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Maize production and environmental costs: Resource evaluation and strategic land use planning for food security in northern Ghana by means of coupled emergy and data envelopment analysis

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ABSTRACT

This paper applies an integrated methodology which is constituted of the following: (i) the Emergy-Data Envelopment Analysis (EM-DEA), (ii) environmental Cost-Benefit Analysis (CBA), (iii) Value Chain Analysis (VCA), and (iv) Sustainability Balanced Scorecard (SBSC) approaches, -to support multicriteria decision analysis (MCDA) for strategic agricultural land use planning, which could contribute to improve food security in northern Ghana. Five scenarios of land use and resource management practices for maize production were modelled. The business-as-usual scenario was based on primary data, which were collected using semi-structured questionnaires administered to 56 small-scale maize farmers through personal interviews. The dominant land use was characterised by an external input ≤12 kg/ha/yr inorganic fertilizer with/without the addition of manure in rainfed maize systems. The project scenarios were based on APSIM simulations of maize yield response to 0, 20, 50 and 100 kg/ha/yr urea dosages, with/without supplemental irrigation. The scenarios were dubbed as follows: (1) no/low input systems were denoted by *Extensive0, Extensive12*, and *Intercrop20*, and (2) moderate/high input systems were denoted by *Intensive50,* and *Intensive100*. The EM-DEA approach was used to assess the resource use efficiency (RUE) and sustainability in maize production systems, Ghana. The measured RUE and sustainability were used as a proxy for further analyses by applying the environmental CBA and VCA approaches to calculate: (a) the environmental costs of producing maize, i.e. resource use measured as total emergy (U), and (b) benefits from the yielded maize, i.e. (b i) food provision from grain measured in kcal/yr, and (b ii) potential electricity (bioenergy) which could be generated from residue measured in MWh/yr. The information which was derived from the applications of the EM-DEA, CBA and VCA approaches was aggregated by applying the SBSC approach to do a sustainability appraisal of the scenarios. The results show that, when labour and services are included in the assessment of RUE and sustainability, *Intercrop20* and *Intensive50* achieved greater marginal yield, better RUE, sustainability and appraisal score. The same scenarios caused lesser impacts in terms of expansion of area cultivated compared to *Extensive0* and *Extensive12*. Meanwhile the impacts of *Intercrop20* and *Intensive50* in terms of ecotoxicity, emissions, and demand for resources (energy, materials, labour and services) were lesser compared to *Intensive100*. The implications of the various scenarios are discussed. The environmental performance of the scenarios are compared to maize production systems in other developing regions in order to put this study within a broader context. We conclude that, the EM-DEA approach is useful for assessing RUE and sustainability of agricultural production systems at farm and regional scales, as well as in connecting the management planning level and regional development considerations.

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1. Introduction

Land is central to human livelihood, sustenance and development (De Wrachien, 2003; Akram-Lodhi et al., 2007). The rapid growth of global population is a driving force which is increasing the demand for food, fuelwood and other biomass-based products. Arable land is finite, and food security is endangered (Hertel, 2011). Agriculture is the only means to produce more food and other biomass-based products. Hence, agriculture is a dominant form of land use which impacts the environment (SDSN, 2013; Marrison and Larson, 1996; Smith et al., 2014; Pereira, 1993). More land, water, energy and other environmental resources will be required for the production of more food to feed the increasing global population (Hertel, 2011; Pimentel et al., 1997).

Often, difficulties arise when assessing the impacts of land use in developing countries, because data on the concrete management of a piece of land are not readily available or non-existent (Kuemmerle et al., 2013; Musakwa and Van Niekerk, 2013; Zinck and Farshad, 1995). The need to transform agricultural production systems by adapting the land use, such that it could better contribute to improve productivity, while minimising the environmental impacts of agriculture is frequently called for (McIntire, 2014; Nin-Pratt and McBride, 2014). Sustainable land use planning and management could contribute to sustainable agriculture (FAO, 1993; Ziadat et al., 2018), through practices which could meet current and future societal needs for food, fibre, and ecosystem services for healthy lives, and where this is achievable by maximising the net benefits to society when all costs and benefits are taken into consideration (Tilman et al., 2002), as well as using an approach which could ensure proper environmental accounting (Odum, 1996).

Food security is a global development challenge (Godfray et al., 2010; Tilman et al., 2011), which is difficult to measure (Barrett, 2010). It was estimated that 815 million persons globally were food insecure in 2016. Comparative statistics show that about 900 and 777 million persons were food insecure in 2000 and 2015, and the prevalence was 14.9 and 10.9 %, respectively (FAO et al., 2017, 2015). The majority of these cases were reported to have occurred in developing countries (Smith et al., 2000). In sub-Saharan Africa alone, it was estimated that 203.6 and 220 million persons were food insecure in 2000 and 2015, and the prevalence was 30 and 23.2 %, respectively (FAO et al., 2015). Ghana is one of the developing countries situated within the west African sub-region. It was reported that about 1.6 and 1.3 million persons, which correspond to the prevalence of 5.8 and < 5% were undernourished during the period 2008–2010 and 2011–2013, respectively (FAO, 2015). Northern Ghana (herein referring to the following: the Northern, Savannah, North East, Upper West, and Upper East Regions) is vulnerable to food insecurity (Table 1).

This study focuses on the Upper East Region (UER), which is one of the food insecurity hotspots in Ghana (Abane, 2015; Quaye, 2008). As of 2016, the UER was least connected to the national electricity grid (Table 2). The majority were inaccessible to reliable electricity (Sackeyfio, 2018; Guvele et al., 2016). Intuitively, poor access to reliable electricity could be a factor, which is aggravating the risks of food insecurity in the UER, because access to reliable energy (Sola et al., 2016), and in particular electricity is necessary to boost the productive capacity in the agri-food sector (Eshun and Amoako-Tuffour, 2016).

The goal of this study is to apply an integrated methodology to support Multi-Criteria Decision Analysis (MCDA) for strategic agricultural land use planning, while considering maize cropping in northern Ghana. Maize is the most cultivated cereal in Ghana. It is a commodity crop which could better contribute to the food secirity situation in Ghana (Mustapha et al., 2016; Andam et al., 2016; Mangnus and van Westen, 2018), if adequate value could be added throughout the value chain. An integrated analysis is preferable, because it could lead to useful information, which could eventually contribute to efficient use of resources for regional development (Fürst, 2013; Fürst et al., 2013). This paper is composed of five sections. In section 1, an overview of this study is presented. In section 2, the study area is described. Five land use scenarios for maize production are modelled, and the research methods are described as follows: The Emergy and Data Envelopment Analysis methods are aggregated into a framework, and the concept of eco -efficiency is integrated to obtain the Emergy-Data

Table 1
Food insecurity in Ghana, 2009, by region.
Source: adapted after WFP (2009 p.13). See the explanatory note below.

Region	Food insecurity (actual)		Vulnerability to food insecurity (risk)	
	No. of people	% pop.	No. of people	% pop.
Western (rural)[a]	12,000	0.05	93,000	0.40
Central (rural)	39,000	0.17	56,000	0.24
Greater Accra (rural)	7,000	0.03	14,000	0.06
Volta (rural)[b]	44,000	0.19	88,000	0.38
Eastern (rural)	58,000	0.25	116,000	0.50
Ashanti (rural)	162,000	0.70	218,000	0.95
Brong Ahafo (rural)[c]	47,000	0.20	152,000	0.66
Northern (rural)[d]	152,000	0.66	275,000	1.20
Upper East (rural)	126,000	0.55	163,000	0.71
Upper West (rural)	175,000	0.76	69,000	0.30
Accra (urban)	69,000	0.30	158,000	0.69
Others (urban)	297,000	1.29	572,000	2.49
Total	*1,200,000*[e]	*5.15*	*2,007,000*[f]	*8.58*

Note: The population of Ghana in 2009 was about 23 million persons.[1] The total *e* and *f* correspond to the population that were food insecure and at risk in 2008–2009. The number of persons in columns 2 and 4 represent the population which were food insecure and at risk in 2008–2009 by regions, while the % pop. in columns 3 and 4 have been calculated as decimal digits in relation to the population of Ghana in 2009, respectively.

[a] Former Western Region has been split into Western, and Western North Regions (since February 2019).

[b] Former Volta Region has been split into Volta, and Oti Regions (since February 2019).

[c] Former Brong Ahafo Region has been split into Brong Ahafo, Bono East, and Ahafo Regions (since February 2019).

[d] Former Northern Region has been split into Northern, North East, and Savannah Regions (since February 2019).

Table 2
Accessibility to electricity in Ghana, 2016, by region.
Source: Sackeyfio (2018).

Region	Access rate (%)
Greater Accra	96.43
Ashanti	90.48
Central	84.32
Volta [i]	79.09
Eastern	78.56
Western [ii]	78.12
Brong–Ahafo [iii]	75.77
Upper West	71.62
Northern [iv]	54.53
Upper East	51.65
National Average	*80.51*

Note: (i) Former Volta Region is currently Volta and Oti Regions (since February 2019).
(ii) Former Western Region is currently Western and Western North Regions (since February 2019).
(iii) Former Brong Ahafo Region is currently Brong Ahafo, Bono East and Ahafo Regions (since February 2019).
(iv) Former Northern Region is currently Northern, Savannah and North East Regions (since February 2019).

[1] https://www.populationpyramid.net/ghana/2009/ [Retrieved on 04/01/19].

Envelopment Analysis (EM-DEA) approach. The EM-DEA approach is applied to assess the resource use efficiency (RUE) and sustainability of maize production systems in northern Ghana (Mwambo and Fürst, 2019). The measured efficiency and sustainability are used as a proxy to further analyse the costs and benefits, by applying the environmental Cost-Benefit and Value Chain Analysis (CBA & VCA) approaches to calculate: (a) the environmental costs of producing maize, and (b) the benefits from the yielded maize, i.e. (b i) food provision from grain, and (b ii) electricity which could be generated from residue, respectively. The information which was obtained from using the various approaches was aggregated by applying the Sustainability Balanced Scorecard (SBSC) approach to do a sustainability appraisal of the various scenarios of maize production. In section 3, the results are presented in detail. In section 4, the results are discussed to provide a holistic analysis of the scenarios. Furthermore, the environmental performance of the scenarios are compared to similar systems of maize production in other developing regions of the world. Finally, in section 5 the main findings are summarised in the conclusions.

2. Materials and methods

2.1. Study area

The study area is Bolgatanga and Bongo Districts located in the UER, in Ghana (Fig. 1). The UER is one of the 16 administrative regions in the Republic of Ghana (herein referred to as Ghana). The study area is between latitudes 10° 10′ and 10° 15′ N of the equator, and longitudes 0° and 1° 4′ W of the prime meridian. The ecology is a mix of Sudanian and Guinea savannahs, which have been degraded due to the impacts of climatic stress and pressure from agro-pastoral activities. The climate is semi-arid. The annual rainfall is between 800 and 1000 mm, and the distribution is unimodal. The rainy season lasts between April/May and September/October. In recent decades, the rainfall distribution pattern shows increasing variability. Such erratic pattern is influenced by changes in the global climate (Issahaku et al., 2016). The primary economic activity in the area is small-scale agriculture, and it is adversely impacted by changes in climate (Ibn Musah et al., 2018). Much of the production of crops takes place in small-scale and rainfed systems (Månsson, 2011). The major crops cultivated are: guinea corn, millet, maize, sorghum, beans, tomatoes and vegetables. The livestock reared are: goat, sheep, pig, donkey, cattle, and poultry (Adzitey, 2013).

The UER constitutes about 3.7 % of Ghana's land surface area. In 2016, the UER had an estimated population of 1.188.800 inhabitants,[2] and the population density was between 103 and 118 inhabitants[3] per square kilometre (MOFA, 2016). Meanwhile agricultural productivity in rainfed systems is increasing marginally (Mohan and Matsuda, 2013), and assuming the rate of population growth is 1.2 %, this implies that in 2040 the population of the UER could approximate to 2.8 million inhabitants.[4] The risks of food insecurity could become greater if the population grows faster than food production. Challenges in the area include environmental and climatic stress, as well as limited arable land (Callo-Concha et al., 2013). Despite recent improvement in food security situation at the national level following the implementation of the Millennium Development Goals (UNDP Ghana and NDPC/GOG, 2012), the risks of food insecurity are still greater in the UER when compared to other localities in Ghana (Abane, 2015) (Table 1). Extreme poverty in the UER is estimated at 21 %, and this value is above 8 % which is assumed to be the average poverty rate in Ghana (Alhassan, 2015). Food insecurity in northern Ghana is caused by many factors such as: poverty (WFP, 2012), low agricultural productivity (Alhassan, 2015; Wood, 2013), limited socio-economic opportunities to diversify the livelihood of the local population (Hesselberg and Yaro, 2006), including socio-political factors which induce food insecurity through the marginalisation and creation of landless peasant farmers (Nyantakyi-Frimpong, 2014). The impacts of climate variability (Amikuzino and Donkoh, 2012, Klutse et al., 2013; Issahaku et al., 2016), and seasonality on rainfed agriculture further aggravate food insecurity in northern Ghana (Kleemann et al., 2017).

Inaccessibility to reliable electricity (energy poverty) is another challenge in the UER. Access to electricity is 80 % for Ghana when compared to some other countries in west Africa (Lecoque and Wiemann, 2015). However, access to electricity is less than 80 % for some regions within Ghana. As of 2016, access to electricity was 51.65 % for the UER. This implies that the UER was the most vulnerable when compared to the other regions in Ghana (Table 2) (Sackeyfio, 2018). As of 2015, barely 65 % and 39 % of households had access to electricity in Bolgatanga and Bongo Districts, respectively (Guvele et al., 2016).

The reliance of Ghana on hydro- and thermal electricity is significant (Kumi, 2017). Most of the plants operate at low efficiency, because they are made of obsolete technologies or they are poorly maintained (IEA, 2014). Hence, break-down of plants and subsequent interruption of electricity is commonplace. The variability in climate is also driving temperature to rise, while rainfall is decreasing in the Volta Basin (Oyebande and Odunuga, 2010; Kabo-Bah et al., 2016). This situation is adversely affecting the production of hydro-electricity. More so, the average end user tariff of electricity consumption in Ghana is expensive when compared to some other countries (IEA, 2014; Kumi, 2017; Energy Commission, 2018). The need to diversify the sources of electricity, as well as to use improved technologies, and in particular biomass to provide electricity is called for (Dasappa, 2011).

2.2. Data description, sources and processing

The data which were used for this study were from primary and secondary sources. The primary data were on agricultural land use and resource management practices. The snowball sampling method was used to select farmers for the personal interview survey, which was conducted in 2015. In total, $n = 56$ small-scale farmers were interviewed. Data were collected using semi-structured questionnaires. The dominant land use was extensification agriculture, and the external input was low. Farm labour was primarily manual, including draft animals to provide power for ploughing. Seeds for sowing were mostly local varieties. Farm labour (L) included the following tasks: land preparation, sowing, fertilizer/manure application, weeding, harvesting and threshing. The services (S) were as follows: cost of inputs (seeds, solar powered irrigation pump, draft animal for ploughing, animal feed and phytosanitary care, and hired labour, i.e. shadow wage for human labour). On average, farmers' experience was 13 years, and farm size was 1.5 ha, respectively. Standard statistical tools in Microsoft Excel 2007 were used to process the data (Table 3).

The representativeness of the primary data was checked by comparing the mean yields, i.e. 1.06 ton/ha considering the field data given in Table 3, and 1.20 ton/ha/yr considering the production data for Bolgatanga and Bongo Districts during the period 2003–2011 (Ministry of Food and Agriculture –MoFA, Ghana). The difference between the mean yields was marginal, and because most farmers lacked records to support their estimates, the primary data was adapted as follows: The mean yield in Table 3 was substituted with the mean yield that was calculated from the production data which was provided by MoFA, Ghana (Table A1).

The primary data (Table 3) were supplemented with secondary data, which were generated using the Agricultural Productivity SIMulator (APSIM) (Holzworth et al., 2014), i.e. by simulating maize yield response to 0, 20, 50 and 100 kg/ha/yr N as urea dosages. The following cropping systems were simulated: maize mono-cropping, and maize-legume intercropping in rainfed and irrigated systems. The

[2] http://citypopulation.info/Ghana-Cities.html [Retrieved on 04/01/18]
[3] https://mofa.gov.gh/site/?page_id=654 [Retrieved on 05/02/18]
[4] www.npc.gov.gh/images/REGIONALPROFILE/upper_east.pdf [Retrieved on 05/02/18]

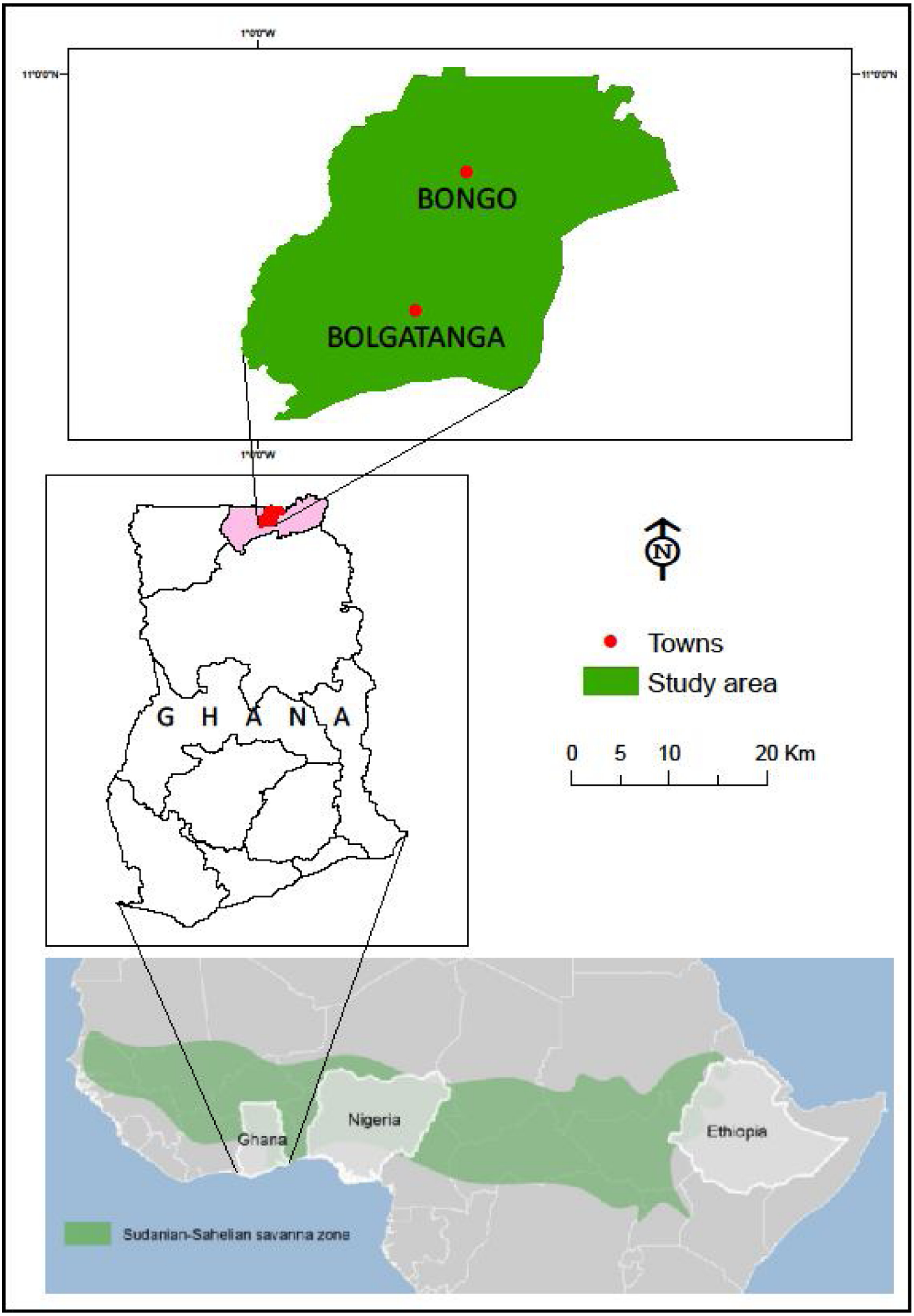

Fig. 1. Study area.

Table 3
Field data.
Source: Field survey in Bolgatanga & Bongo, 2015. *1 man day = 6 h, **1 animal day = 4 h.

Variable	Minimum	Maximum	Mean
Farmer's experience (years)	1	45	13.4
Farm size (ha)	0.4	2.07	1.5
Fertilizer application (kg/ha)	0	27	12
Seeds (kg/ha)	14	22	16
Human labour (man days/ha)*			
Land preparation (ploughing 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 labour (ploughing) (animal days/ha)**	5.5	9	7.5
Grain yield (ton/ha)	0.23	2.71	1.06

yielded maize residue (stover and cob) was calculated as shown in *Eqs.* (1) - (2), which are based on empirical studies (Lang, 2002). The assumption was that on average, above ground maize plant dry matter has 50 % of the dry matter weight in the grain and 50 % in the residue (stalk, leaf, cob, shank, and husk). Biophysical data from published literature (Table 4) were integrated to complement the datasets. The datasets were modelled into five scenarios (Table 5), by integrating options of land use and external input intensity, which exist in many real-world practices for maize cropping. The scenarios were in two major categories: (1) no/low input systems included: *Extensive0*, *Extensive12*, and *Intercrop20*, and (2) moderate/high input systems included: *Intensive50*, and *Intensive100*, respectively.

$$Residue\ (bushel/arce) = Grain\ yield^{*}\left(\frac{56}{2000}\right), \tag{1}$$

$$Residue\,(ton/ha) = \left[\left(grain\,yield^{*}14.86\right)^{*}\left(\frac{56}{2000}\right)^{*}2.25\right], \tag{2}$$

2.3. Methods

2.3.1. Emergy accounting (EMA)

EMA is a method of environmental accounting in a production system, and in particular closed systems (Odum, 1996; Brown and Ulgiati, 1997). EMA is useful to provide comprehensive information on resource use such as materials, energy, resource generation time, labour, economic and societal infrastructures, as well as other resources whose market value are difficult to monetise(Odum, 1996; Brown and Ulgiati, 2011, 2016a, Campbell and Tilley, 2014; Campbell et al., 2014). Thus, EMA is suitable when there is a need to account for labour as a factor of production (Kamp et al., 2016). EMA applies the concept of Energy Memory (EMergy) to explain the accounting of resource use as shown in *Eq.* (3) (Scienceman, 1987). Emergy is "*the energy of one type previously used up directly and indirectly to make a product or deliver a service*" (Odum, 1996), i.e. the embodied energy which is represented as a "memory" of the solar energy that had been used previously to produce a product or service in a given system (Brown and Herendeen 1996). The solar emjoule (*sej*) is the common base for measuring emergy in EMA. In this study, the emergy baseline was 12.0E + 24 sej/yr (Brown and Ulgiati, 2016b), and EMA was applied using the EM-DEA approach (Mwambo and Fürst, 2019).

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

where,

$Emergy_{resource}$ = emergy of a given resource (measured in *sej*)
$exergy_{resource}$ = the available energy of a given resource (measured in *J*)
$\tau_{resource}$ = transformity (measured in sej/J) or Unit Emergy Value (UEV of a given
resource, measured in *sej/unit*)

2.3.2. Data Envelopment Analysis (DEA)

DEA is a nonparametric linear programming based technique to estimate the relative productive efficiency or performance of peer entities, which are generally referred to as Decision Making Units (DMUs) in a given system (Farrell, 1957; Ludwin and Guthrie, 1989; Toloo and Nalchigar, 2009; Wen, 2015). DEA is useful when assessing the productive efficiencies of multiple DMUs with multiple inputs and outputs (Charnes et al., 1978). Hence, DEA is suitable when there is a need to assess the relative sustainability efficiencies of peer units (De Koeijer et al., 2002; Gomes et al., 2009). The productive efficiency (E_p) of a

Table 4
Biophysical data.

Data	Value	Source
Grain yield	1.2 ton/ha	[Table A1]
Rainfall in study area during 2003–2011	0.911 m/yr	MoFA (2012)
Manure input	29.25 kg/ha	Awunyo-Vitor et al. (2016)
Moisture content in manure	0.7	Sonko et al., 2016
Solar insolation	1.20E + 21 J/m^2/yr	CEP - University of Florida (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 (n.d.)[1]
Fraction of evapotranspired 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	2,30 Gh¢/kg	MoFA (2016)
urea N fertilizer	2,10 Gh¢/kg	
Cost of maize seeds	1.00 Gh¢/kg	Ghana Business News (2013)
Cost of solar pump (1.5 hp) for irrigation	800 Gh¢/yr	Dey and Avumegah (2016)
Capital cost of 1 draft animal	728 Gh¢	Houssou et al. (2013)
Maintenance cost of 1 draft animal	730 Gh¢/yr	

** The assumption was that the practice of intercropping (*Intercrop20*) is capable of reducing erosion by 50 % as demonstrated by Tuan et al. (2014).
[1] https://www.worldweatheronline.com/ [Retrieved on 04/01/2017].

Table 5
Land use and resource management scenarios.

Scenario	Description	External Input	Output
Extensive0	Extensification agriculture, no urea/NPK fertilizer in rainfed maize systems, and may include other non-leguminous crops.	Rainfed system 0 kg/ha/yr N fertilizer, with/without manure	1.17 ton/ha (grain wet matter)[b] 0.93 ton/ha (grain dry matter) 0.93 ton/ha (residue wet matter) 0.88 ton/ha (residue dry matter)
Extensive12	Extensification agriculture, low input of NPK fertilizer in rainfed maize systems, and may include other non-leguminous crops.	Rainfed system, 12 kg/ha/yr NPK, with/without manure	1.2 ton/ha (grain wet matter)[a] 0.96 ton/ha (grain dry matter) 0.96 ton/ha (residue wet matter) 0.899 ton/ha (residue dry matter)
Intercrop20[c]	Maize-legume (cowpea -*Vagna unguiculata,* ground nuts - *Arachis hypogaea* or soybean –*Glycine max*) intercropping, modest input of urea in rainfed systems.	Rainfed system, 20 kg/ha/yr urea, with/without manure	1.88 ton/ha (grain wet matter)[b] 1.5 ton/ha (grain dry matter) 1.41 ton/ha (residue wet matter) 1.17 ton/ha (residue dry matter)
Intensive50	Intensification agriculture, moderate input of urea mineral in maize monoculture, rainfed including supplemental irrigation.	Rainfed + spplemental irrigation (0.18 m/ha/yr), 50 kg/ ha/yr urea	2.75 ton/ha (grain wet matter)[b] 2.20 ton/ha (grain dry matter) 2.20 ton/ha (residue wet matter) 2.06 ton/ha (residue dry matter)
Intensive100	Intensification agriculture, high input of urea mineral in maize monoculture, rainfed including supplemental irrigation.	Rainfed + supplemental irrigation (0.18 m/ha/yr), 100 kg/ha/yr urea	2.81 ton/ha (grain wet matter)[b] 2.25 ton/ha (grain dry matter) 2.25 ton/ha (residue wet matter) 2.11 ton/ha (residue dry matter)

[a] = Interview survey and secondary data provided by MoFA.
[b] = simulated in APSIM.
[c] = It was assumed that intercropping increased ground cover and suppressed weeds, thus, contributing to less labour, because of fewer weeds as in the empirical study by Silva et al. (2009).

DMU is calculated as the ratio of the weighted sum of outputs to the weighted sum of inputs. When comparing multiple DMUs, the optimisation function in DEA attributes weights to the various inputs and outputs produced by peer DMUs. The optimisation function reduces the ratio of weighted sum of outputs to weighted sum of inputs into a ratio of a single virtual numerator to a single virtual denominator as shown in *Eq*. (4) (Hartwich and Kyi, 1999; Kao, 2014). By applying the least square regression analysis method shown in *Eq*. (5), the optimisation function estimates the relative efficiency scores as the ratio of E_p of each DMU to the E_p of the most productive DMU for a given batch DMUs. The calculated relative efficiency, i.e. relative Technical Efficiency (rTE) scores lie in the interval $0 \leq score \leq 1$. An inefficient DMU is denoted by a score less than 1, and an efficient DMU is denoted by a score equal to 1, respectively. In this study, DEA was applied using the EM-DEA approach (Mwambo and Fürst, 2019).

$$E_P = \frac{u_1y_1 + u_2y_2 + u_3y_3 + u_4y_4 + u_my_m}{v_1x_1 + v_2x_2 + v_3x_3 + v_4x_4 + v_nx_n} = \frac{\sum_{o=1}^{m} u_{o1}y_{o1}}{\sum_{i=1}^{n} v_{i1}x_{i1}} \tag{4}$$

where,
E_P = productive efficiency of a DMU
u_o = weight given to output o
v_i = weight given to input i
y_o = amount of output o from a DMU
x_i = amount of input i to a DMU

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

The coupling of EMA and DEA leads to the EM-DEA approach (Mwambo and Fürst, 2019). EMA and DEA were aggregated into a framework (Mwambo and Fürst, 2014), and the concept of eco-efficiency was integrated (Mwambo and Fürst, 2019). The EM-DEA approach was applied in this study to assess the resource use efficiency (RUE), and sustainability of maize cropping scenarios as follows. The scenarios (Table 5) were considered as the comparable units of production, i.e. by analogy the DMUs for maize production in northern Ghana. The scenarios were sketched using emergy diagrams (Figs. A1–A3) to visually represent the production systems, and to ease the accounting process. Using a top-down approach, the annual agricultural input and output resources are measured in their standardised physical units (Brown et al. 2000). Using Microsoft Excel, the measured resources are itemised categorically, and their available energy contents (exergy) are calculated using appropriate standard formulae (Table C1). The resource exergies measured in Joule (J), are transformed into their corresponding emergies as shown in *Eq*. (3). The calculated emergies are summed up categorically, and in accordance with the refined emergy accounting procedure (Brown and Ulgiati, 2016a), which then leads to a retainment of selected inputs (Table C2) from the basic pool of resources (Table C1). The retained resources become the shortlisted variables for evaluating the RUE and sustainability.

The scenarios, output emergies and input emergies are concatenated into a table in Microsoft Excel (Table C2), and then imported into an input-oriented model of the Open Source Data Envelopment Analysis (OSDEA).[5] The model specifications used for this study are stated in Table B1. The model of DEA uses the imported data (Table C2) to calculate the relative Technical Efficiency (rTE) scores, i.e. by using the optimisation function which applies a nonparametric treatment to the imported data (Table C2). The optimisation function in DEA assumes the least square regression analysis method whose general formula is shown in *Eq.* (5), and applies Pareto efficiency to select the weights for input and output variables. The rTE scores are calculated by DEA as the ratio of E_P for each of the scenarios to the E_P of the most productive scenario. The calculated rTE scores are considered the proxy for the relative sustainability (Table D1).

$$Y_i = \beta_0 + \beta_1\chi_1 + \beta_2\chi_2 + \beta_3\chi_3 + \beta_4\chi_4 + \beta_5\chi_5 + \beta_6\chi_6 + \beta_7\chi_7 + \mu_i \quad (5)$$

where,

Y_i = yield or resource output of the i^{th} DMU
β_0 = Coefficient of the intercept
β_z = Weight of variable
χ_1 = Evapotranspiration
χ_2 = Topsoil loss
χ_3 = NPK/urea N fertilizer application rate
χ_4 = Draft animal labour
χ_5 = Maize seeds
χ_6 = Human labour
χ_7 = Services
μ = slacks (residual)

Note: χ_1, ……… χ_7 were the selected resource inputs (variables). (See also, Table C2).

2.3.3.1. Evaluation of resource use efficiency (RUE). The RUE is calculated by equating the Unit Emergy Value (UEV) of the agricultural product, i.e. the yielded maize (dry matter) to the eco-efficiency. The concept of eco-efficiency was interpreted herein as the ratio of environmental impact to economic value (Kortelainen and Kuosmanen, 2004). The assessment of RUE is decomposed further into two sub-categories: (i) UEV in terms of Resource use (UEV_R), and (ii) UEV in terms of Exergy use (UEV_E). Both indicators were calculated as shown in *Eqs.* (6) - (10).

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

$$UEV_{R(withoutL\&S)} = \frac{U_{(without\ L\&S)}}{yielded\ product} = \frac{R+N+F}{yield\ matter\ dry\,(g)} \quad (7)$$

$$UEV_{R(withL\&S)} = \frac{U_{(with\ L\&S)}}{yielded\ product} = \frac{R+N+F+L+S}{yield\ matter\ dry\,(g)} \quad (8)$$

$$UEV_{E(withoutL\&S)} = \frac{U_{(without\ L\&S)}}{yielded\ exergy\ (J)} = \frac{R+N+F}{yield\ matter\ dry\,(g)*LHV} \quad (9)$$

$$UEV_{E(withL\&S)} = \frac{U_{(with\ L\&S)}}{yielded\ exergy\ (J)} = \frac{R+N+F+L+S}{yield\ matter\ dry\,(g)*LHV} \quad (10)$$

where,

F = Imported sources (see also, Table C1)
g = mass of yield matter dry, measured in grams
J = energy content of yield matter dry, measured in Joule
L&S = labour and Services (see also, Table C1)
LHV = lower Heating Value of yielded agricultural biomass
N = Non-renewable sources (see also, Table C1)
R = Renewable sources (see also, Table C1)
U = Total emergy of a system
$UEV_{(product)}$ = Unit Emergy Value of product, i.e. yielded maize measured as dry matter (Table C1)

2.3.3.2. Evaluation of absolute sustainability. The absolute sustainability was evaluated using selected emergy-based indicators of empirically proven reliability (Brown and Ulgiati, 2004; Ulgiati et al., 2011; Dong et al., 2014; Viglia et al., 2017) as shown in *Eqs.* (11) – (20). The selected emergy-based indicators were as follows: Total emergy (U), Emergy Yield Ratio (EYR), Environmental Loading Ratio (ELR), Emergy Sustainability Index (ESI) and Percentage Renewability (%REN). If the environmental accounting is limited to resources from nature and materials, the indicators for absolute sustainability were evaluated as shown in *Eqs.* (11) – (15).

$$Total\ emergy\ (U) = R + N + F \quad (11)$$

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

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

$$ESI = \frac{EYR}{ELR} \quad (14)$$

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

where,

F, g, *J*, L&S, LHV, N, R, and U are same as defined above.

Alternatively, if the environmental accounting considers resources from nature, materials, labour and services, the indicators for absolute sustainability were evaluated as shown in *Eqs.* (16) – (20).

$$Total\ emergy\ U = R + N + F + L + S \quad (16)$$

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

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

$$ESI = \frac{EYR}{ELR} \quad (19)$$

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

where,

F, g, *J*, L&S, LHV, N, R, and U are same as defined above.

2.3.3.3. Evaluation of relative sustainability. The performance in a production system is usually described in terms of Technical Efficiency (TE) (Farrell, 1957). The TE is the degree to which the actual output of a production unit approaches its maximum (Färe and Lovell, 1978). By analogy, the rTE is the scalar indicator to express the performance of peer scenarios on a relative basis, i.e. the scenarios as comparable units of the same batch. Hence, the rTE was the proxy for expressing the relative sustainability. On this note, the environmental information which is derived from using the EM-DEA approach, becomes the proxy for further analysis by applying the environmental Cost-Benefit and Value Chain Analysis approaches.

2.3.4. Environmental cost-benefit analysis (CBA) approach

Environmental CBA is the systematic thinking about decision-making concerning environmental services, i.e. by ranking policy options based on an economic point of view, which takes into account both the benefits and costs of a policy (Kelman, 1981; Boadway, 2006; Atkinson and Mourato, 2008). In traditional practice of CBA, costs and

[5] http://opensourcedea.org/ [Retrieved on 13/03/2016]

Table 6
CRR, MC and LHV for maize.
Source: Otchere-Appiah and Hagan (2014).

Residue type	Crop to Residue Ratio	Moisture content (%)	LHV (MJ/kg)
Stover	1	15.5	15
Cob	0.25	8	15

benefits are usually measured in a domestic monetary value, by converting the values of traded inputs and outputs using a shadow exchange rate of a common currency (Ray, 1990). In this study, the environmental CBA approach was adapted as follows. The resources which are accounted using the EM-DEA approach (Mwambo and Fürst, 2019) are measured as emergies, which is the common currency of the economy of nature (Odum, 1996; Pelletier et al., 2011; Campbell and Tilley, 2014), and hence emergy was the currency. The scenarios for maize production (Table 5), were considered as the policy scenarios. The total emergy (U) for each scenario was considered as the environmental costs (environmental impacts or pressure). The agricultural produce (yielded maize dry matter) was considered as the benefit (economic value).

The information obtained using the environmental CBA was the proxy for evaluating the impact distribution, and it was assessed in two levels: (i) ranking of the scenarios on the basis of the environmental impacts which each scenario could cause, and (ii) ranking the scenarios on the basis of the environmental impacts which could result following a change from the business-as-usual scenario (*Extensive12*) to the various project scenarios (*Extensive0*, *Intercrop20*, *Intensive50* or *Intensive100*).

2.3.5. Value chain analysis (VCA) approach

The concepts of value chain (Gereffi and Fernandez-Stark, 2016), and polygeneration (Serra et al., 2009) were integrated and applied by considering the maize value chain, i.e. adding value to the agriculturally produced biological resource (maize biomass) so as to contribute to food security (Fig. B1 and Fig. B2) The obtainable benefits were as follows: (i) grain for food provision, and (ii) residue as feedstock for electricity generation (bioenergy). The assumption was that the process of dehydration from maize grain added value to the produce.

2.3.5.1. Food provision from grain. The area that was cultivated with maize in Bolgatanga and Bongo Districts in 2011 was 3310 ha (MoFA, 2012). This surface area was assumed to be equivalent to the area which was cultivated with maize in 2015 when the field survey for this study was conducted. The food provision measured in kilocalories per year (kcal/yr) was calculated as shown in *Eqs*. (21) – (23).

$$Y_{dm} = Y \times (1 - 0.2) \quad (21)$$

$$GP_{Adm} = Y_{dm} \times A_T \quad (22)$$

$$FP_{AES} = GP_{Adm} \times 3650000 \quad (23)$$

where,
Y = yield at harvest (measured in ton/ha)
Y_{dm} = yield matter dry
GP_{Adm} = annual matter dry (maize grain measured in ton)
A_T = total area of cultivation (measured in ha)
FP_{AES} = food provision per annum (measured in kcal)
Assumptions:

- moisture content in grain at time of harvest is 20 % (Aggrey, 2015).
- area cultivated with maize in Bolgatanga and Bongo Districts in 2011 was 3310 ha (MoFA, 2012).
- 100 g of white/yellow maize has a value of 365 kcal (Nuss and Tanumihardjo, 2010).

2.3.5.2. Electricity generation from residue. The area that was cultivated with maize in Bolgatanga and Bongo Districts in 2011 was 3310 ha (MoFA, 2012). This surface area was assumed to be equivalent to the area which was cultivated with maize in 2015 when the field survey for this study was conducted. The amount of electricity (measured in Megawatt-hour per year, MWh/yr) which could be generated from residue was calculated as shown in *Eqs*. (24) – (28).

$$G_A = A_P \times CRR \quad (24)$$

$$A_A = G_A \times 60\% \quad (25)$$

$$D_A = A_A - [A_A \times MC] \quad (26)$$

$$E_T = \frac{D_A \times LHV}{1000} \quad (27)$$

$$MWh = \frac{D_A \times 1.5 MWh}{1 tonne} \quad (28)$$

where,
G_A = Annual Generated residue in tonnes
A_P = Annual production in tonnes
CRR = Crop to Residue Ratio
A_A = Annual availability of ratio
D_A = Annual dry maize residue
MC = moisture content
E_T = Total energy in TJ/yr
LHV = lower Heating Value
Assumptions:

- Average availability of maize crop residue was 60 %
- Average conversion of 1.5 MW h per ton of dry biomass with efficiency in the range of 20–40 %
- 40 kW gasifier plant used for a twelve-hour operation per day for 365 days in a year
- CRR, MC and LHV for maize stover and cob are stated in Table 6.

2.3.6. Sustainability balanced scorecard (SBSC) approach

The environmental information which was derived from the application of the EM-DEA, environmental CBA and VCA approaches, was aggregated by applying the SBSC approach to do a sustaianbility apraisal of the various scenarios. The framework showing the integration of the various methods is illustrated in Fig. 2. The architectural design of the SBSC approach consists of five perspectives and nine metrics of evaluation (Möller and Schaltegger, 2005; Alewine and Stone, 2013; Jassem et al., 2018). The metrics were evaluated by quantifying the environmental information to obtain scores in the economic, social and environmental dimensions. The emergy-based ratios were adopted, while Likert scales were developed to quantify other non emergy-based information. The perspectives which constitute a dimension were summed to obtain a score in that dimension. The overall sustainability appraisal score for a scenario was the cumulative score, which was obtained by summing the score from the economic, social and environmental dimensions.

2.3.7. Validation method

The scenarios (Table 5) were validated by comparing the trend in maize yield which was obtained using APSIM, and the trend in maize yield which was observed over a 4-year experimentation in the northern Guinea savannah, in Ghana. The experimental setup consisted of maize-cowpea mixed cropping, maize-cowpea relay intercropping, maize-cowpea rotation cropping, and maize monocropping. The cropping systems in the experiment were treated with two levels of N treatment, i.e. 0 and 80 kg/ha/yr N as urea, as well as two levels of P treatment, i.e. 0 and 60 kg/ha/yr P as Volta phosphate rock (Härdter et al., 1991).

3. Results

3.1. Results obtained using the EM-DEA approach

Agricultural systems occur at the interface between nature and the human economy. As such, agricultural production consumes resources from nature and human economy, i.e. purchased inputs including labour (L) and services (S) to produce agricultural output biomass. Hence, the assessment of RUE and sustainability is presented in two categories: (1) environmental accounting on the basis of input resources from nature and materials excluding labour and services, i.e. without labour and services (without L&S), and (2) environmental accounting on the basis of input resources from nature, materials, labour and services, i.e. nature and purchased inputs including labour and services (with L&S). The former category focuses primarily on raw materials used by production, meanwhile the latter focuses on the complete economy (both nature and human economy), respectively. On this note, the results are as follows:

3.1.1. RUE and sustainability (without L&S)

The results (Table 7) show that, when labour (L) and services (S) were excluded from the environmental accounting, the various indicators gave the following information about the scenarios. The total emergy (U) of the scenarios increases as the quantity of input resources increase. The smaller the demand for resources by a scenario, the more efficient and sustainable will a given scenario be, because fewer resources would be needed to sustain production. The ranking of the scenarios from least to most demanding was as follows: *Extensive0*, *Intercrop20*, *Extensive12*, *Intensive50,* and *Intensive100*. This implies that, *Extensive0* demanded the least amount of environmental support which was needed from the biosphere, while *Intensive100* demanded the greatest quantity of environmental support from the biosphere. Furthermore, the smaller the value of UEV_R and UEV_E is, the more efficient will a scenario be. The ranking of the scenarios in terms of UEV_R was as follows: *Intercrop20*, *Intensive50*, *Extensive0*, *Intensive100* and *Extensive12*. This implies that, *Intercrop20* was the most efficient when it comes to transforming the allocated resources into maize biomass, while *Intensive100* and *Extensive12* were the least efficient at transforming the allocated resources into maize biomass. A similar trend was observed for the UEV_E. The magnitude of the values for UEV_E were smaller compared to the magnitude of the values for the UEV_R. The EYR is a connotation for a scenario's reliance on local resources. A scenario which is reliant on local resources will be more resilient compared to a scenario which is reliant on resources that are imported from outside the system. The ranking of the scenarios on the basis of the EYR was as follows: *Extensive0*, *Intercrop20*, *Extensive12*, *Intensive50,* and *Intensive100*. This implies that, *Extensive0* relied on mostly local resources. *Intercrop20*, *Extensive12*, and *Intensive50* relied on a combination of both local and imported resources. The dependence on imported resources increases as the urea input dosage increases. *Intensive100* relied much more on imported resources. A similar trend was observed when the scenarios were assessed in terms of ELR. The ELR is a measure of how far a system is from equilibrium. The closer a system is from the equilibrium, the more sustainable will the system be. Hence, considering excess pressure from outside the system, *Extensive0* was closest to the equilibrium, while *Intensive100* was furthest away from the equilibrium. The ESI, i.e. higher yield per unit of environmental loading was as follows: The value was high for *Extensive0*, low for *Extensive12* and *Intercrop20*, much lower for *Intensive50* and *Intensive100*. The ranking of the scenarios in terms of the ESI was as follows: *Extensive0*, *Intercrop20*, *Extensive12*, *Intensive50,* and *Intensive100*. The scenarios showed a similar trend in terms of %REN. *Extensive0* achieved the greatest fraction of renewability of product (84 %), while *Intensive100* achieved the least fraction of renewability of the product (30 %). *Extenive12*, *Intercrop20*, and *Intensive50* achieved intermediate values for the %REN as follows: 58, 60 and 45 %, respectively.

3.1.2. RUE and sustainability (with L&S)

Alternatively, when labour (L) and services (S) were included in the environmental accounting, the various indicators (Table 7) provided the following information about the scenarios. The total emergy (U) increases as the quantity of inputs increase. The ranking of the scenarios from least to most demanding was as follows: *Intercrop20*, *Extensive0*, *Extensive12*, *Intensive50*, and *Intensive100*. *Intercrop20* demanded the least amount of environmental support needed from the biosphere, while *Intensive100* demanded the greatest amount of environmental support from the biosphere. The ranking of the scenarios in terms of UEV_R was as follows: *Intercrop20*, *Intensive50*, *Intensive100*, *Extensive0*, and *Extensive12*. A similar trend was observed for the UEV_E. In other words, *Intercrop20* was comparatively the most resources efficient, while *Extensive12* was the least efficient in terms of transforming the allocated resources into maize biomass. The ranking of the scenarios in terms of EYR was as follows: *Extensive0*, *Extensive12* and *Intercrop20* showed equal performance with a value of 1.05, meanwhile *Intensive50* and *Intensive100* showed equal performance with a value of 1.03. In other words, *Extensive0, Extensive12* and *Intercrop20* relied more on local resources, while *Intensive50* and *Intensive100* relied much more on imported resources. Based on the ELR, which is the distance from equilibrium, the scenarios were ranked as follows: *Intercrop20*, *Extensive0*, *Extensive12*, *Intensive50*, and *Intensive100*. *Intercrop20* was closest to the equilibrium, while *Intensive100* was farthest from the equilibrium. The ranking of the scenarios in terms of ESI was as follows: *Extensive0* and *Intercrop20* showed equal performance with a value equivalent to 0.05. *Extensive12* followed closely with a value equal to 0.04, meanwhile *Intensive50* and *Intensive100* both achieved a value equal to 0.03, respectively.

3.1.3. Relative sustainability

The relative sustainability of the scenarios was evaluated on the basis of the rTE scores, which were estimated by applying the Open Source Data Envelopment Analysis (OSDEA) model. The estimated score for *Extensive12* was about 64.7 %, meanwhile the scores for *Extensive0*, *Intercrop20*, *Intensive50*, and *Intensive100* were 100 %. Hence, *Extensive12* was inefficient when compared to the project scenarios. This implies that, the productive efficiency of *Extensive12* could be improved by as much as 35.3 % without additional input resources (see also, Table D1). The results of the assessment using the EM-DEA approach are summarised in Table 7. The detailed calculation of efficiencies and sustainabilities are presented in Appendix D.

3.2. Results obtained using the environmental CBA approach

When input resources from nature and materials (without L&S) are considered, the assessment results show that the order of the scenarios from the most cost-efficient to least cost-efficient was as follows: *Intercrop20*, *Intensive50*, *Extensive0*, *Intensive100* and *Extensive12*. Alternatively, when input resources from nature, materials and human economy (with L&S) are considered, the assessment results show that the scenarios were in the following order from the most cost-efficient to least cost-efficient: *Intercrop20*, *Intensive50*, *Intensive100, Extensive0*, and *Extensive12*. The results of the assessment using the environmental CBA approach are summarised in Table 8. The detailed calculation of the environmental costs are presented in Appendix E.

In addition, the information which was derived from the application of the environmental CBA approach, was useful for assessing the environmental impacts of the scenarios in the following themes: (i) expansion of area cultivated, (ii) ecotoxicity, (iii) water demand, (iv) emission, (v) soil erosion, and (vi) material resources consumption. These thematic impacts were assessed using the following proxy indicators: (a) grain yield, (b) NPK/urea dosage, (c) quantity of water needed for crop evapotranspiration, (d) services, (e) topsoil loss, and (f) %REN, respectively. The assessment shows that *Extensive0* caused the least impacts in terms of plausible ecotoxicity, emission and demand for material resources when compared to *Extensive12*. However, *Exensive0* is more likely to cause greater impacts in terms of expansion of area cultivated, because the yield is much lower when compared to the yield by *Extensive12*. *Intensive100* caused the greatest impacts in terms of plausible ecotoxicity, emission and demand for material resources including energy, labour and services. Furthermore, *Intensive100* is less likely to cause impacts in terms of plausible expansion of area cultivated, because its yield was higher. *Intensive50* achieved moderate impacts in terms of plausible ecotoxicity, emission, and demand for resources. The irrigated scenarios *Intensive50* and *Intensive100* caused greater demand for water when compared to the following rainfed scenarios *Extensive0*, *Extensive12*, and *Intercrop20*, respectively. *Intercrop20* caused the least impacts in terms of erosion when compared to the other scenarios, because intercropping increases the percentage cover, and ultimately minimises erosion. The distributional impacts are illustrated in Table 9, and the trend is summarised using Likert scale in Table 10.

3.3. Results obtained using VCA approach

The assessment using the VCA approach shows that, increase in the input resources contributed to increase in the absolute yield obtained by the scenarios. The yield was proportionate to the food provision. Nonetheless, the ranking of the scenarios was based on the environmental costs incurred and the marginal yield. The order of the scenarios from the most cost-effective to least cost-effective was as follows: *Intercrop20*, *Intensive50*, *Intensive100*, *Extensive0*, and *Extensive12*. The food provision from grain, and electricity which could be generated from residue are summarised in Table 11. The detailed calculation of food provision, and electricity generated are presented in Appendix F and G, respectively.

3.4. Results obtained using SBSC approach

The environmental information which was derived from the application of the EM-DEA, environmental CBA and VCA approaches, was aggregated using the SBSC approach. The applied SBSC approach (Table 12) shows that *Intercrop20* achieved the greatest overall sustainability appraisal score. Such high score was an attribute of the following: (i) high performance in the economic dimension (net profit), (ii) better performance in the social dimension (diverse food provision, i.e. maize and legume), and (iii) fewer environmental impacts. The order of the scenarios on the basis of the sustainability appraisal score from high to low was as follows: *Intercrop20*, *Intensive50*, *Intensive100*, *Extensive0,* and *Extensive12*, respectively. The detailed calculation of the scores are presented in Appendix H.

4. Discussion

4.1. Validation of scenarios

The experimentation (Härdter et al., 1991) which was used to validate this study shows that, at all levels of N and P fertilization, the maize yield by the monocropping systems were significantly higher when compared to the maize yield by maize-cowpea cropping systems (mixed, relay and rotation). The maize yield obtained by the maize-cowpea rotation cropping system showed no reduction over the 4-year period (Härdter et al., 1991). This trend in maize yield is similar to the one which was obtained by the scenarios as follows: The yield obtained by the intensive monocropping scenarios (*Intensive50* and *Intensive100*) was greater when compared to the yield obtained by the maize-legume intercropping scenario (*Intercrop20*), as well as *Extensive12* and *Extensive0*, respectively (Table 5). When the resources from nature and human economy were considered in the assessent, the maize-legume intercropping scenario (*Intercrop20*) showed superior environmental performance when compared to *Extensive0*, *Extensive12*, *Intensive50* and *Intensive100* (Table 7, Table 9 and Table 12). On the basis of these similarities between the trend in maize yield which was obtained by the scenarios, and the trend in maize yield that was observed in a real-world experimentation, which was conducted in an identical agroecological zone, this study was considered valid.

4.2. Holistic analysis

Extensive12 was the business-as-usual scenario. The scenario was rainfed and the external input was about 12 kg/ha/yr NPK. The yield was 0.96 ton/ha (dry matter) (Table 5). The results (Table 7) show that, *Extensive12* was both less efficient and less sustainable when compared to the project scenarios (*Extensive0*, *Intercrop20*, *Intensive50* and *Intensive100*). Among the project scenarios, *Extensive0* was rainfed and consumed 0 kg/ha/yr urea, and the yield was 0.93 ton/ha (d.m.). When the high demand for maize-based products is coupled with such low yield which is obtained by *Extensive0* and *Extensive12*, one of the impacts is a high rate of expansion of cultivated areas (Table 9). Another evidence comes from the evaluation of the fertilizer subsidy programme in Ghana during the period 2007–2012. The evaluation confirms that the increase in maize production which was reported during the stated period was due an increase in the area cultivated rather than from an increase in productivity (Fearon et al., 2015).

Intensive100 was irrigated and consumed 100 kg/ha/yr urea, and the yield was 2.25 ton/ha (d.m.). The marginal yield which was obtained by *Intensive100* was lesser when compared to the marginal yield obtained by the moderately intensive scenario (*Intensive50*). More so, the carbon footprint of *Intensive100* was greater when compared to the carbon footprint of the other scenarios (Mwambo et al. Forthcoming). On the other hand, *Intensive50* was irrigated and consumed 50 kg/ha/yr urea, and the yield was 2.20 ton/ha (d.m.). Meanwhile, *Intercrop20* was rainfed and consumed 20 kg/ha/yr urea, and the yield was 1.50 ton/ha (d.m.). *Intercrop20* achieved the greatest marginal yield compared to *Intensive50* and *Intensive100* (Table 5), as well as the greatest overall sustainability appraisal score (Table 12), and the least environmental impacts in terms of erosion (Table 9 and Table 10). When the assessment considers resources from nature and human economy, the greatest amount of benefits which was obtained at the least environmental costs was achieved by *Intercrop20* (Table 11). Hence, the environmental performance of *Intercrop20* and *Intesive50* were better when compared to the performance of *Extensive0*, *Extensive12* and *Intensiven100* (Table 7).

Increase in agricultural productivity could contribute to food availability. However, increase in productivity alone is not a guarantee for food security, and in particular when all the four dimensions of food security are taken into consideration (Leroy et al., 2015; Barrett, 2001). Hence, increase in productivity and in combination with adequate value addition to agricultural produce could better contribute to food security (Devaux et al., 2018). A reliable supply of energy, and in particular electricity is necessary for boosting the productive capacity in the agri-food sector (Leroy et al., 2015; Eshun and Amoako-Tuffour, 2016; Sola et al., 2016). On this note, the food provision at the regional scale (herein assumed to be equal to the UER) was as follows: *Extensive0*, *Extensive12*, *Intercrop20*, *Intensive50,* and *Intensive100* provided 11.308.284.000, 11.598.240.000, 18.170.576.000, 26.579.300.000, and 27.159.212.000 kcal/yr, respectively (Table 11). Assuming that the average minimum dietary energy requirement for a healthy human with a sedentary lifestyle is 1800 kcal/day (FAO et al., 2004),[6] this implies that the food provision by the various scenarios could be used to feed about 17212, 17653, 27656, 40455, and 41338 persons in 1 year. The detailed calculation is shown in Appendix F. Considering that 126,000 persons were food insecure in the UER in 2009 as shown in

[6] https://en.wikipedia.org/wiki/List_of_countries_by_food_energy_intake#cite_note-3 [Retrieved 16/01/2019]

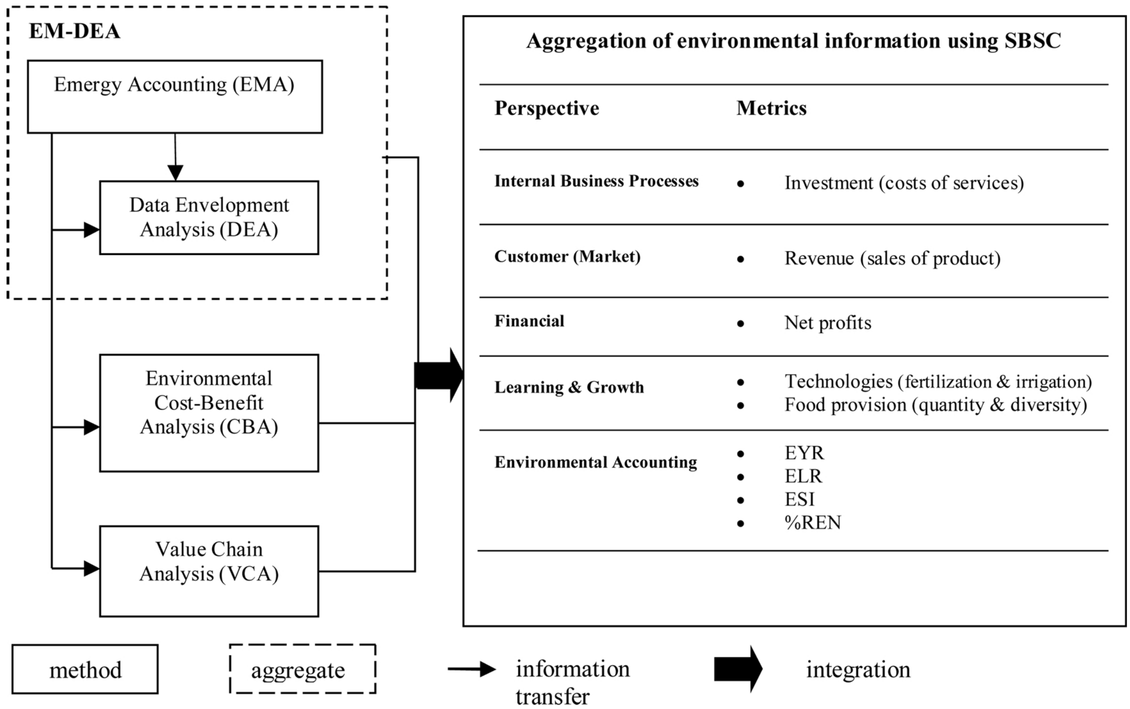

Fig. 2. Framework showing the integration of methods.
Note: See also the explanation of the metrics in the footnotes[7]

Table 7
RUE and sustainability per hectare.

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)	0.273	5.35	0.396	5.87	0.385	4.64	0.611	8.85	0.904	9.55
UEV_R (E+09 sej/g)	0.292	5.72	0.412	6.12	0.256	3.09	0.278	4.02	0.402	4.25
UEV_E (E+05 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	
UEVcurrency (E+12 sej/Gh¢)	1.30		1.30		1.30		1.30		1.30	

Table 1, the various scenarios could have enabled the food insecure population to be reduced to 108788, 108347, 98344, 85545 and 84662 persons, respectively.

In addition, the residue produced by *Extensive0*, *Extensive12*, *Intercrop20*, *Intensive50,* and *Intensive100* could be used to generate about 3746.84, 3842.91, 6020.56, 8806.67, and 8998.81 MW h/yr electricity (bioenergy), respectively (Table 11). The detailed calcuation is shown in Appendix G. Such a projection of energy production using improved technology and agricultural biomass, could be useful when making informed decision on land use adaptation and energy planning to improve diversification and access to energy. This could ultimately contribute to improve food security. This holistic analysis shows that, *Intercrop20* and *Intensive50* represent the best-case scenarios for land use adaption, which could contribute to resource optimisation in small-scale maize production, while minimising the impacts in the long term (Table 9, Table 11 and Table 12).

4.3. Comparison between the environmental performance of scenarios for maize cropping in Ghana and systems in other developing regions of the world

The environmental performance of the following: (1) no/low input scenarios: *Extensive0*, *Extensive12*, and *Intercrop20*, and (2) moderate/high input scenarios: *Intensive50* and *Intensive100*, for maize cropping in northern Ghana, were compared to the following low intensity maize cropping systems: (1) Maya traditional system in Mexico, (2) low intensity hybrid maize system in Brazil, and (3) hybrid maize systems in Argentina (Rótolo et al., 2015). The maize yield obtained by the scenarios was between 0.93 and 2.25 ton/ha (d.m.) (Table 5). On the other hand, the maize yield by the counterpart systems was between 3.04 and 5.84 ton/ha (d.m.). The difference in maize yield between this study scenarios and the counterpart systems could have been caused by biophysical factors such as maize varieties, agroclimatic conditions, and to a lesser extent agronomic land use practice. Most small-scale farmers in Ghana cultivate local varieties, because they have limited access to improved varieties (Poku et al., 2018). Such local varieties are low

[7] Investment = costs of services, Revenue = yield matter dry in kg x price per kg, Net profit = revenue − investment, Technologies = techniques of introducing external inputs, Food provision = quantity & diversity food (i.e. quantity = quantity of food in kcal, diversity of food = solely maize or maize & legume), [EYR, ELR, ESI, and %REN] = consider definitions provided above when L&S are included.

Table 8
Aggregated costs and yield.

Land use scenarios	Environmental cost (total emergy, U)				Yield	
	Farm scale (e.g. 1 ha) (E+15 sej)		Regional scale (3310 ha cultivated in Bolgatanga & Bongo, 2011) (E+19 sej)		Farm scale	Regional scale
	without L&S	*with L&S*	*without L&S*	*with L&S*	*yield matter dry* (ton/ha)	*yield matter dry* (ton)
Extensive0	0.273	5.35	0.0905	1.77	0.94	3098.2
Extensive12	0.396	5.87	0.131	1.94	0.96	3177.6
Intercrop20	0.385	4.64	0.127	1.54	1.50	4965
Intensive50	0.611	8.85	0.202	2.93	2.20	7282
Intensive100	0.904	9.55	0.299	3.16	2.25	7447.5

yielding when compared to improved varieties such as the hybrids -as was the case of the counterpart systems (Rótolo et al., 2014, 2015). Moreover, small-scale maize systems in sub-Saharan Africa are dominantly rainfed (Edreira et al., 2018), and in particular the productivity in rainfed agriculture in northern Ghana is severely threatened by changes in climate (Ibn Musah et al., 2018).

The pairwise comparison between the scenarios and the counterpart systems (Table 13) shows that, when the assessment considers resources from nature and materials excluding labour and services (without L&S), the scenarios in northern Ghana were more efficient and less sustainable relative to the counterpart systems. Meanwhile, when the assessment considers resources from nature, materials, labour and services (with L&S), the scenarios in northern Ghana were less efficient and less sustainable relative to the counterpart systems (Table 13). This implies that, the amount of human labour and costs of services which were invested into the production of maize in northern Ghana were not adequately compensated by the output yield. Hence, maize production systems in Ghana could be improved if the NPK/urea dosage, irrigation and seed varieties are improved, while topsoil loss (erosion), human labour and costs of services are reduced. This evidence is similar to the findings by Awunyo-Vitor et al. (2016). They state that, in order to improve maize output in Ghana, the fertilizer input, seed, manure, and land should be increased, while the quantity of labour and capital should be reduced. The detailed comparison between the environmental performance of this study scenarios and the counterpart systems

Table 10
Trend for a change from the business-as-usual scenario to the project scenarios.

Likert Scale	Trend	….. impacts of *Extensive12* are
+ +	↓	very high
+	↘	high
0	→	same
–	↗	low
- -	↑	very low
		compared to a land use conversion to *Extensive0, Intensive50, Intensive100* or *Intercrop20*

Table 11
Environmental costs and benefits at regional scale.

Land use scenario	Environmental costs (total emergy, U) (E+19 sej)		Benefits (food and bioenergy)	
	without L&S	*with L&S*	Food provision from grain per annum (kcal x10^3)	Potential electricity from residue per annum (MWh)
Extensive0	0.0905	1.77	11,308,284	3746.84
Extensive12	0.131	1.94	11,598,240	3,842.91
Intercrop20	0.127	1.54	18,170,576	6,020.56
Intensive50	0.202	2.93	26,579,300	8,806.67
Intensive100	0.299	3.16	27,159,212	8998.81

Table 9
Distributional impact.

Scenarios	**Environmental impacts**					
	Cultivated area expansion	Ecotoxicity	Water demand	Emission	Soil erosion	Material resource consumption
Extensive12	→ (red)	→ (green)	→ (green)	→ (green)	→ (red)	→ (green)
Extensive0	↗ (red)	↘ (green)	→ (green)	↘ (green)	→ (red)	↘ (green)
Intensive50	↘ (green)	↗ (yellow)	↗ (yellow)	↗ (yellow)	→ (red)	↗ (yellow)
Intensive100	↘ (green)	↑ (red)	↗ (yellow)	↑ (red)	→ (red)	↑ (red)
Intercrop20	↘ (yellow)	↗ (green)	→ (green)	↗ (green)	↘ (yellow)	↗ (green)

Current impact

Low (green)	Moderate (yellow)	High (red)
<26% impact of Ext.12	26 – 65% impact of Ext..12	>65% impact of Ext.12

Future trends

→	↘	↓	↗	↑
continuing impact	decreasing impact	very rapid decrease of the impact	increasing impact	very rapid increase of the impact

Table 12
Application of the SBSC approach for the aggregation of inclusive environmental information per hectare.

Vision	Strategy	Sustainability dimension	Perspective	Metrics	*Extensive0* *Score*	*Extensive12* *score*	*Intercrop20* *score*	*Intensive50* *score*	*Intensive100* *score*
To improve food security	Stock agricultural produce, add value to produce & market product when price is highest (e.g. add value to maize produce in order to enhance the availability & diversification of maize-based products in times of need)	Economic	Internal Business Process	● **Investment** [a] (cost of seed, NPK/urea, irrigation, animal, stable & feed)	(-) 513.5	(-) 541.1	(-) 547.5	(-) 1618.5	(-) 1723.5
			Customer	● **Revenue** (revenues = yield matter dry in kg * price per kg)	1336.39	1364.82	2132.54	3127.72	3198.80
			Financial	● Net profits (revenue – investment)	822.89	823.72	1585.04	1509.22	1475.30
		Economic score total			*822.89*	*823.72*	*1585.04*	*1509.22*	*1475.30*
	Use cost efficient technologies & crop diversification (e.g. modest application of urea + legume intercropping enhances maize productivity in low input systems. Legumes as additional food provision)	Social	Learning & Growth	● **Technologies** (fertilization & irrigation) (NPK/urea = 1.0, NPK/urea app. rate every 10 kg/ha = 0.01, manure = 0.1, N_2 fixation with legumes = 0.3, rainfed = 0, irrigation = 0.4)	0.1	1.11	1.42	1.45	1.50
				● **Food provision** (quantity & diversity) quantity = food provision (1000000 kcal = 1) diversity = (solely maize = 1, maize & legume = 1.5)	4.40	4.50	6.90	9.00	9.20
		Social score total			*4.50*	*5.61*	*8.32*	*10.45*	*10.70*
	Promote practices which do not compromise resource availability, productivity, & which are environmentally friendly (e.g. *Intercrop20* for low input maize systems, *Intensive50* for high input maize systems)	Environmental	Environmental Accounting	● EYR	1.05	1.05	1.05	1.03	1.03
				● ELR [b]	(-) 22.27	(-) 24.54	(-) 19.19	(-) 31.18	(-) 33.73
				● ESI	0.05	0.04	0.05	0.03	0.03
				● **%REN**	4	4	5	3	3
		Environmental score total [c]			*(-)17.17*	*(-)19.45*	*(-)13.09*	*(-)27.12*	*(-)29.67*
Overall					810.22	809.88	1580.27	1492.55	1456.33

[a] Investment was assigned a negative value to reflect costs.
[b] ELR was assigned a negative value to reflect distance of a scenario away from the equilibrium.
[c] The negative sign infront of the Environmental score total originates from the ELR, and it reflects the impact of agricultural production on the environment e.g. resource depletion. The greater the magnitude of the Environmental score total, the greater the environmental impact.

Table 13
Comparison between environmental performance of maize systems in Ghana and other regions [a].

Indicators	This study Ghana	Counterpart system Mexico	This study Ghana		Counterpart system Brazil	This study Ghana	Counterpart system Argentina	This study Ghana	Counterpart system Argentina
	Exten.0	*Trad. low intensity*	*Exten.12*	*Inter.20*	*Hybrid 2009*	*Inten.50*	*Hybrid 1986*	*Inten. 100*	*Hybrid 1995*
Yield (ton/ha) d.m.	0.94	3.04	0.96	1.5	4.07	1.20	4.74	2.25	5.84
EYR (without L&S)	6.77	31.95	2.43	2.51	73.72	1.83	2.28	1.44	1.83
ELR (without L&S)	0.18	0.48	0.72	0.67	0.37	1.22	1.34	2.28	2.04
ESI (without L&S)	36.91	66.25	3.39	3.75	197.86	1.51	1.70	0.63	0.90
%REN (without L&S)	85.0	67.47	58.0	60.0	72.86	45.0	42.73	30.0	32.91
U (without L&S) (E+15 sej/ha/yr)	0.27	1.85	0.39	0.38	2.25	0.61	3.04	0.90	3.97
UEV_R (without L&S) (E+09 sej/g)	0.29	0.61	0.41	0.26	0.55	0.28	0.64	0.40	0.68
UEV_E (without L&S) (E+05 sej/J)	0.19	0.32	0.27	0.17	0.29	0.19	0.34	0.27	0.36
$UEV_{currency}$ (without L&S) (E+12 sej/USD)	5.05	4.09	5.05	5.05	0.80	5.05	6.96	5.05	4.47
EYR (with L&S)	1.04	10.87	1.04	1.04	2.91	1.03	1.98	1.03	1.64
ELR (with L&S)	26.77	0.58	29.64	23.08	1.06	37.48	1.65	40.34	2.55
ESI (with L&S)	0.04	18.70	0.04	0.05	2.75	0.03	1.20	0.03	0.64
%REN (with L&S)	4.0	63.24	3.0	4.0	48.51	3.0	37.70	2.0	28.18
U (with L&S) (E+15 sej/ha/yr)	6.39	1.98	7.05	5.54	3.39	10.6	3.45	11.6	4.64
UEV_R (with L&S) (E+09 sej/g)	6.82	6.5	7.34	3.68	0.83	4.81	0.73	5.06	0.79
UEV_E (with L&S) (E+05 sej/J)	4.55	0.34	4.89	2.45	0.44	3.21	0.39	3.37	0.42
$UEV_{currency}$ (with L&S) (E+12 sej/USD)	5.05	4.37	5.05	5.05	1.20	5.05	7.88	5.05	5.22

Scenarios in Ghana include: Extensive0, Extensive12, Intercrop20, Intensive50 and Intensive100 (this study).

[a] Environmental information on the counterpart systems include: *Maya traditional systems* in Mexico, *Hybrid2009* in Brazil, *Hybrid1986* in Argentina, and *Hybrid1995* in Argentina (after Rótolo et al., 2015).

in other developing regions of the world is shown in Table 13.

4.4. Strengths and weaknesses

The strengths were as follows: the various approaches which constituted this integrated methodology were compatible, and hence the complementarity contributed to comprehensive information. The application of the EM-DEA approach is primarily useful for quantitative accounting of human labour, draft animal power including other resources, which are difficult to account for using some other methods. This leads to information that could contribute to complete assessment, and hence resource optimisation in small-scale agricultural systems. The scarcity of data was a weakness. However, we overcame this weakness by combining data from primary and secondary sources including simulations using APSIM. Hence, another strength of this study is that limited data was used to obtain meaningful results, which could be useful to planners when making informed decision on strategic agricultural land use planning.

5. Conclusion

This study applied an integrated methodology, which was constituted of the following: the EM-DEA, environmental CBA, VCA, and SBSC approaches, -to support MCDA for strategic agricultural land use planning, which could contribute to improve food security in northern Ghana, while considering a maize value-web approach. The results are based on limited data from primary sources, and in combination with data from secondary sources including simulations using APSIM. The datasets were used to model the following five scenarios: *Extensive0*, *Extensive12*, *Intercrop20*, *Intensive50* and *Intensive100* for maize production.

The results show that, the total emergy (U) increases as the quantity of inputs are increased. When labour and service were excluded from the accounting, the value of U was between 0.27 E + 15 and 9.55 E + 15 sej/ha/yr. When labour and services were included in the accounting, the value of U was between 5.35 and 9.55 sej/ha/yr. The yield obtained by the scenarios was between 0.93 and 2.25 ton/ha (d.m.). By assuming that the regional scale was equal to the UER, the food provision from grain was between 11,308,284,000 and 27,159,212,000 kcal/yr, while the electricity which could be generated from residue was between 3,746.84 and 8,998.81 MW h/yr, respectively. The integration of agricultural land use adaptation and energy planning presents a useful link for improving food security.

Among the scenarios for maize cropping in Ghana, *Intercrop20* and *Intensive50* represent the best-case scenarios for agricultural land use adaptation, which could contribute to resource optimisation and ultimately improve food security, while minimising the environment impacts of maize production. When the scenarios for maize cropping in Ghana are compared to similar systems in other developing regions in the world, the results show that when the assessment considers resources from nature and materials, the scenarios in northern Ghana show better environmental performance as compared to the counterpart systems. However, when the assessment considers resources from nature, materials, labour and services, the counterpart systems were more efficient and sustainable as compared to the scenarios in Ghana. Based on this evidence, it is advisable to improve maize cropping in Ghana by improving the NPK/urea dosage, sow seeds of high yielding varieties as well as practice supplemental irrigation, while human labour input and cost of services could be reduced.

The EM-DEA approach is primarily useful for detailed assessment of RUE and sustainability, by providing quantitative accounting of all resources of a system. Hence, the EM-DEA approach could empower decision makers with comprehensive information, which could lead to resource optimisation. Thus, this study demonstrates a pragmatic application of the EM-DEA approach to assess the RUE and sustainability of maize production systems at farm and regional scales, as well as in connecting the management planning level and regional development considerations. The integration of such information into land use –at the planning stage is envisioned as a means which could lead to ecodesign of agricultural production systems for the fight against hunger. This paper could be improved further by: (i) increasing the sample size of the primary data, and (ii) substituting the simulations with reliable real-world empirical data on maize production.

Declaration of Competing Interest

There is no conflict of interest

CRediT authorship contribution statement

Francis Molua Mwambo: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Christine Fürst:** Validation, Writing - review & editing. **Benjamin K. Nyarko:** Writing - review & editing. **Christian Borgemeister:** Writing - review & editing. **Christopher Martius:** Writing - review & editing.

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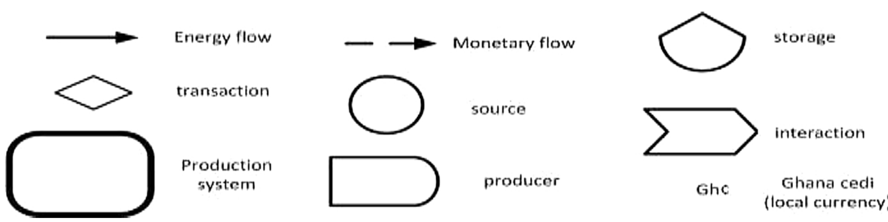
Appendix A. Other data and Emergy diagrams



Source: Energy systems symbols from Odum (1996).

Table A1
Maize yield for Bolgatanga and Bongo for the years 2003 – 2011.
Source: Statistics, Research and Information (SRID), Ministry of Food and Agriculture (MoFA), Ghana

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	

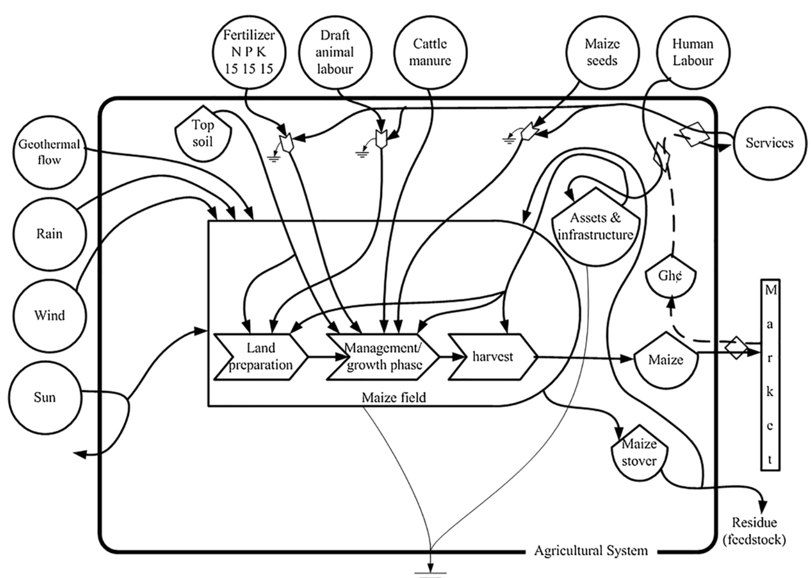


Fig. A1. A simplified emergy diagram of *Extensive12* and *Extensive0.*
Note: Manure is provided for free or produced locally, and therefore no service is associated.
Source: Adapted from Zucaro et al. (2013).

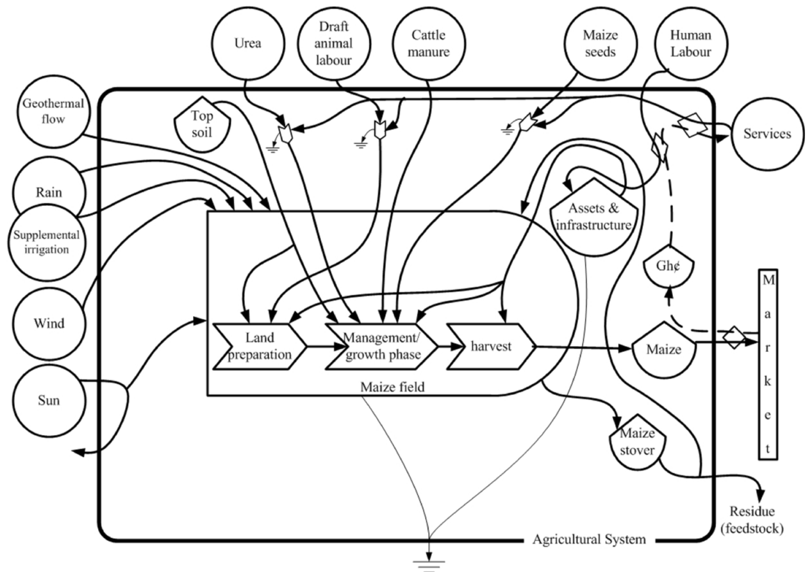


Fig. A2. A simplified emergy diagram of *Intensive50* and *Intensive100*.
Note: Manure is provided for free or produced locally, and therefore no service is associated.
Source: Adapted from Zucaro et al. (2013).

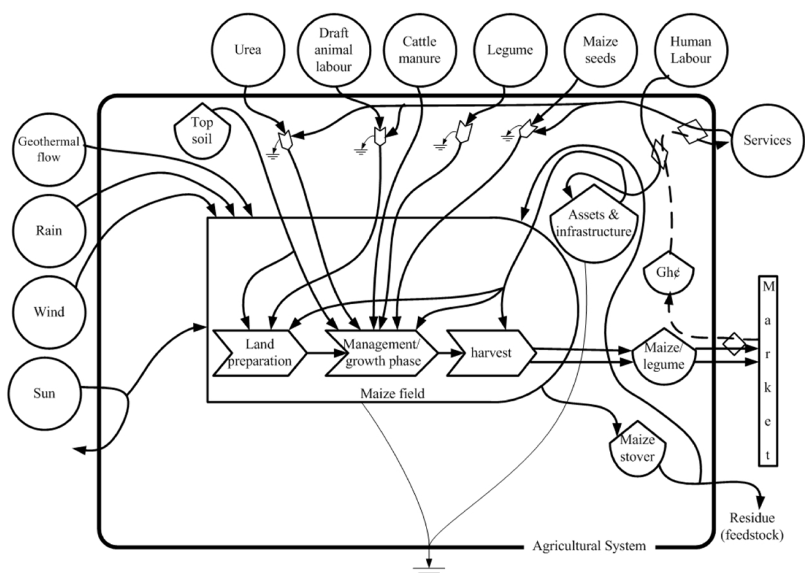


Fig. A3. A simplified emergy diagram of *Intercrop20*.
Note: Manure is provided for free or produced locally, and therefore no service is associated.
Source: Adapted from Zucaro et al. (2013).

Table A2
Distinction between emergy diagrams.

Diagrams	Scenario	Characteristic features
Fig. 3	*Extensive0* and *Extensive12*	no irrigation, no legume
Fig. 4	*Intensive50* and *Intensive100*	supplemental irrigation
Fig. 5	*Intercrop20*	legume as an intercrop

Appendix B. Integrated conceptual models of polygeneration in agricultural resource use

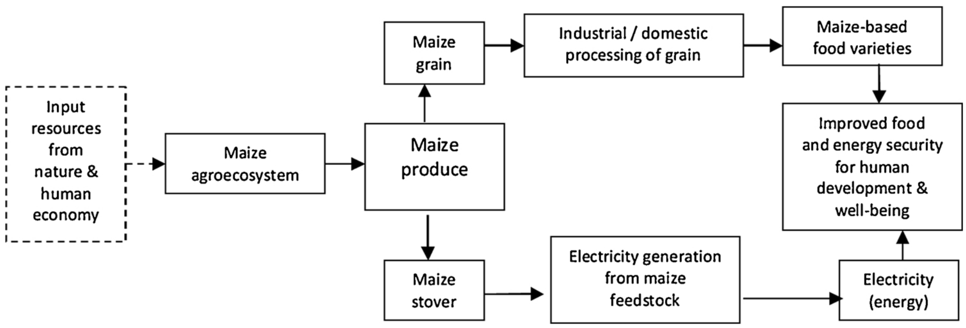


Fig. B1. A schematic value chain model to fit *Extensive12*, *Extensive0*, *Intensive50* and *Intensive50*.

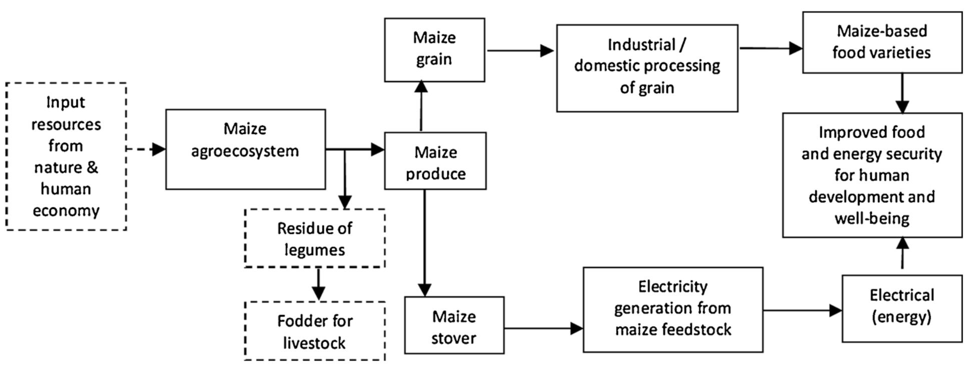


Fig. B2. A schematic value chain model to fit *Intercrop20*.

Table B1
Specifications of the OSDEA model.

Model Name	Maize agricultural land use planning
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. Data and Emergy accounting Pimentel and Pimentel (1980)

Table C1
Emergy evaluation of annual inputs and outputs normalised at 1 ha of land.

Note	Item	Unit	Raw amount for Extensive0	UEV (sej/unit)	Emergy flow for Extensive (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 (l. avail.) (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 labour	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]
	Labour & Services (L & S)													
11	Human labour (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	Grain (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]
	Grain (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	Grain (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]
	Grain (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] CEP http://www.cep.ees.ufl.edu/emergy/nead.shtml, [n] This study [o] This study.

Table C2
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 los s (sej/ha/yr)	NPK/urea (sej/ha/yr)	Animal labour (sej/ha/yr)	Seeds(sej/ha/yr)	Human labour (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	.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

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 normalised 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 (normalised 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, m²)(heat flow per area, Jm-²y^{-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 (normalised 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 (normalised 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 (normalised 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 (normalised 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 labour:
Area: 1.00E+04 m^2 (normalised to 1ha)
Total time to plough = 2.40E+01hr/yr
UEV = 1.39E+12 sej h^{-1} (this study)

8 **Maize seeds**
Area: 1.00E+04 m^2 (normalised 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 labour**
Area: 1.00E+04 m^2 (normalised to 1ha)
Fraction of labour 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 labour = 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 (normalised 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 & 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 **Grain**
Area: 1.00E+04 m^2 (normalised 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 & 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 (normalised 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*)

Appendix D. Evaluation of efficiency and sustainability

Evaluation of efficiency (Note: $UEV_R \equiv$ EcoERU, $UEV_E \equiv$ EcoEEU)

Extensive0

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

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

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

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

Extensive12

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

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

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

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

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

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

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

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

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

Evaluation of sustainability

Extensive0 (without L&S)

$$Total\ emergy\ U = 2.30E+14 + 1.96E+12 + 0.00E+00 + 3.32E+13 + 8.19E+12 = 2.73E+14sej$$

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

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

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

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

Ext.0 (with L&S)

$$Total\ emergy\ U = 2.30E+14 + 1.96E+12 + 0.00E+00 + 3.32E+13 + 8.19E+12 + 4.41E+15 + 6.67E+14 = 5.35E+15sej$$

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

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

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

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

Extensive12 (without L&S)

$$Total\ emergy\ U = 2.30E+14 + 1.96E+12 + 1.22E+14 + 3.32E+13 + 8.19E+12 = 3.96E+14sej$$

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

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

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

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

Ext.12 (with L&S)

$$Total\ emergy\ U = 2.30E+14 + 1.96E+12 + 1.22E+14 + 3.32E+13 + 8.19E+12 + 4.77E+15 + 7.03E+14 = 5.87E+15sej$$

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

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

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

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

Intercrop20 **(without L&S)**

$$Total\ emergy\ U = 2.30E{+}14 + 4.89E{+}11 + 1.17E{+}14 + 3.32E{+}13 + 4.10E{+}12 = 3.85E{+}14\,sej$$

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

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

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

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

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

$$Total\ emergy\ U = 2.30E{+}14 + 4.89E{+}11 + 1.17E{+}14 + 3.32E{+}13 + 4.10E{+}12 + 3.55E{+}15 + 7.11E{+}14 = 4.64E{+}15\,sej$$

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

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

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

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

Intensive50 **(without L&S)**

$$Total\ emergy\ U = 2.75E{+}14 + 1.96E{+}12 + 2.93E{+}14 + 3.32E{+}13 + 8.19E{+}12 = 6.11E{+}14\,sej$$

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

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

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

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

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 D1
Results of relative sustainability assessment in OSDEA.

Scenario Name	Objective Value	Efficient
Extensive0	1	Yes
Extensive12	0.647	No
Intercrop20	1	Yes
Intensive50	1	Yes
Intensive100	1	Yes

Appendix E. Calculation of environmental costs

Assumption: Environmental costs (impacts) = Total emergy U (see also Table 17)

Costs at Local scale (without L&S)

Area = 1ha

Environmental costs = 2.73E+14 *sej* (*Extensive0*)
= 3.96E+14 *sej* (*Extensive12*)
= 3.85E+14 *sej* (*Intercrop20*)
= 6.11E+14 *sej* (*Intensive50*)
= 9.04E+14 *sej* (*Intensive100*)

Costs at Local scale (with L&S)

Environmental costs = 5.35E+15*sej* (*Extensive0*)
= 5.87E+15 *sej* (*Extensive12*)
= 4.64E+15 *sej* (*Intercrop20*)
= 8.85E+15 *sej* (*Intensive50*)
= 9.55E+15 *sej* (*Intensive100*

Costs at Regional scale (without L&S)

Cultivated area = 3310ha

Environmental costs = 2.73E+14 * 3310 = 9.05E+17 *sej* (*Extensive0*)
= 3.96E+14 * 3310 = 1.31E+18 *sej* (*Extensive12*)
= 3.85E+14 * 3310 = 1.27E+18 *sej* (*Intercrop20*)
= 6.11E+14 * 3310 = 2.02E+18 *sej* (*Intensive50*)
= 9.04E+14 * 3310 = 2.99E+18 *sej* (*Intensive100*)

Costs at Regional scale (with L&S)

Environmental costs = 5.35E+15 * 3310 = 1.77E+19*sej* (*Extensive0*)
= 5.87E+15 * 3310 = 1.94E+19*sej* (*Extensive12*)
= 4.64E+15 * 3310 = 1.54E+19 *sej* (*Intercrop20*)
= 8.85E+15 * 3310 = 2.93E+19 *sej* (*Intensive50*)
= 9.55E+15 * 3310 = 3.16E+19 *sej* (*Intensive100*

Appendix F. Calculation of food provisions

Extensive0

Y_{dm} = 1.17 *(1-0.2) = 0.936(*Extensive0*)
GP_{Adm} = 0.936 * 3310 = 3098.16
FP_{AES} = 3098.16 * 3650000 = 11308284x10^3 kcal
$FP_{AES/ha}$ = (11308284x10^3)/3310 = 3416400 kcal
Average minimum dietary energy requirement of a human with sedentary lifestyle per day = 1800kcal
Av. minimum dietary energy requirement of human per annum = 1800*365 = 657000kcal
N° persons to feed per annum = (11308284x10^3)/657000 = 17212

Extensive12

Y_{dm} = 1.2 * (1-0.2) = 0.96 (*Extensive12*)
GP_{Adm} = 0.96 * 3310 = 3177.6
FP_{AES} = 3813.12 * 3650000 = 11598240x10^3 kcal
$FP_{AES/ha}$ = (11598240x10^3)/3310 = 3504000 kcal
Average minimum dietary energy requirement of a human with sedentary lifestyle per day = 1800kcal
Av. minimum dietary energy requirement of human per annum = 1800*365 = 657000kcal
N° persons to feed per annum = (11598240x10^3)/657000 = 17653.333

Intercrop20

Y_{dm} = 1.88 * (1-0.2) = 1.504 (*Intercrop20*)
GP_{Adm} = 1.504 *3310 = 4978.24
FP_{AES} = 4978.24 * 3650000 = 18170576x10^3 kcal
$FP_{AES/ha}$ = (18170576x10^3)/3310 = 5489600kcal
Average minimum dietary energy requirement of a human with sedentary lifestyle per day = 1800kcal
Av. minimum dietary energy requirement of human per annum = 1800*365 = 657000kcal
N° persons to feed per annum = (18170576x10^3)/657000 = 27656.889

Intensive50

Y_{dm} = 2.75 * (1-0.2) = 2.2 (*Intensive50*)
GP_{Adm} = 2.2 * 3310 = 7282
FP_{AES} = 7282 * 3650000 = 26579300x10^3 kcal
$FP_{AES/ha}$ = (26579300x10^3)/3310 = 8030000kcal
Average minimum dietary energy requirement of a human with sedentary lifestyle per day = 1800kcal
Av. minimum dietary energy requirement of human per annum = 1800*365 = 657000kcal
N° persons to feed per annum = (26579300x10^3)/657000 = 40455.556

Intensive100

Y_{dm} = 2.81 * (1-0.2 = 2.248 (*Intensive100*)
GP_{Adm} = 2.248 * 3310 = 7440.88
FP_{AES} = 7440.88 * 3650000 = 27159212x10^3 kcal
$FP_{AES/ha}$ = (27159212x10^3)/3310 = 8205200kcal
Average minimum dietary energy requirement of a human with sedentary lifestyle per day = 1800kcal
Av. minimum dietary energy requirement of human per annum = 1800*365 = 657000kcal
N° persons to feed per annum = (27159212x10^3)/657000 = 41338.222

Appendix G. Calculation of electricity generated using residue

Extensive0

G_A = 1.17(3310)* 1 = 3872.7ton (stover)
A_A = 3872.7*0.6 = 2323.62ton (stover)
D_A = 2323.62– [2323.62*0.155] = 1963.4589ton (stover)

G_A =1.17(3310)*0.25= 968.175ton (cob)
A_A = 968.175*0.6 = 580.905ton (cob)
D_A = 580.905-[580.905*0.08] = 534.43ton (cob)
$D_{residue}$ =1963.46+534.43 = 2497.89ton (stover and cob)
E_T = (2497.89*15)1000 = 37.46835TJ
= (534.43*1.5)/1 = 3746.84MWh

Extensive12

G_A = 1.2(3310)*1= 3972ton (stover)
A_A = 3972 *0.6 = 2383.2ton (stover)
D_A = 2383.2- [2383.2*0.155] = 2013.804ton (stover)

G_A = 1.2(3310)0.25 = 993 (cob)
A_A = 993*0.6 = 595.8ton (cob)
D_A = 595.8-[595.8*0.08] = 548.14ton (cob)
$D_{residue}$ = 2013.804+548.14 =2561.936ton (stover+cob)
E_T = (2561.94*15)/1000 = 38.3290TJ
= (2561.936*1.5)/1 = 3842.90MWh

Intercrop20

G_A = 1.88(3310)*1 = 6222.8 (stover)
A_A = 6222.8*0.6 = 3733.68 (stover)
D_A = 3733.68-[3733.68*0.155] = 3154.96ton (stover)

G_A = 1.88(3310)*0.25 = 1555.7 (cob)
A_A = 1555.7*0.6 = 933.42ton (cob)
D_A = 933.42-[933.42*0.08] = 858.75ton (cob)
$D_{residue}$ = 3154.96+858.7464 = 4013.71ton (stover+cob)
E_T = (4013.71*15)/1000 = 60.2056TJ
(4013.71*1.5)/1= 6020.56MWh

Intensive50

G_A = 2.75(3310)*1 = 9102.5ton (stover)
A_A = 9102.5*0.6 = 5461.5ton (stover)
D_A = 5461.5- [5461.5*0.155] = 4614.9675ton (stover)

G_A = 2.75(3310)*0.25 = 2275.625 ton (cob)
A_A = 2275.625*0.6 = 1365.375 ton (cob)
D_A = 1365.375-[1365.375*0.08] = 1256.145
$D_{residue}$ = 4614.9675+1256.145 = 5871.1125ton (stover+cob)
E_T = (5871.11*15)/1000 = 88.0665TJ
= (5871.11*1.5)/1 = 8806.67MWh

Intensive100

G_A = 2.81(3310)*1 = 9301.1ton (stover)
A_A = 9301.1*0.6 = 5580.66ton (stover)
D_A = 5580.66- [5580.66*0.155] = 4715.6577ton (stover)

G_A = 2.81(3310)*0.25 = 2325.275ton (cob)
A_A = 2325.275*0.6 = 1395.165 ton (cob)
D_A = 1395.165-[1395.165*0.08] = 1283.5518 ton (cob)
$D_{residue}$ = 4715.6577+1283.5518 = 5999.2095ton (stover+cob)
E_T = (5999.21*15)1000 = 89.98815TJ
= (5999.21*1.5)/1 = 8998.82MWh

Appendix H. Calculation of scores for the SBSC

Economic dimension

Internal Business Process (IBP) Perspective

Investment considered as Services (see item 12 in Table 17)

Investment Cost = 513.5 (*Extensive0*)
= 541.1 (*Extensive12*)
= 547.5 (*Intercrop20*)
= 1618.5 (*Intensive50*)
= 1723.5 (*Intensive100*)

Customer (market) Perspective

Revenue = yield matter dry * price (it was assumed that dehydration was a process which added value to grain).
Weighted average price of maize = 1421.69 Gh¢/ton (MoFA 2016)

Revenue = 0.94 * 1421.69 = 1336.39 (*Extensive0*)
= 0.96 * 1421.69 = 1364.82 (*Extensive12*)
= 1.50 * 1421.69 = 2132.54 (*Intercrop20*)
= 2.20 * 1421.69 = 3127.72 (*Intensive50*)
= 2.25 * 1421.69 = 3198.80 (*Intensive100*)

Financial Perspective

Return on Investment (ROI) = Revenue - Investment

ROI = 1336.39 – 513.5 = 822.89 (*Extensive0*)
= 1364.82 – 541.1 = 823.72 (*Extensive12*)
= 2132.54 – 547.5 = 1585.04 (*Intercrop20*)
= 3127.72 – 1618.5 = 1509.22 (*Intensive50*)
= 3198.80 – 1723.5 = 1475.30 (*Intensive100*)

Economic score total = ROI (revenue - investment)

ROI = 822.89 (*Extensive0*)
= 823.72 (*Extensive12*)
= 1585.04 (*Intercrop20*)
= 1509.22 (*Intensive50*)
= 1475.30 (*Intensive100*)

Social dimension

Learning & Growth Perspective

Technologies (techniques for introducing fertilization & irrigation)
(NPK/urea = 1.0, NPK/urea application rate every 10kg/ha = 0.01, manure = 0.1, N_2 fixation by legumes = 0.3, rainfed = 0.0, irrigation = 0.4)

Technologies = 0.1 + 0.0 = 0.1 (*Extensive0*)
= 1.0 + 0.012 + 0.1 + 0.0 = 1.11 (*Extensive12*)
= 1.0 + 0.02 + 0.1 + 0.3 + 0.0 = 1.42 (*Intercrop20*)
= 1.0 + 0.05 + 0.4 = 1.45 (*Intensive50*)
= 1.0 + 0.10 + 0.4 = 1.50 (*Intensive100*)

Food provision (quantity + diversity of food provision, i.e. quantity: food provision in kcal. 1000000kcal = 1, diversity: solely maize = 1, maize & legume =1.5)

Food provision = 3.4+1 = 4.4 (*Extensive0*)
= 3.5+1 = 4.5 (*Extensive12*)
= 5.4+1.5 = 6.9 (*Intercrop20*)
= 8.0+1 = 9.0 (*Intensive50*)
= 8.2+1 = 9.2 (*Intensive100*)

Social score total = Technologies + Food provision
= 0.1 + 4.4 = 4.50 (*Extensive0*)
= 1.11 + 4.5 = 5.61 (*Extensive12*)
= 1.42 + 6.9 = 8.32 (*Intercrop20*)
= 1.45 + 9.0 = 10.45 (*Intensive50*)
= 1.50 + 9.2 = 10.70 (*Intensive100*)

Environmental dimension

Environmental Accounting Perspective (L&S included. See also Table 17 & Table 7)

EYR = 1.05 (*Extensive0*)
= 1.05 (*Extensive12*)
= 1.05 (*Intercrop20*)
= 1.03 (*Intensive50*)
= 1.03 (*Intensive100*)

ELR = 22.27 (*Extensive0*)
= 24.54 (*Extensive12*)
= 19.19 (*Intercrop20*)
= 31.18 (*Intensive50*)
= 33.73 (*Intensive100*)

ESI = 0.05 (*Extensive0*)
= 0.04 (*Extensive12*)
= 0.05 (*Intercrop20*)
= 0.03 (*Intensive50*)
= 0.03 (*Intensive100*)

%REN = 0.04 (*Extensive0*)
= 0.04 (*Extensive12*)
= 0.05 (*Intercrop20*)
= 0.03 (*Intensive50*)
= 0.03 (*Intensive100*)

Environmental score total = EYR + (-) ELR + ESI + %REN
= 1.05 -22.27 + 0.05 + 0.04 = (-)21.13 (*Extensive0*)
= 1.05 -24.54 + 0.04 + 0.04 = (-)23.41 (*Extensive12*)
= 1.05 -19.19 + 0.05 + 0.05 = (-)18.04 (*Intercrop20*)
= 1.03 -31.18 + 0.03 + 0.03 = (-)30.09 (*Intensive50*)
= 1.03 -33.73 + 0.03 + 0.03 = (-)32.64 (*Intensive100*)

Overall Total = Economic score +Social score + Environmental score
= 822.89 + 4.50 -21.13 = 806.26 (*Extensive0*)
= 823.72 + 5.61 -23.41 = 805.92 (*Extensive12*)
= 1585.04 + 8.32 -18.04 = 1575.32 (*Intercrop20*)
= 1509.22 + 10.45 -30.09 = 1489.58 (*Intensive50*)
= 1475.30 + 10.70 -32.64 = 1453.36 (*Intensive100*)

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