive0*)

= 12 (2.30E+00) = 2:76E+01 Gh¢/yr (*Extensive12*)

= 20 (2.10E+00) = 4.20E+01 Gh¢/yr (*Intensive20*)

= 50 (2.10E+009 = 1:05E+02 Gh¢/yr (*Intensive50*)

= 100 (2.10E+00) = 2.10E+02 Gh¢/yr (*Intensive100*)

UEV = 1.02E+10 sej g^{-1} (NPK

= 5.85E+09 sej g^{-1} (urea)

7 Animal labor:

Area: 1.00E+04 m^{2} (normalized to 1ha)

Total time to plow = 2.40E+01hr/yr

UEV = 1.39E+12 sej h^{-1} (this study)

8 **Maize seeds**

Area: 1.00E+04 m^2 (normalized to 1ha)

Mass of maize seed sown (kg) = 1.60E+01 kg (estimate from inventory data)

Mass of maize seed sown (g) = 1.60E+04 g (*Extensive0*)

= 1.60E+04 g (*Extensive12*)

=8.00E+03 g (*Intercrop20*)

= 1.60E+04 g (*Intensive50*)

= 1.60E+04 g (*Intensive100*)

Energy content of seeds = 1.47E+04 J g^{-1} (Pimentel & Pimentel, 1980)

Total energy content of sown seeds = (mass of sworn seeds, g)(energy content of maize seed)

= (1.60E+04)(1.47E+04) = 2.35E+08 J (*Extensive0*)

= (1.60E+04)(1.47E+04) = 2.35E+08 J (*Extensive12*)

= (8.00E+03)(1.47E+04) = 1.18E+08 J (*Intercrop20*)

= (1.60E+04)(1.47E+04) = 2.35E+08 J (*Intensive50*)

= (1.60E+04)(1.47E+04) = 2.35E+08 J (*Intensive100*)

Unit cost of seeds = 1.00E+00 Gh¢/kg

Total cost of seeds = (mass of seeds sown)(unit cost)

= (1.60E+01)(1.00E+00)= 1.60E+01 Gh¢/yr (*Extensive0*)

= (1.60E+01)(1.00E+00)= 1.60E+01 Gh¢/yr (*Extensive12*)

= (8.00E+00)(1.00E+00)= 8.00E+00 Gh¢/yr (*Intercrop20*)

= (1.60E+01)(1.00E+00)= 1.60E+01 Gh¢/yr (*Intensive50*)

= (1.60E+01)(1.00E+00)= 1.60E+01 Gh¢/yr (*Intensive100*)

UEV = 5.12E+08 sej J^{-1}

9 **Human labor**

Area: 1.00E+04 m^2 (normalized to 1ha)

Fraction of labor accounted in farm work days = 4.85E+01 days /ha y^{-1} (*Extensive0*)

= 5.25E+01 days /ha y^{-1} (*Extensive12*)

= 3.90E+01 days /ha y^{-1} (*Intercrop20*)

= 6.75E+01 days /ha y^{-1} (*Intensive50*)

= 7.05E+01 days /ha y^{-1} (*Intensive100*)

Daily wage for farm work in the locality = 7.00E+01 Gh¢/dy

Cost of labor = 7.00E+01(4.85E+01) = 3.40E+03 Gh¢/yr (*Extensive0*)

= 7.00E+01(5.25E+01) = 3.68E+03 Gh¢/yr (*Extensive12*)

= 7.00E+01(3.90E+01) = 2:73E+03 Gh¢/yr (*Intercrop20*)

= 7.00E+01(6.75E+01) = 4:73E+03 Gh¢/yr (*Intensive50*)

= 7.00E+01(7.05E+01) = 4:94E+03 Gh¢/yr (*Intensive100*)

UEV = 1:30E+12 sej Gh¢$^{-1}$

10 **Services**

Area: 1.00E+04 m^2 (normalized to 1ha)

Services for seeds (purchase of seeds

Services for fertilizer (purchase cost)

Services for draft animals (forage, water, others)

Services for irrigation using surface water (purchase & annual maintenance solar water pump 1.5 hp cost) = 1.00E+03 (*Intensive50* & *Intensive100*) (Dey and Avumegah, 2016)

Total of services = (seeds services)+(fertilizer services)+(draft animals services)

= (1.60E+01)+(0.00E+00)+(4.98E+02) = 5.14E+02 Gh¢ y^{-1} (*Extensive0*)

= (1.60E+01)+(2.76E+01)+(4.98E+02) = 5.41E+02Gh¢ y^{-1} (*Extensive12*)

= (8.00E+00)+(4.20E+01)+(9.98E+02) = 5.48E+02 Gh¢ y^{-1} (*Intercrop20*)

=(seeds services)+(fertilizer services)+(draft animals services)+(irrigation services)

= (1.60E+01)+(1.05E+02)+(4.98E+02)+(1.00E+03) = 9.16E+02 Gh¢ y^{-1} (*Intensive50*)

= (1.60E+01)+(2.10E+02)+(4.98E+02)+(1.00E+03) = 9.88E+02 Gh¢ y^{-1} (*Intensive100*)

UEV = 1.30E+12 sej Gh¢$^{-1}$

11 **Grains**

Area: 1.00E+04 m^2 (normalized to 1ha)

Estimated mass of maize grain harvested = 1.17E+06 g y^{-1} (*Extensive0*)

= 1.20E+06 g y^{-1} (*Extensive12*)

= 1.88E+06 g y^{-1} (*Intercrop20*)

= 2.27E+06 g y^{-1} (*Intensive50*)

= 2.81E+06 g y^{-1} (*Intensive100*)

Estimated moisture content in maize grain = 0.20 (Aggrey, 2015)

Estimated mass of maize grain (dry matter) = 9.36E+05 g y^{-1} (*Extensive0*)

= 9.60E+05 g y^{-1} (*Extensive12*)

= 1.50E+06 g y^{-1} (*Intercrop20*)

= 2.20E+06 g y^{-1} (*Intensive50*)

= 2.25E+06 g y^{-1} (*Intensive100*)

Estimated mass of mass grain (d.m. in kg) = 9.36E+02 kg y^{-1} (*Extensive0*)

= 9.60E+02 kg y^{-1} (*Extensive12*)

= 1.51E+03 kg y^{-1} (*Intercrop20*)

= 2.20E+03 kg y^{-1} (*Intensive50*)

= 2.25E+03 kg y^{-1} (*Intensive100*)

Energy content of maize grain = 1.47E+04 J g^{-1} (Pimentel and Pimentel, 1980)

Energy of grain yield = (grain mass, d.m. g)(energy content)

= (9.36E+05)(1.47E+04) = 1.38E+10 J y^{-1} (*Extensive0*)

= (9.60E+05)(1.47E+04) = 1.41E+10 J y^{-1} (*Extensive12*)

= (1.50E+06)(1.47E+04) = 2.22E+10 J y^{-1} (*Intercrop20*)

= (2.20E+06)(1.47E+04) = 3.23E+10 J y^{-1} (*Intensive50*)

= (2.25E+06)(1.47E+04) = 3.30E+10 J y^{-1} (*Intensive100*)

UEV = 5.12E+08 sej J^{-1}

12 **Residue (stover)**

Area: 1.00E+04 m^2 (normalized to 1ha)

Grain yield (d.m. ton y^{-1}) = 9.36E-01 ton y^{-1} (*Extensive0*)

= 9.60E-01 ton y^{-1} (*Extensive12*)

= 1.50E+00 ton y^{-1} (*Intercrop20*)

= 2.20E+00 ton y^{-1} (*Intensive50*)

= 2.25E+00 ton y^{-1} (*Intensive100*)

Grain yield (d.m. g y^{-1}) = 9.36E+05 g y^{-1} (*Extensive0*)

= 9.60E+05 g y^{-1} (*Extensive12*)

= 1.50E+06 g y^{-1} (*Intercrop20*)

= 2.20E+06 g y^{-1} (*Intensive50*)

= 2.25E+06 g y^{-1} (*Intensive100*)

Estimated stover yield (d.m. ton y^{-1}) = 8.76E-01 ton y^{-1} (*Extensive0*)

= 8.99E-01 $tony^{-1}$ (*Extensive12*)

= 1.65E+00 ton y^{-1} (*Intercrop20*)

= 2.06E+00 ton y^{-1} (*Intensive50*)

= 2.11E+00 ton y^{-1} (*Intensive100*)

Estimated stover yield (d.m g y^{-1}) = 8.76E+05 g y^{-1} (*Extensive0*)

= 8.99E+05 g y^{-1} (*Extensive12*)

= 1.41E+06 g y^{-1} (*Intercrop20*)

= 2.06E+06 g y^{-1} (*Intensive50*)

= 2.11E+06 g y^{-1} (*Intensive100*)

Table 14. Specifications of the OSDEA model

Model Name	relative technical efficiency of maize production in small-scale land use systems
Model Type	CCT_I
Model Orientation	Input Oriented
Model Efficiency Type	Technical
Model RTS	Constant
Model Description	The Charnes Cooper and Rhodes (CCR)

Appendix C: Assessment of RUE & sustainability indicators

Efficiency assessment *($UEV_R \equiv EcoERU$, $UEV_E \equiv EcoEEU$)*

Extensive0

$$EcoERU_{\left(\substack{without\\ L\&S}\right)} = \frac{2.73E+14}{9.36E+05} = 2.92E+08$$

$$EcoERU_{\left(\substack{with\\ L\&S}\right)} = \frac{5.35E+15}{9.36E+05} = 5.72E+09$$

$$EcoEEU_{\left(\substack{without\\ L\&S}\right)} = \frac{2.73E+14}{9.36E+05(15000)} = 1.95E+04$$

$$EcoEEU_{\left(\substack{with\\ L\&S}\right)} = \frac{5.35E+15}{9.36E+05(15000)} = 3.81E+05$$

Extensive12

$$EcoERU_{\left(\substack{without\\ L\&S}\right)} = \frac{3.96E+14}{9.60E+05} = 4.12E+08$$

$$EcoERU_{(with\ L\&S)} = \frac{5.87E + 15}{9.60E + 05} = 6.12E + 09$$

$$EcoEEU_{(without\ L\&S)} = \frac{3.96E + 14}{9.60E + 05(15000)} = 2.75E + 04$$

$$EcoEEU_{(with\ L\&S)} = \frac{5.87E + 15}{9.60E + 05(15000)} = 4.08E + 05$$

Intercrop20

$$EcoERU_{(without\ L\&S)} = \frac{3.85E + 14}{1.50E + 06} = 2.56E + 08$$

$$EcoERU_{(with\ L\&S)} = \frac{4.64E + 15}{1.50E + 06} = 3.09E + 09$$

$$EcoEEU_{(without\ L\&S)} = \frac{3.85E + 14}{1.50E + 06(15000)} = 1.71E + 04$$

$$EcoEEU_{(with\ L\&S)} = \frac{4.64E + 15}{1.50E + 06(15000)} = 2.06E + 05$$

Intensive50

$$EcoERU_{(without\ L\&S)} = \frac{6.11E + 14}{2.20E + 06} = 2.78E + 08$$

$$EcoERU_{(with\ L\&S)} = \frac{8.85E + 15}{2.20E + 06} = 4.02E + 09$$

$$EcoEEU_{(without\ L\&S)} = \frac{6.11E + 14}{2.20E + 06(15000)} = 1.85E + 04$$

$$EcoEEU_{(with\ L\&S)} = \frac{8.85E + 15}{2.20E + 06(15000)} = 2.68E + 05$$

Intensive100

$$EcoERU_{(without\ L\&S)} = \frac{9.04E + 14}{2.20E + 06} = 4.02E + 08$$

$$EcoERU_{(with\ L\&S)} = \frac{9.55E + 15}{2.20E + 06} = 4.25E + 09$$

$$EcoEEU_{(without\ L\&S)} = \frac{9.04E + 14}{2.25E + 06(15000)} = 2.68E + 04$$

$$EcoEEU_{(with\ L\&S)} = \frac{9.55E + 15}{2.25E + 06(15000)} = 2.83E + 05$$

Sustainability assessment

***Extensive0* (without L&S)**

$$Total\,emergy\,U = 2.30\text{E}+14 + 1.96\text{E}+12 + 0.00\text{E}+00 + 3.32\text{E}+13 + 8.19\text{E}+12 = 2.73\text{E}+14\,\text{se}$$

$$EYR = \frac{(2.30\text{E}+14 + 1.96\text{E}+12 + 0.00\text{E}+00 + 3.32\text{E}+13 + 8.19\text{E}+12)}{3.32\text{E}+13 + 8.19\text{E}+12} = 6.60$$

$$ELR = \frac{(1.96\text{E}+12 + 0.00\text{E}+00 + 3.32\text{E}+13 + 8.19\text{E}+12)}{2.30\text{E}+14} = 0.19$$

$$ESI = \frac{6.60}{0.19} = 34.97$$

$$\%REN = \frac{1}{(1 + 0.19)} = 0.84$$

***Ext.0* (with L&S)**

$$Total\,emergy\,U = 2.30\text{E}+14 + 1.96\text{E}+12 + 0.00\text{E}+00 + 3.32\text{E}+13 + 8.19\text{E}+12 + 4.41\text{E}+15 + 6.67\text{E}+14 = 5.35\text{E}+15\,\text{se}$$

$$EYR = \frac{(2.30\text{E}+14 + 1.96\text{E}+12 + 0.00\text{E}+00 + 3.32\text{E}+13 + 8.19\text{E}+12 + 4.41\text{E}+15 + 6.67\text{E}+14)}{3.32\text{E}+13 + 8.19\text{E}+12 + 4.41\text{E}+15 + 6.67\text{E}+14} = 1.05$$

$$ELR = \frac{(1.96\text{E}+12 + 0.00\text{E}+00 + 3.32\text{E}+13 + 8.19\text{E}+12 + 4.41\text{E}+15 + 6.67\text{E}+14)}{2.30\text{E}+14} = 22.27$$

$$ESI = \frac{1.05}{22.27} = 0.05$$

$$\%REN = \frac{1}{(1 + 22.27)} = 0.04$$

***Extensive12* (without L&S)**

$$Total\,emergy\,U = 2.30\text{E}+14 + 1.96\text{E}+12 + 1.22\text{E}+14 + 3.32\text{E}+13 + 8.19\text{E}+12 = 3.96\text{E}+14\,\text{se}$$

$$EYR = \frac{(2.30\text{E}+14 + 1.96\text{E}+12 + 1.22\text{E}+14 + 3.32\text{E}+13 + 8.19\text{E}+12)}{1.22\text{E}+14 + 3.32\text{E}+13 + 8.19\text{E}+12} = 2.42$$

$$ELR = \frac{(1.96\text{E}+12 + 1.22\text{E}+14 + 3.32\text{E}+13 + 8.19\text{E}+12)}{2.30\text{E}+14} = 0.72$$

$$ESI = \frac{2.42}{0.72} = 3.35$$

$$\%REN = \frac{1}{(1 + 0.72)} = 0.58$$

***Ext.12* (with L&S)**

$$Total\,emergy\,U = 2.30\text{E}+14 + 1.96\text{E}+12 + 1.22\text{E}+14 + 3.32\text{E}+13 + 8.19\text{E}+12 + 4.77\text{E}+15 + 7.03\text{E}+14 = 5.87\text{E}+15\,\text{se}$$

$$EYR = \frac{(2.30\text{E}+14 + 1.96\text{E}+12 + 1.22\text{E}+14 + 3.32\text{E}+13 + 8.19\text{E}+12 + 4.77\text{E}+15 + 7.03\text{E}+14)}{1.22\text{E}+14 + 3.32\text{E}+13 + 8.19\text{E}+12 + 4.77\text{E}+15 + 7.03\text{E}+14} = 1.05$$

$$ELR = \frac{(1.96\text{E}+12 + 1.22\text{E}+14 + 3.32\text{E}+13 + 8.19\text{E}+12 + 4.77\text{E}+15 + 7.03\text{E}+14)}{2.30\text{E}+14} = 24.54$$

$$ESI = \frac{1.05}{24.54} = 0.04$$

$$\%REN = \frac{1}{(1 + 24.54)} = 0.04$$

Intercrop20 **(without L&S)**

$$Total emergy U = 2.30E+14 + 4.89E+11 + 1.17E+14 + 3.32E+13 + 4.10E+12 = 3.85E+14 se$$

$$EYR = \frac{(2.30E+14 + 4.89E+11 + 1.17E+14 + 3.32E+13 + 4.10E+12)}{1.17E+14 + 3.32E+13 + 4.10E+12} = 2.49$$

$$ELR = \frac{(4.89E+11 + 1.17E+14 + 3.32E+13 + 4.10E+12)}{2.30E+14} = 0.67$$

$$ESI = \frac{2.49}{0.67} = 3.70$$

$$\%REN = \frac{1}{(1 + 0.67)} = 0.60$$

Inter.20 **(with L&S)**

$$Total emergy U = 2.30E+14 + 4.89E+11 + 1.17E+14 + 3.32E+13 + 4.10E+12 + 3.55E+15 + 7.11E+14 = 4.64E+15 se$$

$$EYR = \frac{(2.30E+14 + 4.89E+11 + 1.17E+14 + 3.32E+13 + 4.10E+12 + 3.55E+15 + 7.11E+14)}{1.17E+14 + 3.32E+13 + 4.10E+12 + 3.55E+15 + 7.11E+14} = 1.05$$

$$ELR = \frac{(4.89E+11 + 1.17E+14 + 3.32E+13 + 4.10E+12 + 3.55E+15 + 7.11E+14)}{2.30E+14} = 19.19$$

$$ESI = \frac{1.05}{19.19} = 0.05$$

$$\%REN = \frac{1}{(1 + 19.19)} = 0.05$$

Intensive50 **(without L&S)**

$$Total emergy U = 2.75E+14 + 1.96E+12 + 2.93E+14 + 3.32E+13 + 8.19E+12 = 6.11E+14 se$$

$$EYR = \frac{(2.75E+14 + 1.96E+12 + 2.93E+14 + 3.32E+13 + 8.19E+12)}{2.93E+14 + 3.32E+13 + 8.19E+12} = 1.83$$

$$ELR = \frac{(1.96E+12 + 2.93E+14 + 3.32E+13 + 8.19E+12)}{2.75E+14} = 1.22$$

$$ESI = \frac{1.83}{1.22} = 1.50$$

$$\%REN = \frac{1}{(1 + 1.22)} = 0.45$$

Inten.50 **(with L&S)**

$$Total emergy\,U = 2.75E{+}14{+}1.96E{+}12{+}2.93E{+}14{+}3.32E{+}13{+}8.19E{+}12{+}6.14E{+}15{+}2.10E{+}15{=}8.85E{+}15 sej$$

$$EYR = \frac{(2.75E+14+1.96E+12+2.93E+14+3.32E+13+8.19E+12+6.14E+15+2.10E+15)}{2.93E+14+3.32E+13+8.19E+12+6.14E+15+2.10E+15} = 1.03$$

$$ELR = \frac{(1.96E+12+2.93E+14+3.32E+13+8.19E+12+6.14E+15+2.10E+15)}{2.75E+14} = 31.18$$

$$ESI = \frac{1.03}{31.18} = 0.03$$

$$\% REN = \frac{1}{(1+31.18)} = 0.03$$

Intensive100 **(without L&S)**

$$Total emergy\,U = 2.75E{+}14{+}1.96E{+}12{+}5.85E{+}14{+}3.32E{+}13{+}8.19E{+}12{=}9.04E{+}14 sej$$

$$EYR = \frac{(2.75E+14+1.96E+12+5.85E+14+3.32E+13+8.19E+12)}{5.85E+14+3.32E+13+8.19E+12} = 1.44$$

$$ELR = \frac{(1.96E+12+5.85E+14+3.32E+13+8.19E+12)}{2.75E+14} = 2.28$$

$$ESI = \frac{1.44}{2.28} = 0.63$$

$$\% REN = \frac{1}{(1+2.28)} = 0.30$$

Inten.100 **(with L&S)**

$$Total emergy\,U = 2.75E{+}14{+}1.96E{+}12{+}5.85E{+}14{+}3.32E{+}13{+}8.19E{+}12{+}6.41E{+}15{+}2.24E{+}15{=}9.55E{+}15 sej$$

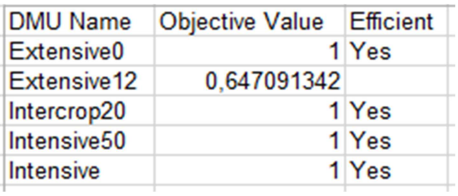
$$EYR = \frac{(2.75E+14+1.96E+12+5.85E+14+3.32E+13+8.19E+12+6.41E+15+2.24E+15)}{2.93E+14+3.32E+13+8.19E+12+6.14E+15+2.10E+15+6.41E+15+2.24E+15} = 1.03$$

$$ELR = \frac{(1.96E+12+5.85E+14+3.32E+13+8.19E+12+6.41E+15+2.24E+15)}{2.75E+14} = 33.73$$

$$ESI = \frac{1.03}{33.73} = 0.03$$

$$\% REN = \frac{1}{(1+33.73)} = 0.03$$

Table 15. Relative Technical Efficiency scores



DMU Name	Objective Value	Efficient
Extensive0	1	Yes
Extensive12	0,647091342	
Intercrop20	1	Yes
Intensive50	1	Yes
Intensive	1	Yes

Source: calculated using OSDEA

Appendix D: Assessment of carbon footprint

Table 16. Carbon budget

Carbon (C) source / stock	**Conversion factor**	**Unit**	***Extensive0***	***Extensive12***	***Intercrop20***	***Intensive50***	***Intensive100***	**Unit of emitted C**	**Ref.**
Fertilizer/urea dosage			0	12	20	50	100	kg/ha	[this study]
NPK (15 15 15)	12.32	kg CO_2 e/kg	/	0.148	/	/	/	ton CO_2 e/ha/yr	[a]
Urea (CH_4N_2O)	16.34	kg CO_2 e/kg	0	/	0.327	0.817	1.634	ton CO_2 e/ha/yr	[a]
Shipment NPK/urea	8	g CO_2/ton-km							ECTA, 2011
Morocco - Ghana	2389 ≈ 424.43	nautical mile ≈ km	/	0.00043	/	/	/	ton CO_2 e/ha/yr	[b]
Turkey - Ghana	4569 ≈ 8461.79	nautical mile ≈ km	0	/	0.0014	0.0034	0.0068	ton CO_2 e/ha/yr	[b]
Transport NPK/urea by road	832.9	(Tkd. – Bolga.) km							[c]
Road transport	62	g CO_2/ton-km	0	0.00062	0.0010	0.0023	0.00516		ECTA, 2011
Applied manure		kg/ha/yr	29.25	29.25	29.25	0	0		[this study]
Composting	368.4	kg CO_2 e/Mg	0.10776	0.10776	0.10776	0	0	ton CO_2 e/ha/yr	Hao 2004
C loss after plowing	4	kg C e/ha	0.004	0.004	0.004	0.004	0.004	ton C e/ha/yr	Lal, 2004
C due to human labor	14.4 , 0.36	MJ/day, kg CO_2/MJ	0.251	0.272	0.202	0.35	0.365	ton CO_2 e/ha/yr	[d]
Total GHG emissions			**0.266**	**0.436**	**0.546**	**1.177**	**2.015**	ton CO_2 e/ha/yr	
C stock in above ground biomass	43.6	%							[e]
Vegetative biomass (residue)			0.88	0.899	1.17	2.06	2.11	ton/ha/yr	[this study]
Carbon stock in residue			0.384	0.392	0.510	0.898	0.920	ton C	
Grain biomass			0.93	0.96	1.5	2.2	2.25	ton/ha/yr	[this study]
Carbon stock in grain			0.405	0.419	0.654	0.959	0.981	ton C	
Total Carbon Stocks			**0.789**	**0.811**	**1.164**	**1.857**	**1.901**	ton C/ha/yr	
Carbon balance			**- 0.523**	**- 0.374**	**- 0.618**	**-0.680**	**0.114**	ton CO_2 e/ha/yr	

Carbon balance / ton grain			**- 0.563**	**- 0.390**	**- 0.412**	**-0.309**	**0.051**	tonCO$_2$e/ton grain	
Index of sustainability (I_s)			**2.97**	**1.86**	**2.13**	**1.58**	**0.94**		

[a] Fertilizers Europe https://www.fertilizerseurope.com/fileadmin/user_upload/publications/agriculture_publications/carbon_footprint_web_V4.pdf, [b] https://sea-distances.org/, [c] https://www.google.com/maps/dir/Sekondi-Takoradi,+Ghana/Bolgatanga, [d] Bleiberg et al., (1980); Brun et al., (1981); Houshyaret al., (2015), [e] Latshaw and Miller, 1924.

1 **Carbon emission from production + use on-farm of NKP (15 15 15)/urea**

= (mass of NPK/urea,) (factor, ton CO_2e/kg) = 0 (0.01634) = 0 ton/CO_2e/ha (*Extensive0*)

= 12 (0.01232) = 0.148 ton/CO_2e/ha (*Extensive12*)

= 20 (0.01634) = 0.327 ton/CO_2e/ha (*Itercrop20*)

= 50 (0.01634) = 0.817 ton/CO_2e/ha (*Intensive50*)

= 100 (0.01634) = 1.634 ton/CO_2e/ha (*Intensive100*)

2 Carbon emission from shipment of NKP (15 15 15)/urea

= (mass of NPK/urea) (emission factor) (sea distance, km) = 0 (8) (8461.79) = 0 ton/CO_2e/ha (*Extensive0*)

= 0.012 (8) (4424.43) = 0.00043 ton/CO_2e/ha (*Extensive12*)

= 0.020 (8) (8461.79) = 0.0014 ton/CO_2e/ha (*Intercrop20*)

= 0.020 (8) (8461.79) = 0.0034 ton/CO_2e/ha (*Intensive50*)

= 0.1(8) (8461.79) = 0.0068 ton/CO_2e/ha (*Intensive100*)

3 Carbon emission from road transportation of NKP (15 15 15)/urea (from Takoradi to Bolgatanga)

= (mass of NPK/urea) (emission factor) (road distance, km) = 0 (62) (832.9) = 0 ton/CO_2e/ha (*Extensive0*)

= 0.012 (62) (832.9) = 0.00062 ton/CO_2e/ha (*Extensive12*)

= 0.020 (62) (832.9) = 0.0010 ton/CO_2e/ha (*Intercrop20*)

= 0.020 (62) (832.9) = 0.0023 ton/CO_2e/ha (*Intensive50*)

= 0.1(62) (832.9) = 0.00516 ton/CO_2e/ha (*Intensive100*)

4 Carbon emission from compose/manure

= (manure applied) (emission factor) = 29.25 (0.003684) = 0.10776 ton/CO_2e/ha (*Extensive0*)

= 29.25 (0.003684) = 0.10776 ton/CO_2e/ha (*Extensive12*)

= 29.25 (0.003684) = 0.10776 ton/CO_2e/ha (*Inercrop20*)

= 0 (0.003684) = 0 ton/CO_2e/ha (*Intensive50*)

= 0 (0.003684) = 0 ton/CO_2e/ha (*Intensive100*)

5 Carbon loss due to plowing and cultivation of soil

= (area, ha) (emission factor) = 1 (0.004) = 0.004 ton/CO_2e/ha (*Extensive0*)

= 1 (0.004) = 0.004 ton/CO_2e/ha (*Extensive12*)

= 1 (0.004) = 0.004 ton/CO_2e/ha (*Intercrop20*)

= 1 (0.004) = 0.004 ton/CO_2e/ha (*Intensive50*)

= 1 (0.004) = 0.004 ton/CO_2e/ha (*Intensive100*)

6 Emission from human labor

= [(time, days) (14.4 MJ/day) (0.36 kg CO_2/MJ)]/1000 = [48.5 (14.4) (0.36)]/1000 = 0.251ton/CO_2e/ha (*Extensive0*)

= [52.5 (14.4) (0.36)]/1000 = 0.272 ton/CO_2e/ha (*Extensive12*)

= [39 (14.4) (0.36)]/1000 = 0.202 ton/CO_2e/ha (*Intercrop20*)

= [67.5 (14.4) (0.36)]/1000 = 0.35 ton/CO_2e/ha (*Intensive50*)

= [70.5 (14.4) (0.36)]/1000 = 0.365 ton/CO_2e/ha (*Intensive100*)

Total GHG emission = [emission from NPK/urea prod. & use] + [emission from shipment of NPK/urea] + [emission from composting] + [emission from plowing & cultivation of soil] + [emission from transportation of NPK/urea by road] + [emission from labor]

= 0 + 0 + 0+ 0.10776 + 0.004 + 0.251 = 0.266 ton CO_2 e/ha (*Extensive0*)

= 0.148 + 0.00043 + 0.00062 + 0.10776 + 0.004 + 0.272 = 0.436 ton CO_2 e/ha (*Extensive12*)

= 0.327 + 0.0014 + 0.0010 + 0.10776 +0.004 + 0.202 = 0.546 ton CO_2 e/ha (*Intercrop20*)

= 0.817 + 0.0034 + 0.0023 + 0 +0.004 + 0.35 = 1.177 ton CO_2 e/ha (*Intensive50*)

= 1.634 + 0.0068 + 0.00516 + 0+ 0.004 + 0.365 = 2.015 ton CO_2 e/ha (*Intensive100*)

Carbon stock in the above-ground biomass

= carbon stock in residue + carbon stock in gain

= carbon stock factor (dry weight of above-ground residue + grain)

= 0.436 (0.88 + 0.93) = 0.789 ton CO_2 e (*Extensive0*)

= 0.436 (0.899 + 0.96) = 0.812 ton CO_2 e (*Extensive12*)

= 0.436 (1.17 + 1.5) = 1.164 ton CO_2 e (*Intercrop20*)

= 0.436 (2.06 + 2.2) = 1.857 ton CO_2 e (*Intensive50*)

= 0.436 (2.11 + 2.25) = 1.901 ton CO_2 e (*Intensive100*)

Carbon balance

= Total GHG emission – Carbon stock in above-ground biomass

= 0.266 – 0.789 = -0.523 ton CO_2 e/ha (*Extensive0*)

= 0.436 - 0.8120 = -0.375 ton C e/ha (*Extensive12*)

= 0.546 - 1.164 = -0.618 ton CO_2 e/ha (*Intercrop20*)

= 1.177 - 1.857 = -0.680 ton ton CO_2 e/ha (*Intensive50*)

= 2.015 - 1.901 = 0.114 ton ton CO_2 e/ha (*Intensive100*)

Average C emission from the five scenarios

= (C emission from *Exten.0* + C emission from *Exten.12* + C emission from *Inter.20* + C emission from *Inten.50* + C emission from *Inten.100*) / 5

= (0.266 + 0.436 + 0.546 + 1.177 + 2.015) /5 = 0.888 ton CO_2 e/ha/yr

Appendix E: Production data for Bolgatanga and Bongo

Table 17. Maize yield for Bolgatanga and Bongo for the years 2003 - 2011

Yield (ton/ha)	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**Mean**
Bolgatanga	2.02	0.86	1.43	1.28	0.42	1.88	0.17	2.2	2.29	1.2
Bongo	/	/	/	/	0.62	1.32	0.04	1.2	1.06	

Source: Statistics, Research and Information Directorate (SRID) - Ministry of Food and Agriculture (MoFA) Ghana.

Appendix F: Trade-off calculations

1a Resource saving (without L&S)

= Total Emergy (U) for *Intensive100* – Total Emergy (U) for the various practices

= 0.904 – 0.273 = 0.631 E+15 sej/ha/yr, (0.631 E+15/0.904 E+15) (100) = 69.69% (*Extensive0*)

= 0.904 – 0.396 = 0.508 E+15 sej/ha/yr, (0.508 E+15/0.904 E+15) (100) = 56.19% (*Extensive12*)

= 0.904 - 0.385 = 0.519 E+15 sej/ha/yr, (0.519 E+15/0.904 E+15) (100) = 57.41% (*Intercrop20*)

= 0.904 – 0.611 = 0.293 E+15 sej/ha/yr, (0.293 E+15/0.904 E+15) (100) = 32.41% (*Intensive50*)

= 0.904 – 0.904 = 0.00 E+15 sej/ha/yr, (0.00 E+15/0.904 E+15) (100) = 0.00% (*Intensive100*)

1b Resource saving (with L&S)

= Total Emergy (U) for *Intensive100* – Total Emergy (U) for the various practices

= 9.55 – 5.35 = +4.2 E+15 sej/ha/yr, (4.2 E+15/9.55 E+15) (100) = 43.98% (*Extensive0*)

= 9.55 – 5.87 = +3.68 E+15 sej/ha/yr, (3.68 E+15/9.55 E+15) (100) = 38.53% (*Extensive12*)

= 9.55 – 4.64 = +4.91 E+15 sej/ha/yr, (4.91 E+15/9.55 E+15) (100) = 51.41% (*Intercrop20*)

= 9.55 – 8.85 = +0.7 E+15 sej/ha/yr, (0.7 E+15/9.55 E+15) (100) = 7.33% (*Intensive50*)

= 9.55 – 9.55 = 0.00 E+15 sej/ha/yr, (0 E+15/9.55 E+15) (100) = 0.00% (*Intensive100*)

2 Carbon saving

= C-balance/ ton grain yield of *Intensive100* – C-balance/ ton grain yield of the various practices

NB: C-balance of Intensive100 was 0.05, C-balance of Extensive0 was -0.56. The absolute interval between 0.051 + 0.563 = 0.614

= -0.56 ton CO_2e/ha/yr, (056/0.614) *(100) = 91.80% (*Extensive0*)

= -0.39 ton CO_2e/ha/yr, (0.39/0.614) *(100) =63.93% (*Extensive12*)

= -0.41 ton CO_2e/ha/yr, (0.41/0.614)* (100) = 67.21% (*Intercrop20*)

= 0.41 ton CO_2e/ha/yr, (0.31/0.614) *(100) = 50.82% (*Intensive50*)

= 0.051 –0.051 = 0.00 ton CO_2e/ha/yr, (0.00/2.015)* (100) = 0.00% (*Intensive100*)

3 Yield gap

= Yield (d.m.) for the various farm practices – Yield (d.m) for *Intensive100*

= 0.93 - 2.25 = -1.32 ton/ha/yr, (1.32/2.25) (100) = 58.67% (*Extensive0*)

= 0.96 - 2.25 = -1.29 ton/ha/yr, (1.29/2.25) (100) = 57.33% (*Extensive12*)

= 1.5 - 2.25 = -0.75 ton/ha/yr, (0.75/2.25) (100) = 33.33% (*Intercrop20*)

= 2.20 - 2.25 = -0.5 ton/ha/yr, (0.5/2.25) (100) = 2.22% (*Intensive50*)

= 2.25 – 2.25 = 0.00 ton/ha/yr, (0.00/2.25) (100) = 0.00% (*Intensive100*)

4 Yield, area cultivated & C emission

For the yield (d.m.) & area cultivated (see, Table 3), C emission (see, Table 16)

= 0.93 ton/ha, 1.0 ha, 0.266 ton CO_2 e (*Extensive0*)

if the yield was 1.50 ton/ha, i.e. the threshold yield at which small-scale maize production is economic & contributes to food security at household level in Ghana, SSA (Scheiterle and Birner, 2018)

then the area cultivated will be = 1.6 ha, & C emission will be = 0.419 CO_2 e (projection from *Extensive0*)

if the yield was 2.25 ton/ha, i.e. equivalent to the yield which was obtained by *Intensive100* (this study)

then the area cultivated will be = 2.4 ha, & C emission will be 0.623 CO_2 e (projection from *Extensive0*)

= 0.96 ton/ha, 1.0 ha, 0.436 ton CO_2 e (*Extensive12*)

= 1.5 ton/ha, 1.0 ha, 0.546 ton CO_2 e (*Intercrop20*)

= 2.20 ton/ha, 1.0 ha, 1.177 ton CO_2 e (*Intensive50*)

= 2.25 ton/ha, 1.0 ha, 2.015 ton CO_2 e (*Intensive100*)

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: