Energy efficiency analysis of biomass production
-
Considering human and draft animal labor inputs in maize-based production systems in the Sudanian savanna agroecological zone, Ghana

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"Human and animal labour requirements fall outside the traditional boundaries of energy sector planning, and their dynamics are far more complex than those of fuel and electricity supply. However, since human labour remains the predominant source of energy for agricultural production in much of Africa, and transitions to animal traction and fuel using machinery are important for the social and economic effects, human and animal labour requirements and trade-offs remains an important area for research".

(FAO 1995 p. 59)

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Dedication

I dedicate this thesis to

my family, for their special love and support,

and also to

the lovely memories of my late mother, Anastasia Nalova Mwambo.
She believed in my capabilities to success in my academic career, and she always supported me with the best that she could offer. The unexpected passing of my late mother led to an excruciating psychological shock that I had to deal with, and in particular as it happened barely two months before I defended this thesis.

It suffices to say that though she did not live long enough to witness the defense of this thesis, her belief in my capabilities and the encouragement that I received from my family were great motivation that contributed in making this journey a success.
This dedication is a special feeling of gratitude to my family and late mother.

Summary

This doctoral thesis entitled "Energy efficiency analysis of biomass production - Considering human and draft animal labor inputs in maize-based production systems in the Sudanian savanna agroecological zone, Ghana", is one out of the two final outputs that constitute the Deliverable 4.5: "Integrated assessment of land use adaptation", within the context of the BiomassWeb Project. The overall goal of the Project was "to provide concepts to increase the availability of and access to food in sub-Saharan Africa through more and higher-value biomass for food and non-food purposes in the next decades". The Project was funded by the German Federal Ministry of Education and Research (BMBF, FZK: 031A258A) with support fund from the German Federal Ministry of Economic Cooperation and Development (BMZ). The main objectives of this research were as follows:

1. To develop a holistic assessment framework that assesses energy efficiency in agronomic land use as a whole.
2. To supply the value web system analysis with additional information on possible trade-offs regarding the challenge of world-wide increasing energy scarcity.

In this research, the Emergy-Data Envelopment Analysis (EM-DEA) approach was developed by coupling the Emergy Accounting (EMA) and Data Envelopment Analysis (DEA) methods to form an assessment framework, and integrating the concept of eco-efficiency into the framework to assess resource as well as energy use efficiency (RUE & EUE) and sustainability of agricultural production systems, while considering various input resources and land use characteristics as a whole. The EM-DEA approach was then empirically tested, while doing a comparative analysis of five maize production scenarios in two studies. The study area was Bolgatanga and Bongo Districts, Ghana, sub-Saharan Africa. Data curation was by combining land use, resource management and production data that were acquired through field survey, with geophysical data that were acquired from published secondary sources. To cope with the fragmented data, the Agricultural Production Systems sIMulator (APSIM) was used to simulate maize productivity in four out of the five maize production scenarios that were modeled in this research as follows:

1. Extensive rainfed maize system if the external input is 0 kg/ha/yr urea, with/ without manure (*Extensive0*).
2. Extensive rainfed maize system if the external input is 12 kg/ha/yr NPK, with/ without manure (*Extensive12*).
3. Rainfed maize-legume (cowpea - *Vigna unguiculata*, soybean - *Glycine max*, or groundnut - *Arachis hypogaea*) intercropping system if the external input is 20 kg/ha/yr urea, with/ without manure (*Intercrop20*).
4. Intensive maize system if the external input is 50 kg/ha/yr urea, including supplemental irrigation (*Intensive50*).
5. Intensive maize system if the external input is 100 kg/ha/yr urea, including supplemental irrigation (*Intensive100*).

The first study applies the EM-DEA approach together with the approach, which was adapted from the Ex-Ante Carbon balance Tool (EX-ACT) in this research, to assess the environmental impacts of the various maize production scenarios. The EM-DEA approach was used to assess the RUE, EUE and sustainability, while the adapted EX-ACT approach was used to assess the carbon footprint of the scenarios. The results show that *Extensive12* is inefficient when compared with *Extensive0*, *Intercrop20*, *Intensive50*, and *Intensive100*. *Intercrop20* used modest amount of input resources and achieved the greatest marginal

yield, better RUE, EUE, sustainability, and low carbon footprint. To a lesser extent, *Intensive50* achieved similar results as *Intercrop20*. *Intensive100* produced the greatest yield, but also incurred the greatest demand for resources (i.e. energy, materials, labor and services) and emitted the greatest amount of greenhouse gas emissions.

The second study applies the EM-DEA approach to assess the RUE, EUE and sustainability of the maize production scenarios. The emergy-based analysis was used as the proxy to further quantify and analyze benefits, which could be derived from maize produce through value addition. An integrated methodology which was composed of the following approaches: environmental Cost-Benefit Analysis, Value Chain Analysis, and Sustainability Balanced Scorecard, was used to support a multi-criteria decision analysis for strategic agricultural land use planning, which aims at improving food security and efficient use of resources. The results show that *Intercrop20* and *Intensive50* achieved the greatest amount of benefits (i.e. food and bioelectricity provisions from grain and residue, respectively), which could be obtained at the least environmental costs. Based on this empirical evidence, *Intercrop20* and *Intensive50* are recommended land uses for optimizing resource use while ensuring sustainability in low and high-input maize production systems, respectively.

The strengths of the EM-DEA approach are that it offers flexibility to account for multiple inputs and outputs of diverse types from various sources as emergies that are measured using a common unit (i.e. the solar emjoule), and also the capacity to compare multiple production systems as peers based on their relative ability to convert inputs into outputs. As such, the application of the EM-DEA approach leads to a complete environmental and economic accounting. This contributed in a holistic and comprehensive assessment of RUE, EUE and sustainability of the maize systems. The detailed accounting led to complete assessment information, which could be useful when making informed decisions at farm and regional scales, as well as in connecting the management planning level and regional development considerations.

This thesis was conceived as a cumulative work, comprised of five paper in total. Two of them were published in conferences, i.e. grey literature, and three articles were published in peer-reviewed journals, i.e. ISI listed. The thesis is organized into eight chapters.

Zusammenfassung

Diese Dissertation mit dem Titel „Energieeffizienzanalyse der Biomasseproduktion – Unter Berücksichtigung menschlicher und Zugtierarbeitseinsätze in Mais-basierten Produktionssystemen in der Sudanian Savanna agroecological zone, Ghana“ ist eines der beiden Endergebnisse, die das Ergebnis 4.5 bilden: „Integrierte Bewertung der Landnutzungsanpassung“ im Rahmen des BiomassWeb-Projekts. Übergeordnetes Ziel des Projekts war es, „Konzepte bereitzustellen, um in den nächsten Jahrzehnten die Verfügbarkeit und den Zugang zu Nahrungsmitteln in Subsahara-Afrika durch mehr und höherwertige Biomasse für Food- und Non-Food-Zwecke zu erhöhen“. Das Projekt wurde vom Bundesministerium für Bildung und Forschung (BMBF, FZK: 031A258A) mit Fördermitteln des Bundesministeriums für wirtschaftliche Zusammenarbeit und Entwicklung (BMZ) gefördert. Die Hauptziele dieser Untersuchung waren folgende:

1. Entwicklung eines ganzheitlichen Bewertungsrahmens, der die Energieeffizienz in der agronomischen Landnutzung als Ganzes bewertet.
2. Die Value Web Systemanalyse mit zusätzlichen Informationen über mögliche Kompromisse im Hinblick auf die Herausforderung der weltweit zunehmenden Energieknappheit zu versorgen.

Diese Forschung entwickelte den Ansatz der Emergy-Data-Envelopment-Analyse (EM-DEA), indem die Methoden der Emergy Accounting (EMA) und Data Envelopment Analysis (DEA) zu einem Bewertungsrahmen gekoppelt wurden und das Konzept der Ökoeffizienz in den Rahmen für die Bewertung der Ressourcen- und Energieeffizienz (RUE & EUE) sowie der Nachhaltigkeit landwirtschaftlicher Produktionssysteme unter Berücksichtigung der Ressourcen- und Landnutzungsmerkmale als Ganzes. Anschließend wurde der EM-DEA-Ansatz empirisch getestet, wobei in zwei Studien eine vergleichende Analyse von fünf Maisproduktionsszenarien durchgeführt wurde. Das Untersuchungsgebiet war die Distrikte Bolgatanga und Bongo, Ghana, Subsahara-Afrika. Die Datenkuratierung erfolgte durch die Kombination von Landnutzungs-, Ressourcenmanagement- und Produktionsdaten, die durch Felduntersuchungen gewonnen wurden, mit geophysikalischen Daten, die aus veröffentlichten Sekundärquellen gewonnen wurden. Um mit den fragmentierten Daten fertig zu werden, wurde der Agricultural Production Systems sIMulator (APSIM) verwendet, um die Maisproduktivität in vier der fünf Maisproduktionsszenarien zu simulieren, die in dieser Studie wie folgt modelliert wurden:

1. Umfangreiches Regenmaissystem, wenn die externe Zufuhr 0 kg/ha/Jahr Harnstoff beträgt, mit/ohne Dung (*Extensiv0*).
2. Umfangreiches Regenmaissystem, wenn die externe Zufuhr 12 kg/ha/Jahr NPK beträgt, mit/ohne Dung (*Extensive12*).
3. Regengefütterte Mais-Leguminosen (Kuherbse - Vigna unguiculata, Sojabohne - Glycine max oder Erdnuß - Arachis hypogaea) Mischkultur, wenn die externe Zufuhr 20 kg/ha/Jahr Harnstoff beträgt, mit/ohne Dünger (*Intercrop20*).
4. Intensivmaisanlage, wenn die externe Zufuhr 50 kg/ha/Jahr Harnstoff beträgt, einschließlich zusätzlicher Bewässerung (*Intensiv50*).
5. Intensivmaisanlage, wenn die externe Zufuhr 100 kg/ha/Jahr Harnstoff beträgt, einschließlich zusätzlicher Bewässerung (*Intensiv100*).

Die erste Studie wendet den EM-DEA-Ansatz zusammen mit dem Ansatz an, der aus dem Ex-Ante Carbon Balance Tool (EX-ACT) in dieser Studie adaptiert wurde, um die Umweltauswirkungen der verschiedenen Maisproduktionsszenarien zu bewerten. Der EM-

DEA-Ansatz wurde verwendet, um RUE, EUE und Nachhaltigkeit zu bewerten, während der angepasste EX-ACT-Ansatz verwendet wurde, um den CO_2-Fußabdruck der Szenarien zu bewerten. Die Ergebnisse zeigen, dass *Extensiv12* im Vergleich zu *Extensiv0*, *Intercrop20*, *Intensive50* und *Intensive100* ineffizient ist. *Intercrop20* verwendete bescheidene Mengen an Input-Ressourcen und erzielte den höchsten Grenzertrag, bessere RUE, EUE, Nachhaltigkeit und einen geringen CO_2-Fußabdruck. In geringerem Maße erzielte *Intensive50* ähnliche Ergebnisse wie *Intercrop20*. *Intensive100* produzierte den größten Ertrag, verursachte aber auch den größten Bedarf an Ressourcen (d. h. Energie, Material, Arbeit und Dienstleistungen) und emittiert die meisten Treibhausgasemissionen.

Die zweite Studie wendet den EM-DEA-Ansatz an, um RUE, EUE und Nachhaltigkeit der Maisproduktionsszenarien zu bewerten. Die emergy-basierte Analyse wurde als Proxy verwendet, um den Nutzen, der aus Maisprodukten durch Wertschöpfung abgeleitet werden könnte, weiter zu quantifizieren und zu analysieren. Eine integrierte Methodik, die sich aus folgenden Ansätzen zusammensetzte: Umwelt-Kosten-Nutzen-Analyse, Wertschöpfungskettenanalyse und Nachhaltigkeitsbilanz, wurde verwendet, um eine multikriterielle Entscheidungsanalyse für die strategische landwirtschaftliche Landnutzungsplanung zu unterstützen, die darauf abzielt, die Ernährungssicherheit zu verbessern und effiziente Ressourcennutzung. Die Ergebnisse zeigen, dass *Intercrop20* und *Intensive50* den größten Nutzen (d. h. Nahrungs- und Biostromversorgung aus Getreide und Reststoffen) erzielten, der mit den geringsten Umweltkosten erzielt werden konnte. Basierend auf diesen empirischen Erkenntnissen werden *Intercrop20* und *Intensive50* als Landnutzungen empfohlen, um die Ressourcennutzung zu optimieren und gleichzeitig die Nachhaltigkeit in Maisproduktionssystemen mit geringem bzw. hohem Input sicherzustellen.

Die Stärken des EM-DEA-Ansatzes liegen darin, dass er die Flexibilität bietet, eine Vielzahl von Inputs und Outputs unterschiedlicher Art aus verschiedenen Quellen als Emergien zu berücksichtigen, die in einer gemeinsamen Einheit (d. h. dem Solar-Emjoule) gemessen werden, und auch die Fähigkeit, mehrere Produktionssysteme auf der Grundlage ihrer relativen Fähigkeit, Inputs in Outputs umzuwandeln, als gleichwertig zu vergleichen. Somit führt die Anwendung des EM-DEA-Ansatzes zu einer vollständigen Umwelt- und Wirtschaftsrechnung. Dies trug zu einer ganzheitlichen und umfassenden Bewertung von RUE, EUE und Nachhaltigkeit der Maissysteme bei. Die detaillierte Bilanzierung führte zu Informationen, die für fundierte Entscheidungen auf betrieblicher und regionaler Ebene sowie für die Verknüpfung von Managementplanungsebene und regionalen Entwicklungsüberlegungen nützlich sein können.

Diese Arbeit war als kumulative Arbeit konzipiert und umfasste insgesamt fünf Beiträge. Zwei davon wurden auf Konferenzen veröffentlicht, d.h. graue Literatur, und drei Artikel wurden in Fachzeitschriften mit Peer-Review veröffentlicht, d.h. in ISI-Listen. Die Arbeit ist in acht Kapitel gegliedert.

Content and Structure

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Abbreviations and Acronyms

APSIM	Agricultural Production Systems sIMulator
CBA	Cost-Benefit Analysis
DEA	Data Envelopment Analysis
DMU	Decision Making Unit
ELR	Environmental Loading Ratio
EMA	Emergy Accounting
EM-DEA	Emergy-Data Envelopment Analysis
ESI	Emergy Sustainability Index
EX-ACT	Ex-Ante Carbon balance Tool
EYR	Emergy Yield Ratio
F	Imported resources
FAO	Food and Agriculture Organization
GSS	Ghana Statistical Service
L	Labor
LHV	Lower Heating Value
MCDA	Multi-Criteria Decision Analysis
MoFA	Ministry of Food and Agriculture, Ghana
N	Non-renewable resources
NPK	Nitrogen Phosphorus Potassium
OSDEA	Open Source Data Envelopment Analysis
R	Renewable Resource
%REN	Percentage Renewability
rTE	relative Technical Efficiency
RUE	Resource Use Efficiency
S	Services
SBSC	Sustainability Balanced Scorecard
SE	Sustainability Efficiency
SSA	sub-Saharan Africa
TE	Technical Efficiency
U	Total Emergy
UEV	Unit Emergy Value
VCA	Value Chain Analysis

1 INTRODUCTION

1.1 Motivation

This cumulative thesis entitled "Energy efficiency analysis of biomass production - Considering human and draft animal labor inputs in maize-based production systems in the Sudanian savanna agroecological zone, Ghana", is one out of the two final outputs that constitute the deliverable 4.5: "Integrated assessment of land use adaptation" within the context of the BiomassWeb Project (https://biomassweb.org/), see also Fig. 1. The BiomassWeb Project was one of the projects in the GlobE program. The project was funded by the German Federal Ministry of Education and Research (BMBF, FZK: 031A258A) with support fund from the German Federal Ministry for Economic Cooperation and Development (BMZ). The overall goal of the project was "to provide concepts to increase the availability of and access to food in sub-Saharan Africa through more and higher-value biomass for food and non-food purposes in the next decades".

On that note, this research contributed in the goal stated above through the development of a framework that assesses resource as well as energy use efficiency and sustainability of agricultural land use as a whole, and in particular small-scale agricultural land use schemes such as those practiced in Africa. Efficiency and sustainability are essential for sustainable development. The assessment of resource and energy use efficiency (RUE & EUE) of agricultural systems is important, and in particular when considering the increasing demand for resources and energy by the global agriculture. Besides, it is a challenge to do a complete assessment of most small-scale agricultural land use systems, because some resources that are used in agricultural production are difficult to account using the existing methods. As such, often information that could contribute in improving efficiency and sustainability in African small-scale agriculture is incomplete. This situation cannot continue indefinitely forever. Therefore, it was imperative to develop an alternative approach, which could be reliable for proper environmental accounting that could lead to complete assessment information upon which wise decisions that would contribute in sustainable agriculture would be based. As such, complete environmental accounting in in agriculture is the first pragmatic step towards rational decision making to benchmark efficient and sustainable land use schemes such as those practiced in Africa.

1.2 Research objectives

The main objectives of this thesis were as follows:

1. To develop a holistic assessment framework that assesses energy efficiency in agronomic land use as a whole.
2. To supply the value web system analysis (Cluster 3 of the BiomassWeb Project) with additional information on possible trade-offs regarding the challenge of world-wide increasing energy scarcity.

The focus of the objective #1 was to develop an alternative assessment framework to assess RUE and EUE of agricultural systems as a whole, because existing methods are limited to analyze agricultural systems, and in particular to account for some input resources which are complex to quantify. For example, farm labor in small-scale agricultural production systems in Africa is done manually by humans, and transitions to animal traction and fuel using machinery. The energy expended in the form of farm labor by these sources is difficult to account. As such, it was a challenge to account for input energy from humans and draft animals when assessing African agriculture (FAO 1995). The focus of objective #2 was to apply the framework that was developed in objective #1, to assess the RUE & EUE and sustainability of African agricultural land use schemes. In particular, to provide information which could be useful for the value web system analysis, i.e. Cluster 3 within the context of the BiomassWeb Project. Maize was one of the model crops in BiomassWeb Project. As such, the assessment approach was empirically tested using small-scale maize-based production systems in Ghana, sub-Saharan Africa (SSA).

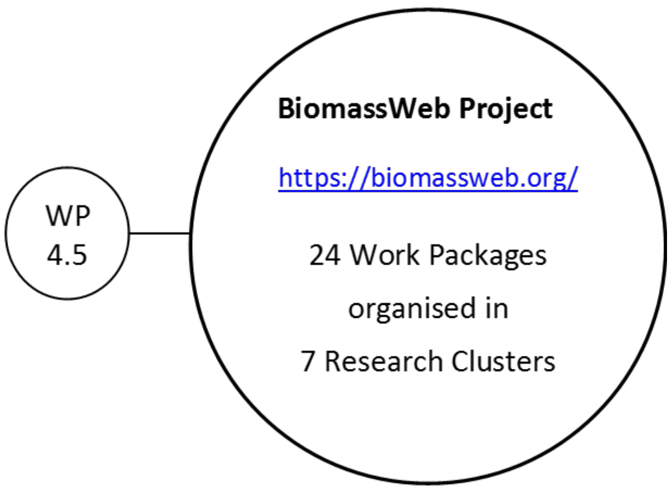

Fig. 1: An illustration of Work Package 4.5 within the context of the BiomassWeb Project

1.3 Research questions

The research questions were as follows:

1. What are meaningful system boundaries to assess the energy efficiency and sustainability of the land use systems?
2. Which types of energy and energy fluxes should be involved into the analysis to account also for energy sources and fluxes specific for land use systems in developing countries?
3. Which energy reference unit (renewable/ non-renewable) should be defined to make comparable different land use systems from traditional management (e.g. extensively used grazing and fuel wood areas) up to highly intensified industrial systems and to support comparison for alternative land use scenarios?

1.4 Strategy

The strategy to achieve the research objectives was as follows: First, the Emergy Accounting (EMA) and Data Envelopment Analysis (DEA) methods were coupled into a conceptual framework. The concept of eco-efficiency was integrated into the framework, and the Emergy-Data Envelopment Analysis (EM-DEA) approach was developed. The EM-DEA approach is an innovative approach to assess the RUE, EUE and sustainability of agricultural production systems as a whole. The article detailing the development of the EM-DEA approach was published in the *Journal of Environmental Accounting and Management*.

Second, the EM-DEA approach was empirically tested, while doing a comparative analysis of five maize production scenarios in two studies. The study area was Bolgatanga and Bongo Districts, Ghana, SSA. Data curation was by combining land use, resource management and production data that were acquired through field survey (Mwambo 2020), with geophysical data that were acquired from published secondary sources. To cope with the fragmented data, the Agricultural Production Systems sIMulator (APSIM) was used to simulate maize productivity in four out of the five maize production scenarios that were modeled in this research as follows:

1. Extensive rainfed maize system if the external input is 0 kg/ha urea, with/ without manure (*Extensive0*).
2. Extensive rainfed maize system if the external input is about 12 kg/ha NPK, with/ without manure (*Extensive12*).
3. Rainfed maize-legume (cowpea - *Vigna unguiculata*, soybean - *Glycine max*, or groundnut - *Arachis hypogaea*) intercropping system if the external input is at least 20 kg/ha urea, with/without manure (*Intercrop20*).
4. Intensive system of maize cultivation if the external input is 50 kg/ha urea, including supplemental irrigation (0.18 m/ha/yr) (*Intensive50*).
5. Intensive systems of maize cultivation if the external input is 100 kg/ha urea, including supplemental irrigation (0.18 m/ha/yr) (*Intensive100*).

The various scenarios were modeled while considering real-world agronomic land use and resource management practices as well as data criteria as follows: On the one hand, in terms of the source of production data, *Extensive12* was modeled based on production data that were gathered through interviews with farmers during the field survey, while *Extensive0*, *Intercrop20*, *Intensive50* and *Intensive100* were modeled based on production data that were simulated using APSIM. As such, *Extensive12* was considered as the "business-as-usual" or reference scenario, while *Extensive0*, *Intercrop20*, *Intensive50* and *Intensive100* were considered as the contrasting scenarios, respectively. On the other hand, in terms of resource management in maize systems, *Extensive0*, *Intercrop20* and *Extensive12* were modeled as extensive scenarios in which the amount of external inputs was limited, while *Intensive50* and *Intensive100* were modeled as intensive scenarios in which the amount of external inputs was unlimited. As such, *Extensive0*, *Intercrop20* and *Extensive12* were considered as traditional low input management systems, while *Intensive50* and *Intensive100* were considered as intensive high input systems, respectively.

The designs of the two empirical studies in which the five scenarios were comparatively analyzed, were as follows:

1. The EM-DEA approach that was developed in this research was subsequently applied to assess the RUE, EUE and sustainability of the five maize production scenarios. In addition, the carbon footprint of the maize production scenarios was evaluated using

the approach, which was adapted from the Food and Agriculture Organization Ex-Ante Carbon balance Tool (EX-ACT) in this research. As such, this study demonstrates the application of the EM-DEA approach to assess the environmental impacts of various agricultural land use production systems, while considering various input resources and land use characteristics. This article was published in the *Journal of Cleaner Production*.

2. The EM-DEA approach was applied to assess the RUE, EUE and sustainability of the five maize production scenarios. The assessment information that was obtained from using the EM-DEA approach was subsequently used as the proxy to account for the food and bioelectricity provisions as the benefits which could be obtained from maize grain and residue, while considering the environmental cost-benefit analysis (CBA) and value chain analysis (VCA) approaches. Finally, the sustainability balanced scorecard (SBSC) approach was used to aggregate the emergy-based assessment, CBA and VCA information into scores to provide an environmental, social and economic appraisal of the various production scenarios. This study demonstrates the application of the EM-DEA approach to support a multi-criteria decision analysis (MCDA) for strategic agricultural land use planning that aims at improving food and energy security. This article was published in *Land Use Policy*.

1.5 Structure

This cumulative thesis is organized into eight chapters and consists of five research papers as follows. Two of the papers were written at the preliminary stage of this research, and they provide the literature review as follows:

1. The review on the agricultural land use practices in west Africa. This paper was presented as an oral presentation at the international colloquium on the theme: "*Ethics of Food Security in a Changing Society – Learning from the Past to Shape the Future*", and was held on September 24, 2014, in Cumberland Lodge, Windsor Great Park, London, United Kingdom.
2. The review on the existing assessment methods and their limitations to analyze agricultural systems. This highlighted the gap that was closed in this research. This paper was published in the *proceedings of the 28th International Conference on Informatics for Environmental Protection (EnviroInfo)*, which was held on September 10 –12, 2014, in Oldenburg, Germany.

These two papers are cited in gray literature and they are embedded into Chapter 2 "Background". In addition, there are three-standalone peer-reviewed journal articles and they support the methods, results and synthesis of this thesis as follows:

3. The article that presents the development of the EM-DEA approach in detail, was published in the *Journal of Environmental Accounting and Management*, and it is embedded into Chapter 3 "Materials and Methods".
4. The article that demonstrates the application of the EM-DEA approach to assess the environmental impacts of agricultural production systems, and in particular small-scale maize production scenarios in Ghana.
5. The article that demonstrates the application of the EM-DEA approach to support a MCDA for strategic agricultural land use planning.

The last two articles were published in the *Journal of Cleaner Production*, and *Land Use Policy*, respectively, and they are embedded into Chapter 4 "Results". The three peer-reviewed journal articles together form the core of this thesis.

The eight chapters are organized as follows:

Chapter 1 "Introduction" provides an overview of this research, and presents the research motivation, objectives, questions, strategy and structure of this thesis.

Chapter 2 "Background" presents the literature review. The two papers that are embedded into this chapter are as follows:

1. Mwambo, F.M., and Fürst, C. (2014). Assessing the ecological-societal impacts of west African farming practices by means of energy efficiency. Oral presentation: *Ethics of Food Security in a Changing Society – Learning from the Past to Shape the Future Colloquium. September 24, 2014. Cumberland Lodge, Windsor Great Park, United Kingdom.*
2. Mwambo, F.M., and Fürst, C. (2014). A framework for assessing the energy efficiency of non-mechanised agricultural systems in developing countries. In: *EnviroInfo 2014. Proceedings of the 28th International Conference on Informatics for Environmental Protection, Information and Communication Technology for Energy Efficiency. September 10 - 12, 2014, Oldenburg, Germany. Gómez, J.M., Sonnenschein, M., Vogel, U., Winter, A., Rapp, B. and Giesen, N. (Eds.) BIS-Verlag, Oldenburg. ISBN 978-3-8142-2317-9, pp. 565-572*.

Chapter 3 "Materials and methods" provides the characterization of the study area, and the research methodology. The article that is embedded into this chapter is as follows:

3. Mwambo, F.M., and Fürst, C. (2019). A holistic method of assessing efficiency and sustainability in agricultural production systems. *JEAM 7(1), 27-43.*

Chapter 4 “Results” presents the empirical applications of the EM-DEA approach, and the articles that are embedded into this chapter are as follows:

4. Mwambo, F.M., Fürst, C., Martius, C., Jimenez-Martinez, M., Nyarko, B.K., and Borgemeister, C. (2021). Combined application of the EM-DEA and EX-ACT approaches for integrated assessment of resource use efficiency, sustainability and carbon footprint of smallholder maize production practices in sub-Saharan Africa*. J. Clean. Prod. 302, 126132*.
5. Mwambo, F.M., Fürst, C., Nyarko, B.K., Borgemeister, C., and Martius, C. (2020). 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*. Land Use Policy 95, 104490*.

Chapter 5 “Discussion” provides a critical reflection on the strengths and weaknesses of the EM-DEA approach compared to other methods, and in particular Ecosystem Service and Life Cycle Assessment. In addition, the validation, reliability and uncertainties of the results that were obtained using the EM-DEA approach, as well as the feasibility and trade-offs analysis are discussed in detail.

Chapter 6 “Conclusions and outlook” encapsulates the key findings of this research. In addition, recommendations based on the research findings are presented. The limitations of this research, and ways to improve this research are highlighted in the outlook.

Chapter 7 “References” provides the bibliography of this thesis.

Chapter 8 “Annexes” presents the full articles that constitute this cumulative thesis.

2 BACKGROUND

2.1 Land use practices in west Africa

2.1.1 Assessing the ecological-societal impacts of west African farming practices by means of energy efficiency.

Mwambo, F.M., and Fürst, C. (2014). Oral presentation presented at the: "Ethics of Food Security in a Changing Society – Learning from the Past to Shape the Future Colloquium", held on 24 September, 2014, in Cumberland Lodge, Windsor Great Park, United Kingdom.

Extended summary

This paper was written during the preliminary stage of this research. It reviews the agronomic land use practices in west Africa, and in particular the Sudanian savanna in northern Ghana, where the study area of this research is situated. This paper was presented as an oral presentation at the international colloquium on the theme: "*Ethics of food security in a changing society – Learning from the past to shape the future*", which was held on September 24, 2014, in Cumberland Lodge, Windsor Great Park, London, United Kingdom[1]. The presentation was awarded the prize for best oral presentation in that colloquium[2]. Subsequently, this paper effectively contributed in drawing the attention of the international community to this research early on. As such, this paper is cited in gray literature, and it is embedded into this chapter -Background.

On that note, this paper reviews the small-scale farming practices and the situation of food insecurity that prevail in the Sudanian savanna agroecological zone, Ghana, west Africa. Small-scale agricultural land use systems dominate in the area. The productivity of small-scale systems is comparatively lower. Several factors are responsible for the low productivity. Small-scale agriculture strongly relies on rainfall to sustain crop growth. The vagary in seasonality and climate that are observed in west Africa implies that small-scale agricultural systems are facing a challenge as rainfall patterns become more unpredictable. Generally, since small-scale farmers have limited access to resources, farming practices in such systems could influence resource optimization and subsequently contribute in low productivity and eventually food insecurity. Therefore, using a reliable method to assess

[1] http://www.cumberlandlodge.ac.uk/learning-resources/ethics-food-security-changing-society
[2] https://biomassweb.org/allgemein/francis-molua-mwambo-won-prize-for-best-paper/

the RUE, EUE and sustainability of small-scale agricultural land use systems could lead to complete assessment. Such assessment information could be the basis for making informed decisions that could optimize resource use and subsequently contribute in improving the productivity and eventually food security. The full paper is included in the Annex (8.2).

2.2 Problem and conceptualization of solution

2.2.1 A framework for assessing the energy efficiency of non-mechanised agricultural systems in developing countries.

Mwambo, F.M., and Fürst, C. (2014). In: Proceedings of the 28th International Conference on Informatics for Environmental Protection, Information and Communication Technology for Energy Efficiency (EnviroInfo 2014). September 10 - 12, 2014, Oldenburg, Germany. Gómez, J.M., Sonnenschein, M., Vogel, U., Winter, A., Rapp, B. and Giesen, N. (eds.) BIS-Verlag, Oldenburg. ISBN 978-3-8142-2317-9, pp. 565-572.

Extended summary

This paper was written during the preliminary stage of this research. It was published in the *proceedings of the 28th International Conference on Informatics for Environmental Protection, Information and Communication Technology for Energy Efficiency (EnviroInfo)*, which was held on September 10 – 12, 2014, in Oldenburg, Germany. This paper identifies the research problematic, and proposes the conceptualization of the solution based on this research.

This paper starts with a general overview of small-scale agricultural production systems in developing countries. Production activities in such systems is predominantly manual – involving the input of energy by humans and draft animals in the form of farm labor. For example, the use of draft animals to provide traction in small-scale agricultural systems is a common practice in west Africa (Starkey & Faye 1990, Blench 1997, Hesse 1997, Fall et al. 1997, Bobobee 1999). The energy expended in the form of work done by humans and draft animals during farm labor is an input resource, which is complex to account using existing methods, because they are limited in analyzing agricultural systems. As such, before this research was conducted, it was a challenge to account for such input energy in small-scale agricultural systems, and well as to do a complete assessment of agricultural production systems (FAO 1995, Jones 1989, Blancard & Martin 2012, 2014, Alvarenga et al.

2013). More so, the increasing demand for resources and energy, as well as the emissions by the global agricultural systems is a cause for concern (Searchinger et al. 2013, FAO 2011, Hillier et al. 2009, Smith 2013, IPCC 2014). Moreover, it is a challenge to assess sustainability in agricultural systems, because it is a complex to measure (Hayati et al. 2010, Schindler et al. 2015). As such, this research problematic warranted a solution and in particular, the development of alternative and reliable method that could applicable to analyze RUE, EUE and sustainability of agricultural systems.

The conceptualization of the proposed solution was to couple Emergy Accounting (EMA) and Data Envelopment Analysis (DEA) methods to form an assessment framework. This paper explains the EMA as a concept that could be applied to achieve complete environmental accounting in a production system -particularly closed systems, while DEA is a method that could be applied to estimate the relative efficiency of peer production systems (otherwise referred to as Decision Making Units - DMUs) with multiple inputs and outputs under varying performances. In addition, the paper shows sketches of the framework, and input energy and material flow fluxes to consider when delineating the system boundary of such small-scale agricultural production systems. The fine-tuning as well as the integration of the concept of economic-ecological efficiency (i.e. eco-efficiency) into this framework, and its subsequent development into the EM-DEA approach to assess RUE, EUE and sustainability of agricultural systems as a whole, is elaborately presented in section 3.2 of this thesis.

3 MATERIALS AND METHODS

3.1 Study area

The BiomassWeb Project (http://biomassweb.org/) region was the Sudanian savanna belt (herein defined on the basis of the phytogeographical zonation by White (1983)) of the following sub-Saharan African countries: Ghana, Nigeria, and Ethiopia. Within this project region, the study area of this research was the mixed Sudanian and Guinea savannas in Bolgatanga and Bongo Districts, Upper East Region, Ghana. The study area is about 1217 km^2 located between latitudes 10° 10' and 10° 15'N, and longitudes 0° and 1° 4'W (Fig. 2).

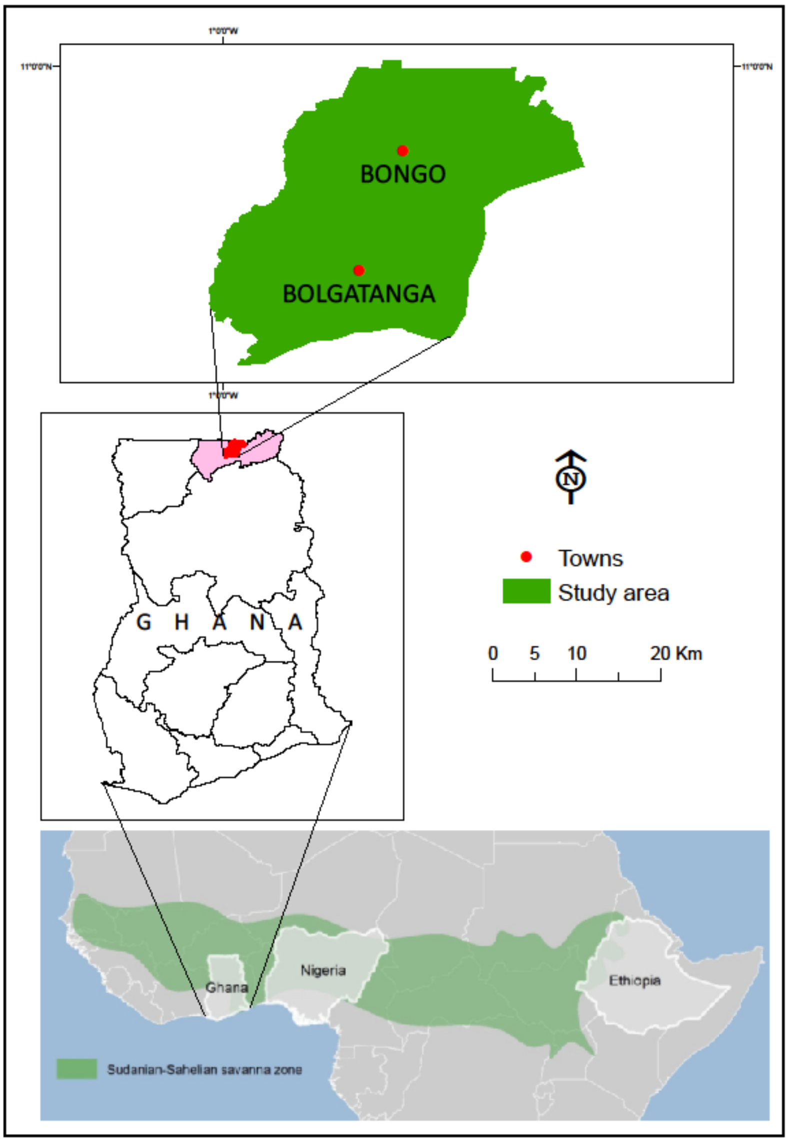

Fig. 2: Study area

The study area has a gentle undulating relief and the climate is sub-arid. The climate is greatly influenced by the circulation of the harmattan and monsoon winds (Mdemu et al. 2009). The rainfall ranges between 700 and 1100 mm per year (Callo-Concha et al. 2013, GSS 2014, Mdemu et al. 2009), and the annual mean precipitation is about 1044 mm (Badmos et al. 2015). The annual maximum temperature is about 34°C, and minimum temperature is between 15 and 18°C (Faulkner et al. 2008). The annual mean temperature is about 29°C (Faulkner et al. 2008, Badmos et al. 2015). The distribution of rainfall during the rainy season is uni-modal. The rainy season lasts from April/ May through September/ October (Mdemu et al. 2009). The length of the growing period is between 90 and 165 days (Mdemu 2008 p.11). The agroecology is a mix of Sudanian and Guinea savannas, which have been degraded due to climatic stress and pressure from agro-pastoral activities. The dominant soil types in the area are sandy clay, clayey as well as sandy loam. Generally, the soil fertility is low -with exceptions in some flood plains, where alluvial soil is deposited seasonally by the White Volta River that drains the area (Mdemu 2008, Mdemu et al. 2009). The natural vegetation is characterized by scanty stunted trees, which form an open canopy over grasses as the under storey (Bagamsah 2005) (Fig. 3).

Fig. 3: Natural vegetation in the study area
Photo was taken in November 2015, Bolgatanga

The major economic activity in the area is small-scale agriculture (Månsson 2011). The majority of small-scale farmers practice mixed cropping in rainfed systems and rear few livestock and poultry (Hailu 1990). Generally, small-scale farmers have limited access to resources and subsequently use few external inputs. The cultivation of crops is typically carried out in two farm types, namely infields and outfields which are commonly referred to as “compound farms” and “bush farms”, respectively. The former are located at close proximity to settlements, while the latter are located distant from settlements (Månsson 2011). Since maize is fast becoming an important commodity crop which could contribute in food security and industrial uses, farmers in the area are beginning to develop an interest in maize cultivation.

The production of crop in rainfed systems is threatened by the erratic rainfall pattern, which is exacerbated by changes in climate (Amikuzino & Donkoh 2012, Issahaku et al. 2016). Sparse rainfall as well as other environmental factors and persistent human pressure in the form of agro-pastoral activities attribute to land degradation (Callo-Concha et al. 2013). Such conditions could complexly combine with pressure from the increasing population -who demand for more food to be produced, and this situation could further exacerbates land degradation through poor agricultural land use practices (Akolgo 2011).

3.2 Methods

3.2.1 A holistic method of assessing efficiency and sustainability in agricultural production systems.

Mwambo, F.M., and Fürst, C. (2019). JEAM 7(1), 27-43.

Extended summary

So far, existing methods are limited in analyzing the energy efficiency of agricultural systems (Jones 1989). As such, some assessment processes in agricultural and forestry systems provide incomplete information, because some sources of input energy are complex to analyze using existing methods (Alvarenga et al. 2013). On that note, this peer-reviewed journal article (3.2.1) presents the Emergy-Data Envelopment Analysis (EM-DEA) approach as an innovative methodical approach, which was developed in this research. The approach has the capacity to assess the resource as well as energy use efficiency (RUE & EUE) and sustainability of small-scale agricultural land use systems as a whole. The approach offers the flexibility to account for various resources including land use characteristics in African small-scale agricultural land use schemes. For example, the input energy that is provided by humans and draft animals in the form of farm labor, including soil erosion as material and energy flows that occur in crop production. As such, this approach leads to complete assessment of agricultural systems. Hence, it is a proposed solution to close the knowledge gap that had existed until now as highlighted in the following excerpt:

> "*Human and animal labour requirements fall outside the traditional boundaries of energy sector planning, and their dynamics are far more complex than those of fuel and electricity supply. However, since human labour remains the predominant source of energy for agricultural production in much of Africa, and transitions to animal traction and fuel using machinery are important for the social and economic effects, human and animal labour requirements and trade-offs remains an important area for research*" (FAO 1995 p. 59).

This article consists of four sections, and they are summarized as follows: Section 1 - Introduction, presents an overview of the increasing demand for energy by the global agricultural systems. More energy will be required for the production of more food to feed the growing human population. Hence, there is a need for agricultural systems to become more efficient. The decision-making processes which could promote efficient and sustainable systems should be backed by methods that can provide comprehensive assessment of the RUE, EUE and sustainability of agricultural systems. In section 2 -Methods, the EMA and DEA methods are described and synthesized into the EM-DEA approach. An illustrative explanation of the synthesis is included in order to ease understanding. In section 3 -Discussion, the novelty of the EM-DEA approach is discussed. In section 4 -Conclusions, the strengths and weaknesses of the EM-DEA approach are highlighted. Finally, the conclusion is that the EM-DEA approach could be useful to access RUE and sustainability of agricultural systems.

In summary, the EM-DEA approach is the coupling of EMA and DEA methods to form a framework, and the integration of the concept of eco-efficiency (Keating et al. 2010), in order to assess the RUE, EUE and sustainability of agricultural systems as a whole achieved in this research (Mwambo & Fürst 2014, 2019). The EM-DEA approach achieves comprehensive assessment and offers the following advantages.

1. It offers flexibility to environmental accounting of various resource types in a system.
2. It provides quantitative accounting which leads to comprehensive information about resource and energy (exergy) use efficiency of a system.
3. The approach provides a means to express absolute and relative sustainability of a system.

To apply the EM-DEA approach, the assessment of RUE was based on the concept of eco-efficiency (herein interpreted as the ratio of environmental pressure or impact to the economic value added). As such, the RUE was calculated by equating the eco-efficiency to the Unit Emergy Value (UEV) of the yielded agricultural product (i.e. agricultural produce measured as dry mass). In other words, the eco-efficiency was equated to the ratio of the total emergy (U) to the yielded agricultural product of a given production system (which by analogy was a decision making unit -DMU) as stated in *Eq*. (1). The RUE was decomposed into two sub-efficiencies as follows:

(i) UEV in terms of Resource use (UEV_R), and

(ii) (ii) UEV in terms of Exergy use (UEV_E).

Both the UEV_R and UEV_E were further evaluated on the basis of two categories of input sources, because agricultural production requires resources from nature including raw materials as well as input resources from the human economy. In this light, agricultural systems occur at the interface between nature and the human economy. The production of an agricultural produce happens at the expense of resources from nature and possibly purchased inputs including labor (L) and services (S) from the human economy. As such, the assessment results for RUE, EUE and sustainability were presented in two distinct categories as follows:

1. Assessment results based on the environmental accounting when considering input resources from nature and raw materials, i.e. excluding labor and services (without L&S), and
2. Assessment results based on the environmental accounting when considering input resources from nature, materials, labor and services, i.e. including labor and services (with L&S).

The former category focuses on expressing the RUE, EUE and sustainability in terms of raw materials that were used up for production, while the latter category focuses on expressing the RUE, EUE and sustainability in term of resource use from the complete economy (i.e. nature including materials and human economy). Hence, the assessment of RUE & EUE based on input resources from nature and materials was evaluated using *Eqs*. (2) and (3), while the assessment of RUE & EUE based on input resources from the whole economy was evaluated using *Eqs*. (4) and (5), respectively.

$$Eco-efficieincy = \frac{Environmental\ impact}{Economic\ value} = \frac{Total\ emergy\ U}{yielded\ product} = UEV_{(product)}, \quad (1)$$

$$UEV_{R(without\ L\&S)} = \frac{U_{(without\ L\&S)}}{yielded\ product} = \frac{R+N+F}{grain\ yield_{dry\ mass\ (g)}}, \quad (2)$$

$$UEV_{E(without\ L\&S)} = \frac{U_{(without\ L\&S)}}{exergy\ of\ yielded\ product_{(J)}} = \frac{R+N+F}{grain\ yield_{dry\ mass\ (g)} * LHV}, \quad (3)$$

$$UEV_{R(with\ L\&S)} = \frac{U_{(with\ L\&S)}}{yielded\ product} = \frac{R+N+F+L+S}{grain\ yield_{dry\ mass\ (g)}}, \quad (4)$$

$$UEV_{E(with\ L\&S)} = \frac{U_{(with\ L\&S)}}{exergy\ of\ yielded\ product_{(J)}} = \frac{R+N+F+L+S}{grain\ yield_{dry\ mass\ (g)} * LHV}, \quad (5)$$

The absolute sustainability was evaluated by adopting the emergy-based indicators (Brown and Ulgiati 2004, Ulgiati et al. 2011, Dong et al. 2014, Viglia et al. 2017). The assessment of absolute sustainability based on input resources from nature and materials was evaluated using *Eqs*. (6) – (10), while the assessment of absolute sustainability based on input resources from the whole economy was evaluated using *Eqs*. (11) - (15), respectively.

$$Total\ emergy\ (U) = R + N + F\ , \tag{6}$$

$$EYR = \frac{(R + N + F)}{F}\ , \tag{7}$$

$$ELR = \frac{(N + F)}{R}\ , \tag{8}$$

$$ESI = \frac{EYR}{ELR}\ , \tag{9}$$

$$\%REN = \frac{1}{(1 + ELR)}\ , \tag{10}$$

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

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

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

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

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

where,

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

The relative sustainability was evaluated by estimating the relative technical efficiency (rTE) scores of peer DMUs (i.e. by analogy the various small-scale maize-based production scenarios that were modeled in this research) that were analyzed as a batch using the DEA. The estimated rTE scores were considered as the proxy indicator to evaluate relative sustainability of peer DMUs (De Koeijer et al. 2002, Gomes et al. 2009). In this light, the optimization function in DEA assumes the multiple ordinary least square regression as stated in *Eq*. (16), and applies Pareto efficiency to select the weights for the imported data of the peer DMUs (Kuosmanen & Johnson 2010). Given that efficiency is the ratio of output to the observed input, the productive efficiency (E_P) was calculated as the ratio of the weighted sum of outputs to the weighted sum of inputs. As such, the linear programming function in DEA reduces the ratio of weighted sum of outputs to inputs into a single virtual output as the numerator and a single virtual input as denominator. Using *Eq*. (17), the ratio of the single virtual output to the single virtual input for each DMU relative to that of the best performing DMU leads to the rTE scores (Hartwich & Kyi, 1999).

$$\gamma_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7 + \mu_i \,, \tag{16}$$

where,

$\gamma_i = yield\ or\ output\ produced\ by\ the\ i^{th} practice$

$\beta_0 = coefficient\ of\ the\ intercept$

$\beta_1, \dots \beta_7 = slopes\ or\ coefficients\ of\ selected\ input\ resources, i.e. x_1, \dots x_7$

$x_1 = evapotranspired\ water$

$x_2 = topsoil\ loss$

$x_3 = NPK\ or\ urea\ application\ intensity$

$x_4 = draft\ animal\ labor\ (plowing)$

$x_5 = maize\ seeds$

$x_6 = human\ labor$

$x_7 = services$

$\mu_i = slacks\ (residuals) of\ the\ i^{th} practice$

$$E_p = \frac{u_1 y_1 + u_2\, y_2 + u_3 y_3 + u_4 y_4 + u_m y_m}{v_1 x_1 + v_2 x_2 + v_3 x_3 + v_4 x_4 + v_n x_n} = \frac{\sum_{o=1}^{m} u_{o1} y_{o1}}{\sum_{i=1}^{n} v_{i1} x_{i1}}, \tag{17}$$

where,

E_P = productive efficiency of a DMU

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

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

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

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

The compilation of the assessment results that are obtained from the evaluations in *Eqs*. (1) – (17), leads to comprehensive information, which could be used to support informed decision making in agriculture. The full article is included in the Annex (8.2).

4 RESULTS

4.1 Application of the EM-DEA approach to assess the environmental impacts of agricultural production systems.

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

Mwambo, F.M., Fürst, C., Martius, C., Jimenez-Martinez, M., Nyarko, B.K., and Borgemeister, C. (2021). J. Clean. Prod. 302, 126132.

Extended summary

Challengingly, as the demand for resources and energy by the global agricultural systems is growing, likewise are the greenhouse gas (GHG) emissions from agriculture. For example, about 70% of fresh water use and 37% of the global land surface area are devoted to agriculture (Searchinger et al. 2013), and in particular 12 out of the 37% is cropland (Wood et al. 2000). The agri-food sector currently consumes 30% of the global energy use, which is about 95 EJ per year, while the GHG emissions are about 9.7 Gton of carbon dioxide equivalent (CO_2 e) (FAO 2011). Global agriculture was the second main source of GHGs, accounting for 24% of GHG emissions in 2010 (IPCC 2014). As such, the carbon footprint of an agricultural production system is a significant indicator as far as agricultural sustainability is concern (Hillier et al. 2009, Smith 2013).

On that note, this article (4.1.1) is an impact assessment study. It applies the EM-DEA approach (Mwambo & Fürst 2019) to assess RUE, EUE and sustainability of maize production systems in Bolgatanga and Bongo Districts, Upper East Region, Ghana, SSA. The information that was obtained using the EM-DEA approach was combined with the information on the carbon footprint of the five maize production scenarios. The carbon footprint was evaluated using the approach, which was adapted from the Food and Agriculture Organization Ex-Ante Carbon balance Tool (EX-ACT) in this research. The EX-ACT is a land-based accounting method to assess GHG emissions (Bernoux et al. 2010, Bockel et al. 2013, Grewer et al. 2013). Our adapted approach measures GHG emissions in tons of CO_2 e/ha/yr, and carbon balance/ton of yielded produce. The combined information from both approaches leads to complete assessment on RUE, EUE and sustainability as well as carbon footprint of an agricultural system. Such detailed assessment information could be useful when making informed decisions that aim at sustainable agriculture.

Data curation was by combining land use, resource management and production data that were acquired through field survey (Mwambo 2020), with geophysical data that were acquired from published secondary sources. To cope with the fragmented data, APSIM was used to simulate maize productivity in four out of the five maize production scenarios that were modeled in this research as follows:

1. Extensive rainfed maize systems if the external input is 0 kg/ha urea, with/ without manure (*Extensive0*).
2. Extensive rainfed maize systems if the external input is about 12 kg/ha NPK, with/ without manure (*Extensive12*).
3. Rainfed maize-legume (cowpea - *Vigna unguiculata*, soybean - *Glycine max*, or groundnut - *Arachis hypogaea*) intercropping systems if the external input is at least 20 kg/ha urea, with/ without manure (*Intercrop20*).
4. Intensive systems of maize cultivation if the external input is 50 kg/ha urea, including supplemental irrigation (0.18 m/ha/yr) (*Intensive50*).
5. Intensive systems of maize cultivation if the external input is 100 kg/ha urea, including supplemental irrigation (0.18 m/ha/yr) (*Intensive100*).

The results show that the reference scenario (*Extensive12*) was inefficient when compared with the four contrasting scenarios (*Extensive0*, *Intercrop20*, *Intensive50*, and *Intensive100*). The rainfed maize-legume intercropping system with modest input of at least 20 kg/ha/yr urea achieved the greatest marginal yield, better RUE, sustainability, and low carbon footprint. The intensive system with high input of 100 kg/ha/yr urea including supplemental irrigation (*Intensive100*) achieved the greatest yield, and also incurred the greatest impacts in terms of resources consumed (energy, materials, labor, services) as well as GHG emissions.

To conclude, both *Intercrop20* and *Intensive50* are efficient and sustainable practices, which could contribute in improving maize productivity, while minimizing the environmental impacts. As such, both practices are recommendable for low and high input maize production systems, respectively. The EM-DEA approach provides flexibility that contributes in detailed environmental accounting of small-scale agricultural land use systems. As such, this approach represents a way forward to assess energy footprint in agricultural land use as a whole. The full article is included in the Annex (8.2).

4.2 Application of the EM-DEA approach to support multi-criteria decision analysis for strategic agricultural land use planning.

4.2.1 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.

Mwambo, F.M., Fürst, C., Nyarko, B.K., Borgemeister, C., and Martius, C. (2020). Land Use Policy 95, 104490.

Extended summary

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 & Van Niekerk 2013, Zinck & Farshad 1995). This situation could hinder efforts to connect the management planning level and regional development considerations, and in particular within the context of the agri-food sector in developing countries (Satterthwaite et al. 2010). Strategic land use planning is an attempt to orient systems toward sustainability by integrating information for future scenario analyses. The process to make a decision to prioritize a system over another ought to consider multiple criteria.

As such, this study (4.2.1) is a multi-criteria decision analysis (MCDA) to support strategic agricultural land use planning, which aims at improving resource use and food security in northern Ghana, SSA. Data curation was by combining land use, resource management and production data that were acquired through field survey (Mwambo 2020), with geophysical data that were acquired from published secondary sources. To cope with the fragmented data, APSIM was used to simulate maize productivity in four out of the five maize production scenarios that were modeled in this research as follows:

1. Extensive rainfed maize system if the external input is 0 kg/ha urea, with/ without manure (*Extensive0*).
2. Extensive rainfed maize system if the external input is about 12 kg/ha NPK, with/ without manure (*Extensive12*).
3. Rainfed maize-legume (cowpea - *Vigna unguiculata*, soybean - *Glycine max*, or groundnut - *Arachis hypogaea*) intercropping system if the external input is at least 20 kg/ha urea, with/ without manure (*Intercrop20*).

4. Intensive system of maize cultivation if the external input is 50 kg/ha urea, including supplemental irrigation (0.18 m/ha/yr) (*Intensive50*).
5. Intensive system of maize cultivation if the external input is 100 kg/ha urea, including supplemental irrigation (0.18 m/ha/yr) (*Intensive100*).

This study applies an integrated methodology that is comprised of the following: (i) the EM-DEA, (ii) environmental Cost-Benefit Analysis (CBA), (iii) Value Chain Analysis (VCA), and (iv) Sustainability Balanced Scorecard (SBSC) approaches. The EM-DEA approach was applied to assess the RUE, EUE and sustainability of the five scenarios. The emergy-based assessment information, which was obtained from using the EM-DEA approach, was then used as the proxy to calculate the following:

(a) the environmental costs to produce maize. In this light, the total emergy (U) was considered as the proxy for environmental costs, by applying the environmental CBA approach.

(b) the benefits that could be derived from the agricultural produce (bioresource), by applying the VCA approach. The benefits were sub-divided as follows:

(b i) food provision from grain, and this was measured in kcal/yr, and

(b ii) potential electricity, which could be generated from residue, and this was measured in MWh/yr, respectively.

The environmental information which was derived from the application of the EM-DEA, CBA and VCA approaches was aggregated into scores using the SBSC approach to appraise the economic, social and environmental sustainability of the five scenarios.

The results show that when labor (L) and services (S) were included in the assessment of RUE, EUE and sustainability, *Intercrop20* achieved the greatest marginal yield, better RUE, sustainability and appraisal score. To a lesser extent, the results of *Intensive50* were similar to those achieved by *Intercrop20*. The same scenarios caused lesser impacts in terms of plausible expansion of area cultivated when compared with *Extensive0* and *Extensive12*. Meanwhile the environmental risk to cause ecotoxicity, emission of greenhouse gases, and demand for resources (energy, materials, labour and services) by *Intercrop20* and *Intensive50* were lesser when compared with *Intensive100*. As such, *Intercrop20* and *Intensive50* are recommendable land use systems for low-input and high-input maize systems, respectively.

Conclusively, the detailed accounting which is obtained using the EM-DEA approach leads to complete assessment of the RUE, EUE and sustainability of agricultural production systems. The approach could be used to obtain assessment of a system at farm and regional scales. This could enhance efforts in connecting the management planning level and regional development considerations. As such, the EM-DEA approach could be useful as a tool for obtaining complete environmental assessment information that could lead to better land use planning. The f article is included in the Annex (8.2).

5 DISCUSSION

5.1 Critical reflection of methods

Emergy Accounting (EMA) and Data Envelopment Analysis (DEA) methods were coupled to form an assessment framework (Mwambo & Fürst 2014). The concept of eco-efficiency was integrated into the framework, and the Emergy-Data Envelopment Analysis (EM-DEA) approach was developed to assess RUE, EUE and sustainability of agricultural production systems (Mwambo & Fürst 2019). The methods and concepts that were used to develop the EM-DEA approach are summarized in Table 1.

As demonstrated by the empirical studies (4.1.1 and 4.2.1), the EM-DEA approach offers flexibility to account for various resources including land use characteristics. This contributes to detailed and complete assessment of RUE, EUE and sustainability of an agricultural system. Summarily, the EM-DEA approach was compared with the Ecosystem Service (ES) and Life Cycle Assessment (LCA) approaches as follows. On the one hand, often, the ES method is used to assess sustainability. However, the ES approach is sometimes criticized for the following weaknesses. There is incomplete scientific basis to back the ES method. More so, ES frameworks are sometimes applied inconsistently (Bull et al. 2016). As such, these are gaps in the literature on the ES framework. In particular when applied to account for nature's intrinsic economic valuation, and the use of such economic valuation to support decision making are sometimes criticized as well (Laurans et al. 2013). On the other hand, the EM-DEA methodology builds on the extensive literature on EMA and DEA, as well as the applications of these methods. For example, EMA is useful for environmental accounting, and in particular closed systems (Odum 1996). DEA is useful for estimating the productive efficiency of peer units of production that have multiple inputs and outputs (Toloo & Nalchigar 2009, Wen 2015).

Furthermore, the Life Cycle Assessment (LCA) method is commonly used for value chain assessment. However, the LCA method does not provide a comprehensive accounting of input energy from diverse sources (Finnveden et al. 2009, Curran 2014). In comparison, the EM-DEA approach provides flexibility to account input energy from diverse sources such as nature, material, energy, resource generation time, labor, economic and societal infrastructures as well as biologically produced resources of a production system. Such level of detailed accounting is not possible with the LCA method. More so, the application of EMA is useful to account diverse input fluxes and measures them unto a common unit, i.e. the solar emjoule (sej). Such a common unit is useful as a reference unit, and in particular this facilitates comparison between two or more production systems on an identical basis even though the input fluxes could be diverse.

However, the EM-DEA method also suffers from the following weaknesses. It inherits DEA's inability to differentiate inefficiency, which could be caused by statistical noise or measurement error such as inlier or outlier. As such, a precautionary measure that could be useful as a check against such weakness is to ensure data accuracy. Another weakness is that comparative interpretation of rTE scores should be limited to peer units of the same batch. As such, rTE scores should be interpreted with caution.

Table 1: Methods and concepts in the EM-DEA approach

Method / concept (study)	**Review**	**Modification for EM-DEA / rationale for suitability**
Energetics (Odum 1967)	Energetics is applied in ecological systems on the basis of accounting the flow of energy in food production systems. Energy efficiency ratio (*E*) is given as the ratio of energy of the edible yield to the energy invested to produce the given yield.	EMA adopted as the conceptual tool for accounting of environmental resources (both inputs and biologically produced outputs) in agricultural systems. EMA provides a means to define system boundaries, flexibility to quantify all resources based on their measured exergy (available energy). By assumption of energy memory, the emergy of a resource is calculated as the multiplicative product of exergy and Unit Emergy Value (UEV). Exergy is useful for obtaining information on the energy content of resources –all measured in solar emjoule (sej) as the reference unit.
Emergy (Odum 1983, Odum 1996)	The concept of Energy memory (Emergy) founded by Odum in the 1980s after combining energetics and systems ecology. Emergy Accounting (EMA) first presentation in 1983 was used on the basis as embodied energy.	
Economic-Ecological Efficiency (Eco-Efficiency) (Jollands 2003, Kortelainen & Kuosmanen 2004, Beltrán-Esteve 2012)	The eco-efficiency concept was developed in the 1980s and presented as an approach which reckons environmental sustainability and economic performance on the basis of "producing more goods and services using fewer resources while causing minimal environmental impacts in the long term".	The concept of eco-efficiency was adopted and applied for calculating the resource use efficiency (RUE), i.e. the eco-efficiency ratio was equated to UEV of product. The efficiency was further decomposed into 2 sub-efficiencies in order to calculate (i) UEV in terms of Resource use (UEV_R), and (ii) UEV in terms of Exergy use (UEV_E).
Emergy Indicators (Ulgiati & Brown 1998, Brown & Ulgiati 2004, Ulgiati et al. 2011, Dong et al. 2014, Viglia et al. 2017)	The cited studies present emergy indicators and their usefulness in providing information related to sustainability is illustrated. The studies provided reliable basis upon which selected indicators were adopted into the EM-DEA method.	Absolute sustainability is assessed using the following indications (i) Unit Emergy Value (UEV), (ii) Total Emergy (U), (iii) Emergy Yield Ratio (EYR), (iv) Environmental Loading Ratio (ELR), (v) Percentage Renewability (%REN), and (vi) Emergy Sustainability Index (ESI).
DEA (Farrell 1957, Charnes et al. 1978, Banker et al. 1984)	Data Envelopment Analysis (DEA) was first introduced by Farrell in 1957, as a method for estimating relative efficiency of peer units (generally referred to as Decision Making Units DMUs) of production with multiple performance criteria.	DEA adopted as the method of assessing the relative Technical Efficiency (rTE). Resources accounted using EMA were quantified into Emergies. The data were imported into Open Source DEA (OSDEA). The non-parametric treatment of data, compatibility between production system's emergetic data and

DEA applications (De Koeijer et al. 2002, Gomes et al. 2009)	Empirical application of DEA in assessing Technical Efficiency (TE) on the basis that the agronomic efficiency of a system is equivalent of the TE under constant return to scale model (TE_{CRS}). TE has a direct correlation with the Sustainability Efficiency (SE). The TE is a suitable proxy for assessing relative sustainability.	importation into DEA including possibility to manage multiple inputs and multiple output data as a batch. The proportional correlation between TE and SE justifies the use of rTE as a proxy for assessing relative sustainability.
Land use systems & energy sources (Vigne 2012)	The studies present concepts of agricultural land use systems including energy fluxes in mixed and livestock/dairy production systems.	Inclusive consideration of land use systems and energy fluxes in agricultural production. Systems theory applied in building the EM-DEA method to make it synergistic for integrated assessments.

5.2 Validation challenge

In this research, *Extensive12* was the business-as-usual scenario, because the production data were from primary sources (i.e. personal interviews with maize farmers), while *Extensive0*, *Intercrop20*, *Intensive50*, and *Intensive100* were the contrasting scenarios, because the production data were simulated using the APSIM, respectively. The results of the empirical assessment of RUE, EUE and sustainability of small-scale maize production systems in the Sudanian savanna agroecological zone Ghana, which were obtained using the EM-DEA approach (4.1.1 and 4.2.1), were validated by comparison with similar empirical studies that had been achieved using different methods as follows.

5.2.1 Validation of the EM-DEA approach in the assessment of resource use efficiency

The metric for this validation was the relative technical efficiency (rTE) score, which was calculated using the EM-DEA approach (Mwambo & Fürst 2019). The rTE score is a scalar indicator to express the relative performance of peer decision making units (DMUs). The rTE of *Extensive12* was compared with the technical efficiency (TE) observed in the empirical study by Wongnaa (2016). The study used a sample size of 576 small-scale maize farmer interviews collected using multistage sampling in northern Guinea, Transitional, Forest and Coastal savanna zones, Ghana. The data were analyzed using the stochastic frontier production function, which assesses TE as the ratio of observed output to the frontier output given the quantity of resources that are used to obtain a given yield. The TE of maize farmers in the northern savanna was 61.2% (Wongnaa 2016). This TE is comparable to 64%, which was the rTE score that was achieved by *Extensive12* (Mwambo et al. 2020, 2021). Hence, the RUE and EUE results that were obtained using the EM-DEA approach are valid.

5.2.2 Validation of the EM-DEA approach to assess sustainability

The metric for this validation was the overall sustainability appraisal obtained by *Extensive12* (i.e. the business-as-usual scenario). This was compared with the sustainability appraisal of a similar maize production system, which was empirically assessed using a different approach. In this research, the overall sustainability appraisal of a scenario was the sum of the economic, social and environmental appraisals, which were obtained using the Sustainability Balanced Scorecard (SBSC) approach to aggregate information that was derived using the EM-DEA approach in application with the environmental Cost Benefit Analysis (CBA) and Value Chain Analysis (VCA) (Mwambo et al. 2020). As such, the economic, social, environmental as well as overall sustainability appraisals achieved by the various scenarios were as follows: *Extensive0* (822.89 + 4.50 + -17.17 = 810.22), *Extensive12* (823.72 + 5.61 + -19.45 = 809.88), *Intercrop20* (1585.04 + 8.32 + -13.09 = 1580.27), *Intensive50* (1509.22 + 10.45 + -27.12 = 1492.55), and *Intensive100* (1475.30 + 10.70 + -29.67 = 1456.33), respectively. *Extensive12* achieved the least overall sustainability appraisal. More so, the relative technical efficiency (rTE) of *Extensive12* was less than 100%. As such, *Extensive12* was described as "unsustainable" relative to *Extensive0*, *Intercrop20*, *Intensive50*, and *Intensive100* (i.e. the contrasting scenarios) (Mwambo et al. 2020). The sustainability appraisal obtained by *Extensive12* (i.e. business-as-usual or reference scenario) was compared with the sustainability appraisal of a similar maize production system, which was empirically evaluated using the participatory indicators approach based on a study that was conducted in Benin (Yegbemey et al. 2014). The sustainability appraisal of the maize production system was as follows: 41, 55 and 40, i.e. the economic, environmental and social appraisal, respectively. The sustainability of the system was described as having shown "weaknesses", because the threshold value of 50 was not achieved in all three dimensions (Yegbemey et al. 2014). To an extent, the sustainability appraisal that was obtained in this research showed similar a trend to the appraisal that was obtained using the participatory indicators approach. As such, the sustainability assessment results that were obtained using the EM-DEA approach, as well as the sustainability appraisal results that were obtained using the SBSC approach are both valid.

5.2.3 Evaluation of the uncertainty and reliability of results

The evaluation of the uncertainty and reliability of the rTE score, which was used as the proxy for assessing the relative sustainability using the EM-DEA approach, were as follows. The rTE score that was obtained by *Extensive12* (i.e. the business-as-usual scenario) was considered in this research (Mwambo et al. 2021), and three other empirical studies which used different methods to assess the technical efficiency (TE) of similar maize production systems in northern Ghana were selected from online literature (Table 2). The standard deviation (SD) as expressed in *Eq*. (18), was used to calculate the variance in the efficiency values achieved by the sample of studies. The Z-score as expressed in *Eq*. (19), was applied to calculate the deviation of the rTE of *Extensive12* from the calculated mean efficiency of the sample studies. The Z-score was considered as the proxy for the uncertainty. The following assumptions were made:

(i) the efficiency distribution of the sample of studies form a Gaussian curve,

(ii) the efficiency values obtained by the three empirical studies that were sourced from online were representative of TE of small-scale maize farmers in northern Ghana, and

(iii) the calculated mean efficiency of the sample of studies was approximate to the true mean efficiency of small-scale maize production in northern Ghana.

The calculated Z-score was -0.25, and this implied that the rTE of *Extensive12* was 0.25 times less than the calculated mean efficiency of the sample. Hence, the uncertainty is small and allowable. To confirm that the uncertainty was small, the difference in mean efficiencies of the sample of studies (i.e. including and excluding the rTE that was obtained by *Extenive12*) was calculated. The difference was about 1%, which reiterates the fact that the uncertainty was actually small, and this implied that the rTE of *Extensive12* was small and was approximate to the calculated mean efficiency of the sample.

Furthermore, the 95% confidence interval (CI) as expressed in *Eq*. (20) was used to calculate the range of efficiency values that lie within the 95% interval of the sample distribution. The 95% CI was between 55.8 and 77.8%. The rTE of *Extensive12* was 64% (Mwambo et al. 2020, 2021), and subsequently lies within this range of efficiency values that satisfy the 95% CI. The 95% CI was considered as the proxy for the reliability. This implies that the rTE of *Extensive12* was reliable, because 64 is between 55.8 and 77.8. Therefore, the uncertainty was small and allowable, and the results are reliable.

$$SD = \sqrt{\frac{\sum(X-\bar{X})^2}{n-1}}\ , \tag{18}$$

$$Z - score = \frac{X - \bar{X}}{SD}\ , \tag{19}$$

$$95\%CI = \bar{X} - \pm Z\frac{SD}{\sqrt{n}}\ , \tag{20}$$

where,

$SD = standard\ deviation$

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

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

$n = sample\ studies$

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

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

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

Table 2: Description of studies used in assessing reliability and uncertainties of results

Study/ Method of assessment	**Technical Efficiency (%)**
Addai & Owusu (2014) Applied the Translog Stochastic Production Frontier Function to estimate the TE of small-scale maize farmers in Forest, Transitional, and Savanna Zones in Ghana. Sample size *n* = 453. The TE were as follows: 79.9, 60.5, & ***52.3***%, respectively. Note: Only the TE for the savanna zone was considered herein, because the agroecology is similar to the one studied in this research.	52.3
Mwambo et al. (2021) Applied the EM-DEA method to assess the rTE of small-scale maize production systems in the mixed Guinea and Sudanian savannas in northern, Ghana. Sample size *n* = 56	64.7
Abdulai et al. (2013) Applied the Stochastic Frontier Approach to estimate the TE of maize farmers in northern Ghana (Northern-, Upper East-, and Upper West-Regions). Sample size *n* = 360.	74
Abdulai et al. (2018) Applied the Data Envelopment Analysis to estimate the TE of maize farmers in northern Ghana (Northern-, Upper East-, and Upper West- Regions). Sample size *n* = 360.	77
Mean efficiency of sample studies (excluding Mwambo et al. 2021)	*67.76*
Mean efficiency of sample studies (including Mwambo et al. 2021)	*67*
Difference between the means of efficiency of sample studies (including and excluding Mwambo et al. 2021)	*0.76*
Standard deviation of efficiency assessment	*11.1*
Z-score of rTE results as a deviation from the calculated mean efficiency of samples	*-0.21*
95% CI	*56.12 – 77.88*

5.3 Evidence-based decision analysis

Some empirical studies suggest that the impacts of climate change on agriculture could be more severe in Africa. For example, the annual rainfall could decrease and the temporal distribution could become more erratic in the future. Under such circumstances, maize cultivation in SSA could face limited availability of water, and the yield could be adversely affected in some areas (Jones & Thornton 2003, Lobell et al. 2011, Cairns et al. 2013). As such, irrigation could become an important factor to be considered when making decisions and planning strategies that aim at boosting productivity in SSA (Rosegrant et al. 2002).

In this research, the empirical studies using the EM-DEA approach (Mwambo et al. 2020, 2021) show that, among the five scenarios (*Extensive0*, *Extensive12*, *Intercrop20*, *Intensive50*, and *Intensive100*) that were analyzed, *Intercrop20* and *Intensive50* were the best-case scenarios, i.e. the two most resource efficient and sustainable scenarios which could contribute in boosting productivity in maize production in the Sudanian savanna, Ghana. More so, *Intercrop20* was rainfed and was an ecological intensive scenario. This scheme consumed modest amount of material resources (20 kg/ha/yr urea), and the demand for environmental resources is affordable. Currently, rainfed systems are the dominant practice for cultivating maize in Ghana (Hailu 1990, Afful 2015), as well as other countries in SSA (Edreira et al. 2018). However, the increasing population and the ensuing demand for more maize-based products, together with climate change could mean that supplemental irrigation might become a strategy for enhancing productivity in small-scale maize production systems in SSA (Rosegrant et al. 2002).

Intensive50 was a moderately intensive scenario that consumed 50 kg/ha/yr urea and required supplemental irrigation. Water for supplemental irrigation in this system was estimated at 0.18 m/ha/yr. Due to climate change, water availability could become a constraint in the Volta basin as well as in other areas in SSA (Oyebande & Odunuga 2010, Kabo-Bah et al. 2016). However, such constraint could be minimized using integrated management planning for water resources (Amisigo et al. 2015). For instance, an empirical assessment conducted in the study area has demonstrated that improved irrigation management could save between 0.13 and 1.325 m of water compared to the traditional irrigation scheme (Sekyi-Annan et al. 2018). Using improved irrigation management, water saved during the cultivation of vegetables in the dry season could be used for supplemental irrigation of maize during the rainy season. The water requirement for maize cultivated in a supplemental irrigation system was 0.107–0.126 and 0.088–0.105 m during weather conditions of low rainfall with frequent dry spells and high rainfall with rare dry spells, respectively (Sekyi-Annan et al. 2018). Therefore, *Intercrop20* and *Intensive50* could be feasible practices given the climate that is prevailing within the Sudan savanna in northern Ghana as well as other countries in SSA.

In terms of productivity, *Intercrop20* and *Intensive50* achieved 1.88 and 2.75 ton/ha, respectively. It was assumed that these schemes could be economically feasible, because the productivity was above 1.5 ton/ha, which is considered as the productivity threshold for small-scale maize production to be profitable at household level in Ghana (Scheiterle & Birner 2018). Hence, *Intercrop20* and *Intensive50* could be implemented alternatively based on climate conditions and resources available to farmers.

5.4 Trade-off analysis

Higher demand for food, feed, biofuel, fiber and other biomass-based products needed by the growing global population is exerting an increasing pressure on land and water resources, which are required by agriculture to produce the needed biomass. Most resources are limited in supply. Land is finite and often the same piece of land could be needed for multiple functions. Such high and competing demand for biomass implies that the situation could increase the risks to food and energy security. Given that the population is growing, the demand for maize-based products may likely increase in the future (Ekpa et al. 2018, Amanor-Boadu 2012, Nuss & Tanumihardjo 2010, Pingali 2001). It is important to improve the productivity of maize in small-scale systems in SSA, and to do so using agricultural practices, which could achieve greater productivity while causing minimal environmental impacts in the long term. This could be the safest way to contribute to the United Nations Sustainable Development Goal (SDG) 2, which is “to end hunger, achieve food security and improve nutrition and promote sustainable agriculture” (UNO 2017).

On that note, the following trade-off analysis was based on the empirical results of this research (Mwambo et al. 2020, 2021). When all resources were taken into account (i.e.

with L & S), the low input traditional land use systems such as *Extensive0* and *Extensive12* achieved low productivity. More so, the tendency to rapidly expand the area cultivated in order to grow more food for a bulging population was more likely when compared to the intensive agricultural scenarios. For example, *Intensive100* achieved greater productivity, and at the same time causes greater environmental costs in terms of high demand for resources as well as greater risks of ecotoxicity and greenhouse gas emissions. Meanwhile, *Intercrop20* achieves the greatest marginal yield, and the risks to expand the area cultivated was lesser when compared to *Extensive0* and *Extensive12*. The carbon footprint of *Intercrop20* was also lower when compared to *Intensive100*. *Intensive50* achieved greater marginal yield compared to *Extensive0*, *Extensive12* and *Intensive100*, and caused lesser threats in terms of expansion of area cultivated when compared to *Extensive0* and *Extensive12*. Besides, the risks of ecotoxicity and emissions, as well as the demand for resources were lesser when compared to *Intensive100*. As such, *Intercrop20* and *Intensive50* could be recommended as the resource efficient and sustainable land use practices, which could contribute in improving maize productivity, while causing minimal environmental impacts. Hence, *Intercrop20* and *Intensive50* represent land use and resource management scenarios, which could contribute to sustainable agriculture (FAO 2014).

Energy poverty could be a limitation to development (Kaygusuz 2011). In particular, electricity is necessary for boosting the productive capacity in the agri-food sector (Sola et al. 2016, Eshun & Amoako-Tuffour 2016, Hammond et al. 2015). The worldwide increasing energy scarcity could threaten food security, because energy is required to produce food, and food could be used to generate biofuel (Popp et al. 2014). This implies that the use of resources such as arable land and water for agricultural production of biomass, which eventually could be used as feedstock for biofuel generation could compete with food production. To reduce such risks, policy making on the exploitation of land and water resources in agriculture, as well as the end-use of biomass should prioritize food sovereignty over biofuel generation (Beuchelt & Virchow 2012, Mohr et al. 2015, 2016). For example, food and energy provision could be co-products within a biomass-based economy. However, such policies should be guided by empirical evidence based on reliable methods that could contribute to complete assessment of an agricultural system. In this research, the EM-DEA approach was applied to achieve complete environmental accounting of small-scale maize production systems. This was integrated with the concepts of polygeneration (Serra 2009), and value chain analysis (Gereffi & Fernandez-Stark 2016). The information that was derived from the empirical study (4.2.1) could be used for strategizing towards land use planning as well as improving resource use, food and energy security in northern Ghana. As such, *Intercrop20* and *Intensive50* emerged the best-case scenarios (Mwambo et al. 2020).

6 CONCLUSIONS AND OUTLOOK

The essence of assessing efficiency and sustainability in agriculture is to avoid compromises in productivity, while protecting the environmental resource base in the long term. Proper accounting is one of the fundamental steps towards ensuring efficiency and sustainability. In this research, the EM-DEA approach was developed as an innovative approach that closes an important gap that had existed in the literature. In this regard, the lack of reliable methods which could be used to achieve complete environmental accounting and subsequently to analyze agricultural systems. In particular, African small-scale agricultural systems such as those in which human and draft animal labor are the predominant source of input energy for farm labor as a resource that contributes in agricultural production (FAO 1995 p. 59). The EM-DEA approach offers flexibility to account input resources from diverse sources (e.g. nature, material, energy, resource generation time, labor, economic and societal infrastructures as well as biologically produced resources), and in particular human and draft animal labor in small-scale agriculture. Such detailed accounting contributes to complete analysis of an agricultural system, and this could lead to information which could be useful when making informed decisions in agriculture. The EM-DEA approach was applied in two empirical studies as follows:

1. To assess the environmental impacts of agriculture, and in particular to assess RUE, EUE and sustainability of maize production practices in northern Ghana, SSA.
2. To support an MCDA for strategic agricultural land use planning, and in particular small-scale maize production, with the aim to contribute in food security in northern Ghana, SSA.

6.1 Main findings

The main findings of the two empirical studies were as follows:

1. When the contribution from nature and material were excluded from the accounting (without L & S), the land use systems were in the following order from best-case to worst-case scenario: *Extensive0, Intercrop20*, *Intensive50*, *Intensive100,* and *Extensive12*.
2. When the contribution from nature, material, labor and services were included into the accounting (with L & S), the land use systems were in the following order from best-

case to worst-case scenario: *Intercrop20*, *Intensive50*, *Intensive100, Extensive0*, and *Extesive12*.

3. When all resources were taken into account (with L & S), the quantity of resources that are consumed (i.e. total emergy U), as well as the greenhouse gas (GHG) emissions by the various systems show an increasing trend as follows: 5.35E+15 sej/ha yr, 0.266 CO2e/ha/yr (*Extensive0*), 5.87E+15 sej/ha yr, 0.436 CO2e/ha/yr (*Extensive12*), 4.64E+15 sej/ha yr, 0.546 CO2e/ha/yr (*Intercrop20*), 8.85E+15, 1.177 CO2e/ha/yr (*Intensive50*), and 9.55E+15 sej/ha yr, 2.015 ton CO2e/ha/yr (*Intensive100*), respectively. Remarkably, the resource consumption by *Intercrop20* was least when compared to the other land use systems. Intercropping improves the percentage cover. This suppresses weeds and subsequently minimizes nutrient loss through erosion, as well as reduces labor required in the form of weeding.
4. *Intercrop20* and *Intensive50* were the most efficient and sustainable land use practices for optimizing resources and improving productivity, while minimizing the environmental impacts of maize production in the Sudanian savanna agroecological zone, Ghana.

6.2 Summarized answers to the research questions

Based on this research, the elaborate answers to the research questions are contained in this cumulative thesis. The summarized answers are as follows:

1. The emergy diagram of a given land use system, which is been analyzed was used as the means to guide the analyst's decision when delineating the appropriate system boundaries. The aspects that were included in the impact assessment of small-scale maize production in Ghana, SSA, were as follows: emissions from the industrial production and long-distance transportation of inputs (NPK, urea), on-farm activities (land preparation/ plowing, sowing, weeding, harvesting and threshing), and ended with the delivery of the product (i.e. maize produce) at the farm-gate.
2. Based on the detailed emergy analysis of small-scale maize production in Ghana, SSA (Appendix III, Mwambo 2021), a summary of the energy and material fluxes are presented in Table 3.

Table 3: Summary of energy and material fluxes in small-scale maize production, Ghana

Accounting	**Source type & Definition**	**Source sub-group**	**Energy flux**	**Explanation and remark**	
Nature & raw materials	Renewable (R), Def.: Renewable sources are sources that are abundant in supply or they are being replenished faster than they are being depleted.	Primary (locally available)	Sun light	Sum of primary sources	Maximum of primary (i.e. the Max. between sum of primary sources and max. of secondary sources (see also note at the foot of Table 3).
			Deep Heat		
			Gravitational potential		
		Secondary	Wind	maximum of secondary sources	
			Evapotranspired water		
	Nonrenewable (N), Def.: Nonrenewable sources can be depleted faster than they can be replenished. They cannot be replenished within the lifetime of one generation of humans.		Topsoil loss (soil erosion)	It is an outflux from a system, and subsequently has a negative impact on production. Eroded soil was considered as the amount of soil used up by a system.	
	Imported (F), Def.: Imported sources are the fraction of used emergy purchased from outside the system.	Purchased input	NPK (15 15 15)/ Urea		
		Local & brought from outside the system	Draft animal labor	Only the maximum input entity was retained since both animal labor and manure were from the same source (i.e. animal labor retained).	
			Cattle manure		
			Maize seeds		
Human economy	Labor and Services (L&S), Def.: Human endeavor and purchased inputs that enable agricultural production.	On-farm activities	Human labor	Activities: land preparation/ plowing, sowing, weeding, harvesting and threshing	
		Purchased inputs brought from outside the system.	Services	Purchase of inputs (maize seeds, NPK/ urea, draft animal, feed for animal, stable for animal, phytosanitary care for animal), and cost of human labor as a shadow price.	

Note: To avoid double counting, the refined approach for emergy calculation was applied (Brown and Ulgiati 2016).

3. The energy reference unit defined for making comparison between different land use systems was the solar emjoule (sej). The scenarios that were modeled in this research were considered as follows: *Extensive0* and *Extensive12* were considered as traditional low input management systems, *Intercrop20* as a low input system that was deliberately adapted to function and provide ecosystem service as in an alternative land use system (i.e. intercropping maize with legume to improve food security, control erosion as a cover crop, and additional residue from legume to provide fodder), while *Intensive50* and *Intensive100* were considered as intensive systems, respectively.

6.3 Recommendations

1. The EM-DEA approach is a recommendable approach for achieving detailed and complete analysis such as RUE, EUE and sustainability of agricultural production systems, because it provides flexibility to account for various resources including land use characteristics as a whole. Such detailed accounting leads to complete assessment, which is useful to support decision making in agricultural production systems.
2. Based on the empirical studies, *Intercrop20* and *Intensive50* are the recommendable land use scenarios for optimizing resources, improving productivity and minimizing environmental impacts in low-input (extensive) and high-input (intensive) maize production systems, respectively, in the Sudanian agroecological zone, Ghana, SSA.

6.4 Evaluation of the objectives

This research achieved its objectives (section 1.2) as follows: The assessment framework was conceived (section 2.1.1), and published in the *proceedings of the 28th EnviroInfo conference* (Mwambo & Fürst 2014). The concept of eco-efficiency was integrated into the framework, and the EM-DEA approach was developed. The development of the EM-DEA approach was published in the *Journal of Environmental Accounting and Management* (Mwambo & Fürst 2019). Both contributions earmarked the achievement of objective #1, which was “to develop a holistic assessment framework that assesses energy efficiency in agronomic land use as a whole”.

The EM-DEA approach was empirically tested using maize systems in Ghana as follows: The study area was Bolgatanaga and Bongo Districts, Upper East Region, Ghana. Data curation was by combining land use and production data which were acquired through field survey, with geophysical data which were acquired from published secondary sources. To cope with data scarcity, the APSIM was used to simulate productivity. Five scenarios of land use and resource management schemes for small-scale maize production were modeled. The EM-DEA approach was applied in two empirical studies, which demonstrated the capacity of the approach as follows: First, to assess the environmental impacts of small-scale maize production. The EM-DEA approach was used for assessing the RUE, EUE and sustainability of the scenarios. In addition, the carbon footprint of maize production was assessed using an approach, which was adapted from the EX-ACT in this research. This article was published in the *Journal of Cleaner Production* (Mwambo et al. 2021).

Second, the EM-DEA approach was used to assess RUE, EUE and sustainability of the five scenarios. The emergy-based information that was derived using the EM-DEA approach was then used as the proxy for further analysis through the application of CBA and VCA. The information that was obtained through these analyses, was aggregated using the SBSC approach. This study demonstrated an MCDA for strategic agricultural land use planning that aims at resource optimization in maize production that could contribute to improve food and energy security in northern Ghana. This article was published in *Land Use Policy* (Mwambo et al. 2020). These empirical studies earmarked the achievement of objective #2, which was "to supply the value web system analysis (Cluster 3 of the BiomassWeb Project, https://biomassweb.org/) with additional information on possible trade-offs regarding the challenge of world-wide increasing energy scarcity". As such, this research contributed in achieving the overall goal of the BiomassWeb Project, which was "to provide concepts to increase the availability of and access to food in sub-Saharan Africa through more and higher-value biomass for food and non-food purposes in the next decades".

6.5 Outlook

Data scarcity was a major limitation to this research. The combination of data from primary and secondary sources, as well as data simulation using APSIM, was the strategy that was adopted to overcome this limitation. The articles on the development of the EM-DEA approach, as well as the two empirical studies could be used as baseline studies for future research. In this light, avenues for future research could be as follows:

1. Application of the EM-DEA approach to assess other forms of agriculture such as livestock, dairy farming, agroforestry and forestry systems.
2. To use an identical dataset, and conduct a detailed comparison between the EM-DEA approach and other methods of analyzing energy efficiency of an agricultural systems.
3. To conduct a detailed and empirical comparison between the EM-DEA approach, Ecosystem Services, and Life Cycle Assessment methods.
4. The sample size of the primary data that was used for this empirical research was *n=56*. This research could be replicated using a larger sample size, and then compare the results in order to verify if there are significant changes.
5. This study could be replicated using data from Nigeria and Ethiopia, which were the other research countries within the context of the BiomassWeb Project. Such cross-country studies could reveal differences or similarities in the efficiency and sustainability trends for a given crop grown in a similar agroecological zone across different countries.
6. The EM-DEA approach could be used in combination with a tiered DEA model, and time-series data to assess changes in efficiency and sustainability for the same land use and resource management schemes within the same geographical area.

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8 ANNEXES

8.1 Overview of the articles included in the thesis

Table 4: Articles constituting this cumulative thesis

Section	Article	Status
2.1.1	Mwambo, F.M., & Fürst, C. (2014). Assessing the ecological-societal impacts of West African farming practices by means of energy efficiency. Oral presentation given at the "Ethics of Food Security in a Changing Society – Learning from the Past to Shape the Future" Colloquium, Cumberland Lodge, Windsor Great Park, United Kingdom, September 24, 2014. Summary [online] at https://www.cumberlandlodge.ac.uk/sites/default/files/Food%20Security%20Colloquium%20Report.pdf.	Presented Award-winning presentation (First place).
2.2.1	Mwambo, F.M., & Fürst, C. (2014). A framework for assessing the energy efficiency of non-mechanised agricultural systems in developing countries. In: Marx Gómez, J., Sonnenschein, M., Vogel, U., Winter, A., Rapp, B., and Giesen, N., (eds.): EnviroInfo 2014 - 28th International Conference on Informatics for Environmental Protection. BIS-Verlag, Oldenburg. ISBN 978-3-8142-2317-9. Pp. 565-572. Available [online] at http://nbn-resolving.org/urn:nbn:de:gbv:715-oops-20009.	Published in Proceedings of the 28th Enviroinfo Conference
3.2.1	Mwambo, F.M., & Fürst, C. (2019). A holistic method of assessing efficiency and sustainability in agricultural production systems. *JEAM* 7(1), 27-43. https://doi.org/10.5890/JEAM.2019.03.003.	Published
4.1.1	Mwambo, F.M., Fürst, C., Martius, C., Jimenez-Martinez, M., Nyarko, B.K., & Borgemeister, C. (2021). Combined application of the EM-DEA and EX-ACT approaches for integrated assessment of resource use efficiency, sustainability and carbon footprint of smallholder maize production practices in sub-Saharan Africa. *J. Clean. Prod.* 302, 126132. https://doi.org/10.1016/j.jclepro.2021.126132.	Published
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8.2 Full Articles (attachments)

Assessing the ecological-societal impacts of west African farming practices by means of energy efficiency

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Abstract

In west Africa, agriculture is dominated by small-scale production systems. Farm labour is usually manual or powered by draft animals. This is embedded into the concept of shifting cultivation and in combination with slash and burn practices, while the fallow period is becoming shorter as time progresses. In addition, the fast growing population is demanding for more food from the low-input farming, and the situation is leading to fast dynamics of land use change with considerable impacts on biodiversity, but also on future food and water security. The study will assess the impacts of different agricultural land use and management practices connected with resource processing schemes by using energy efficiency as a proxy to support decision making, and will relate this to the provision of public goods and ecosystem services. The aim of this study is to conceive a comprehensive and scale sensitive assessment framework that supports consulting land use, but also decisions to which extend and at which scale (local and regional) processing of bio-resources should be combined with the primary production. In this presentation, a review of small-scale agricultural land use practices in West Africa, and a first approach on how to structure the assessment framework, and how to consider scale effects are presented.

Keywords

West Africa, land-use practices, small-scale farming, energy efficiency assessment, food security, ecosystem services.

1 Introduction

Food security is "*a situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life*" (FAO 2002). It is challenging to attain such an ideal situation space and time (Rosegrant & Cline 2003, United Nation 2012, FAO 2010). Hence, food security continues to be a topical agendum at many global, regional, national, and local fora. Besides, food security is multidimensional, and cuts across several disciplines such as: agriculture, health, energy, transport, economics, social, environment, development, sustainability and others.

Though food security is a global challenge (United Nations 2012, FAO 2010), developing countries are more vulnerable to the risks compared to developed countries (Diaz-Bonilla *et al*. 2000). As such, food security could continue to be a topic of relevance in development, because there are more than 800 million people who are still food insecure globally (FAO 2014). For example, food price volatility and shocks as well as food importation are issues of concern in sub-Saharan Africa (SSA) (Minot 2011, Rosegrant *et al*. 2001). Meanwhile projections show that the risks of food insecurity in SSA in the future could be higher when compared to other developing regions (Turral et al. 2011). The production of food in SSA is mostly by small-scale farmers, and their agricultural productivity is limited due to several challenges (Morgan & Solarz 1994). The situation of food security in SSA is improving, but at a slow rate (Wiggins & Keats 2009) (see also, Table 1, and Table 2).

Table 1: Undernourishment around the world, 1990-92 to 2011-13

	Number of undernourished *(millions)* and prevalence *(%)* of undernourishment				
	1990-92	2000-2002	2005-07	2008-10	2011-2013*
World	**1015.3**	**957.3**	**906.6**	**878.2**	**842.3**
	18.9%	**15.5%**	**13.8%**	**12.9%**	**12.0%**
Developed regions	**19.8**	**18.4**	**13.6**	**15.2**	**15.7**
	<5%	**<5%**	**<5%**	**<5%**	**<5%**
Developing regions	**995.5**	**938.9**	**892.9**	**863.0**	**826.6**
	23.6%	**18.8%**	**16.7%**	**15.5%**	**14.3%**
Africa	**177.6**	**214.3**	**217.6**	**226.0**	**226.4**
	27.3%	**25.9%**	**23.4%**	**22.7%**	**21.2%**
Northern Africa	4.6	4.9	4.8	4.4	3.7
	<5%	<5%	<5%	<5%	<5%
Sub-Saharan Africa	173.1	209.5	212.8	221.6	222.7
	32.7%	30.6%	27.5%	26.6%	24.8%
Asia	**751.3**	**662.3**	**619.6**	**585.5**	**552.0**
	24.1%	**18.3%**	**16.1%**	**14.7%**	**13.5%**
Caucasus and central	9.7	11.6	7.3	7.0	5.5
Asia	14.4%	16.2%	9.8%	9.2%	7.0%
Eastern Asia	278.7	193.5	184.8	169.1	166.6
	22.2%	14.0%	13.0%	11.7%	11.4%
South-Eastern Asia	140.3	113.6	94.2	80.5	64.5
	31.1%	31.5%	16.8%	13.8%	10.7%
Southern Asia	314.3	330.2	316.6	309.9	294.7
	25.7%	22.2%	19.7%	18.5%	16.8%
Western Asia	8.4	13.5	16.8	19.1	20.6
	6.6%	8.3%	9.2%	9.7%	9.8%
Latin America and	**65.7**	**61.0**	**54.6**	**50.3**	**47.0**
the Caribbean	**14.7%**	**11.7%**	**9.8%**	**8.7%**	**7.9%**
Caribbean	8.3	7.2	7.5	6.8	7.2
	27.6%	21.3%	21.0%	18.8%	19.3%
Latin America	57.4	53.8	47.2	43.5	39.8
	13.8%	11.0%	9.0%	8.0%	7.1%
Oceania	**0.8**	**1.2**	**1.1**	**1.1**	**1.2**
	13.5%	**16.0%**	**12.8%**	**11.8%**	**12.1%**

(Source: FAO et al. 2013) Note: * Projections

Table 2: Estimated number of people at risk of hunger in 2080

	Year 2000	**A2r 2080 (No CC)**	**A2r 2080 (Had CM^3)**	**A2r 2080 (HadCM^3 mitigation)**
Latin America	57	23	30	26
Sub-Saharan Africa	188	410	450	430
Southeast Asia	42	5	5	5
South Asia	312	43	45	44
East Asia	42	5	5	5
Developing countries	821	554	622	488

Source: copied from Turral *et al*. (2011 p.17), who state the original source.
Note: A2r: revised version of scenario A2; CC: climate change; CM^3: climate modification

If "*efficiency forms the bedrock of policy, planning and business approaches to sustainable development*" (Jollands 2006), then, it is rational to say that proper environmental accounting is a key to efficient and sustainable use of resources (Lange 2003). Until now, methods to analyse resource and energy use efficiency are limited in agriculture (Jones 1989), and in particular small-scale production systems in developing countries, where farm labour is mostly manual as well as the use of draft animals to provide traction (FAO 1995 p. 59). The input energy by draft animals and some resources are complex to assess (Blancard & Martin 2012, 2014, Alvarenga et al. 2013). This highlights a knowledge gap that could be limiting accounting and decision making in small-scale agriculture in developing countries. For example, to support decision making that could lead to optimisation of scarce resources that could enhance domestic productivity, while causing minimal environmental impacts.

The aim of this paper is to present a review on small-scale agricultural land use systems, which are practised in West Africa, and also to introduce the framework that can be useful for the assessment of resource and energy use efficiency of small-scale agricultural production systems as a whole. The assessment framework integrates land use and resource management practices, as well as inputs from nature and human economy. The environmental accounting process leads to comprehensive information on resource and exergy use efficiency. The measured efficiency could be a useful proxy to support informed decision making in agriculture, by assessing the ecological-societal impacts of farming practices.

2 West African farming practices

Western Africa (herein referred to as West Africa) has a heterogeneous climate that varies from humid tropical conditions along the coastal and southern zone, to warmer semi-arid and arid conditions in the hinder lands and northern zone bordering the Sahara desert (USAID 2013). The pattern of rainfall shows a decreasing trend from the south towards the north. In addition to this north-south trend, the impacts of the Monsoon and Inter-Tropical Discontinuity cause local variability in the rainfall in some areas. For example, Accra has a lower rainfall compared to some places that located along the coast (Ofori-Sarpong & Annor 2001). The ecological landscape shows a transition from Guinean rainforest in the south through savannas to dry-land ecosystem bordering the Sahara desert in the north (USAID 2013). The agro-ecosystems characterising this sub-region are as follows: semi-arid, sub humid, humid forest, and inland valley swamp (Fungo 2011).

West Africa is a food insecure hot spot (Flores 2010). This interrelates with other environmental challenges such as ecological and climatic issues, which further complicate the situation of food insecurity, and make resilience difficult (Lebel *et al*. 2009). For instance, the impacts of the infamous Sahelian drought have been pervasive on the ecology, agriculture, livelihood and economy of most countries in West Africa (Dai *et al*. 2004, Gonzalez 2001, Webb & Reardon 1992).

African farming systems are heterogeneous (Giller *et al*. 2011). For example, about 13 agronomic land-use patterns with different farming practices have been distinguished using remote sensing technologies. Five of these systems are dominantly practiced in West Africa (Fungo 2011). The economy of most West African countries and the livelihood of the majority of the population rely on rainfed agriculture (Callo-Concha *et al*. 2013, Turral *et al*. 2011, Flores 2010, Boateng 2013, Fungo 2011), as well as the exploitation of natural resources and other services provided by ecosystems (Egoh *et al*. 2012). Apart from the intensive mono-cultural cultivation of tree crops, whose produce is used for supplying the export market with agricultural commodities, small-scale and rainfed agriculture is the dominant system for growing food crops. The traditional agronomic land-use and farming practices include shifting cultivation in which slash and burn, and rainfed agro-pastoral agriculture are practiced (Callo-Concha *et al*. 2013, Fungo 2011, Jamala 2012) (see, Table 3). Recent studies employing remote sensing technologies further confirm the frequent occurrence of bush fires, which could be attributed to slash and burn practices (Aniah *et al*. 2013, Adanu *et al*. 2013).

Agriculture in West Africa is dominantly carried out by smallholder farmers. Farm labour is mostly manual and transitions to the use of draft animals and fuel driven machines (FAO 1995, Bobobee 1999). The dominant means to improve crop yield is by expansion of area cultivated, and shifting cultivation (Callo-Concha *et al*. 2013, Adanu *et al*. 2013, Soussou *et al*. 2013, Ouedraogo *et al*. 2010). However, overtime continuous expansion of area cultivated is gradually being restricted by the finite availability of arable land. The fast growing population is exerting pressure on the agricultural systems to produce more food and other biomass-based products. This situation is causing the fallow period in traditional farming systems to be shortened (Adanu *et al*. 2013, Adjei-Nsiah *et al*. 2012, Diao & Sarpong, 2007, Hailu 1990), and because of continuous cropping without adequate amendment of soil, crop yield is low compared to the productivity in other developing regions (Hailu 1990, Kariuki 2011).

Some scientists are on the opinion that the current farming practices in West Africa are exacerbating environmental changes including land degradation, desertification, loss of biodiversity, and ecosystem services (Aniah *et al*. 2013, United Nations ECA 2007, Scherr 1999, Charney *et al*. 1975, 1977). The practised low input agricultural systems are stressed to produce more food and other biomass-based products. As such, productivity by these systems is low, which leads to food insecurity, thus, exemplifying an effect-based indicator of environmental impact of the farming practices (Adanu *et al*. 2013). So far, there is no affirmative claim to this hypothesis, because there is neither consensus on the relationship between land degradation and poverty (Nkonya *et al*. 2013). Neither is the relationship between land degradation and farming practices certain (Scherr 1999). Besides, there are arguments or little evidence from an anthropogenically driven land degradation leading to the extensive Sahelian drought in West Africa. On the other hand, the situation is considered as climatic changes driven by global patterns in temperature (Brooks 2006, 2004). More so, there are arguments which contradict the opinion to the ongoing ecosystem degradation in West Africa (Boateng 2013). The argument associates the situation to a dryland development paradigm that focuses on agroecosystem resilience in the context of the dynamic biophysical and socio-economic constraints, i.e. the complex alteration in landscape are considered to be mere dynamic changes and not degradation. State-of-the-art information is required to support policy development for food and water security, environmental integrity, and economic development (Bai *et al*. 2008).

Table 3: Characteristics of agronomic land use schemes in Ghana

Farming system	Farming practice	Effect of soil
Rotational bush burning	Slash & burn. Fallow period with or without fertilizer	Destruction of vegetative cover, Expose soil to erosion, Leaching of soil nutrients.
Permanent tree crop system	Slash & burn but presence of tree canopy	Minimal soil loss by erosion due to tree canopy.
Compound farming system	Slash & burn with or without fertilizer/ manure. Livestock grazing	Soil loss due to erosion, leaching of nutrients, Soil compaction due to livestock.
Mixed farming system	Slash & burn with or without fertilizer/ manure	Soil erosion & nutrient depletion.
Special horticultural farming system	Slash & burn with fertilizer/ manure & chemical application	Soil erosion, eutrophication & acidification due to fertilizer & chemical application.

Source: Diao & Sarpong (2007)

3 Methodological framework for resource and energy efficiency

Given that agricultural productivity is low in small-scale production systems in SSA, the objective to improve productivity is frequently called for. Perhaps, a much more important objective is to ensure food security, while minimising the environmental impacts of agricultural production, and in particular the demand for resources and energy. However, existing methods are limited in analysing resource and energy use efficiency of agricultural production systems (Jones 1989). We respond to this challenge by conceiving a framework, which is scalable and useful for the assessment of resource and energy use efficiency in agricultural production systems as a whole. The framework is developed as follows. The fundamental concept of the method conceived is based on aggregating Emergy Accounting and Data Envelopment Analysis into a framework (Mwambo & Fürst 2014). The application of Emergy Accounting (EMA) is to achieve comprehensive environmental accounting of resource inputs and outputs in a production system (Odum 1996), i.e. EMA provides a means to better environmental accounting, which could be applied to diverse resource types in order to quantify energy fluxes. Data Envelopment Analysis (DEA) is a non-parametric linear programming approach, which is useful when assessing relative efficiency among a given set of peer units (generally referred to as decision making units -DMUs). The application of DEA is the means to assess relative efficiency, and this could be a useful proxy for expressing relative sustainability among a given set of DMUs (Farrell 1957), such as different agricultural land use and resource management practices.

The method conceived in this study achieves comprehensive environmental accounting by considering the input contributions from nature, material resources, services, and agronomic land use including farm labour provided by humans and draft animals in small-scale agricultural systems in developing countries. This approach provides a broader perspective of environmental inputs, direct connection to economics, and internal optimising principle (Herendeen 2004). Further, EMA is applied for detail accounting of all input and output resources. The quantified assessment of resources in emergetic terms, i.e. diverse resource types will be measured using the solar emergy joule (*sej*) as the common reference unit for input energy fluxes. The integration of the concept of economic-ecological efficiency (eco-efficiency) (Ehrenfeld 2005), enhances further the application of this conceived method to assess agricultural systems as a whole. In this way, the ecological-societal impacts of various farming practice could be assessed at local and regional scales, and the information obtained could be useful for supporting decision making that aims at improving food security.

4 Conclusions

The next tasks include the following. To actualise the framework conceived in this study by explicitly developing it into a methodical approach, which could be applied to analyse resource and energy use efficiency of smallholder agricultural systems as a whole. As well as to obtain the necessary data that would be needed for empirical analysis of agricultural production systems in West Africa. Field data is expected to be complimented with secondary data in order to overcome the lack of field data.

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A framework for assessing the energy efficiency of non-mechanised agricultural systems in developing countries

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Abstract

There is a continuously growing global demand for agricultural products, including food, fodder and fuels that urges for reasons of ensuring a sustainable development innovative methods to assess the impact of agricultural management. Existing methods of energy efficiency analysis for agricultural systems take into account human labour and draft animal power as inputs and consider also land-use characteristics as factors affecting the production in systems in most developing African countries. However, most of these methods fail to address properly different scales in decision making, i.e. connecting the management planning level with regional development considerations. With this paper, we introduce an alternative method to assess the energy efficiency in agronomic land-use. Our work intends to conceive a comprehensive and scale sensitive assessment framework that supports consulting land-use, decision making, and policy planning.

1. Introduction

Agricultural intensification which involves the cultivation of high-yielding crop varieties combined with the application of sufficient fertilizers, pesticides and irrigation has been proposed as a relevant solution to address the problem of food insecurity which is menacing the majority of the population in many developing countries. But such strategy may likely be constrained by the rapidly increasing energy demand by the global agricultural systems. Based on a projection of the global population and its demands for food and other biomass-based products, the global agricultural productivity is expected to increased by as much as 50-70% by 2030 [6]. The increase which is expected from developing countries might have to be at the upper margin, because crop productivity in developing countries is lower and at the same time most of the population growth is occurring in these countries when compared to the developed countries. Figure 1 shows an agricultural performance review of Africa and 2 other developing regions over the last 50 years. The trend reveals that Africa is grossly lagging behind in productivity when compared to the other developing regions [10]. Africa’s productivity is hampered mostly by constraints of energy and land-use among other factors. Tackling the problem from a sustainable development standpoint has provoked the need for an alternative method which can be used to better analyse the energy efficiency of agricultural land-use, and in particular African land-use schemes including inputs from human and draft animal labour. An accurate analysis will reveal decisive information through which the energy efficiency in agriculture can be improved, including the necessary support for the formulation of such energy efficiency oriented policy.

Furthermore, we are faced with a continuously growing global demand for energy that is intended to be fed more and more by renewables and here especially by biofuels [11]. Consequently, for agriculture being a consumer and producer of energy at the same time [9], energy efficiency analysis supports optimising the sustainable use of energy [11, 13, 18, 1, 2].

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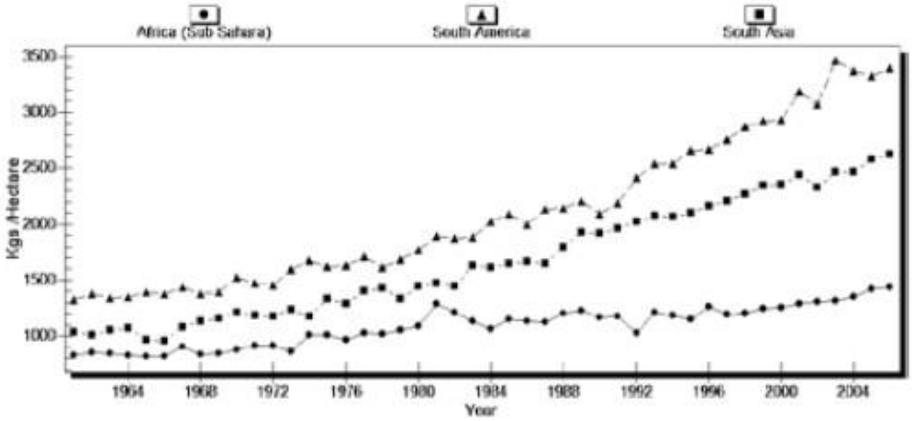

Figure 1: Cereal Yields per Hectare: Africa versus Latin America versus South Asia
Source: copied from [10], who states the original source

Energy efficiency analysis describes the role of direct and indirect energy inputs in a production system. Until now, relatively few studies on energy efficiency analysis have been conducted on agricultural systems in developing countries [26]. So far, there is no standardized and sufficiently reliable method for analysing energy efficiency in non-mechanised agricultural systems as is the case in most African developing countries where human labour and draft animal power are still predominant input energy sources as shown in Table 1.

Region		**Percentage of area cultivated by different power sources**		
		Human Labour	**Draught Animal**	**Tractor**
All developing countries	1997/99	35	30	35
	2030	25	20	55
Sub-Saharan Africa	1997/99	65	25	10
	2030	45	30	25
North East/North Africa	1997/99	20	20	60
	2030	10	15	75
Latin America and the Caribbean	1997/99	25	25	50
	2030	15	15	70
South Asia	1997/99	30	35	35
	2030	15	15	70
East Asia	1997/99	40	40	20
	2030	25	25	50

Table 1: Proportion of area cultivated by different power sources
Source: [6 p.153]

In 1995, the FAO had stated that "*Human and animal labour requirements fall outside the traditional boundaries of energy sector planning, and their dynamics are far more complex than those of fuel and electricity supply. However, since human labour remains the predominant source of energy for agricultural production in much of Africa, and transitions to animal traction and fuel using machinery are important for the social and economic effects, human and animal labour requirements and trade-offs remains an important area for research*" [5], (see also Figure 2). Hence, it is rational to close this gap. Consequently, adapted approaches that respect the specifics of subsistence agriculture need to be developed.

As a preliminary approach, this paper presents the conceptualisation of a comprehensive framework for assessing energy efficiency in subsistence agricultural production systems. In section 1, the introduction is provided. In section section 2, we examine shortcomings of current methods of energy efficiency in analysing non-mechanised agricultural systems in developing countries. In section 3, the focus is how to conceive the methodological framework. Finally, in section 4, we summarise how we envisage the further development and application of the framework.

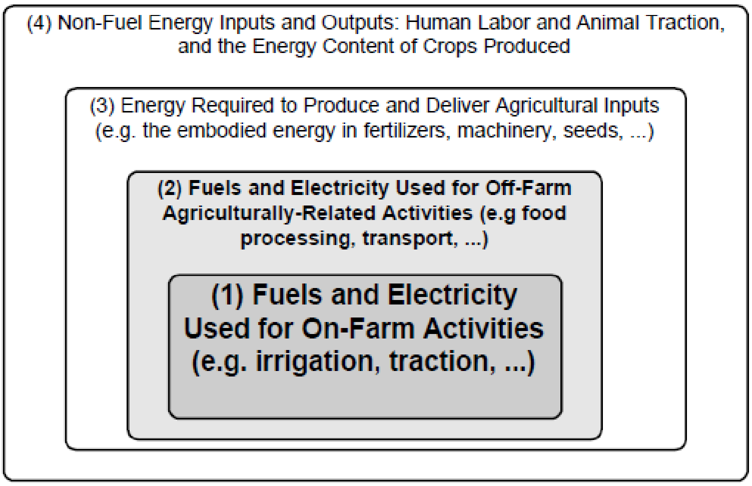

Figure 2: Levels of agricultural energy analysis by FAO
Source: copied from [5]

2. Requests for improving energy efficiency analysis

There has always been a need for alternative approaches through which energy analysis could lead to sustainable development in developing countries' agriculture. In 1993, the United Nations emphasised on the relationship between energy and agriculture [25 Chapter 14]. It underscores the need to enhance productivity and thus, sustainable development in developing countries. In 1995, the FAO reiterated that agricultural productivity is closely associated to direct and indirect energy inputs; and policies were required to consolidate this relationship to the benefit of farmers [5]. However, agricultural development policies in most African countries are designed and implemented with little or no regard to this association. Consequently, opportunities which could enhance production in both quantitative and qualitative terms are often lost. Energy development plans in most developing African countries rarely take into consideration the present and future energy needs of agriculture.

Efficiency is the ability to produce an output from the minimum input resources required [22]. The ratio of energy output to energy input defines the energy efficiency [19]. Energy efficiency is a widely used term in public policy. As such, information about energy efficiency could be applied in different ways to achieve energy savining. For example, energy conservation and energy efficiency, with the distinction being that the former is a change in behaviour while the latter involves an adoption of a particular technology which could enhance energy saving [17]. The advent of the concept of energy analysis was initiated in order to account for the fact that when heat or work is put into or taken out of a system, such a system ends up in a different state. Consequently, some property of the system has to account for the difference which has taken place. Thus, a given system under a given set of conditions has a certain energy content [24]. As sich, using the example of the distinction stated above [17], a combination of both energy conservation and energy efficiency may be necessary in some developing countries. For instance, it may require farmers in developing countries to primarily change their behaviour from traditional land-use practices before adopting alternative land-uses which could contribute in improving energy efficiency in agriculture.

The shortcomings of existing methods of energy efficiency analysis stem from the fact that the energy inputs from human, and draft animal labour in developing countries are often ignored [23], even though these inputs could be enormous [21]. Hence, energy inputs from various sources including humans and draft animals in agricultural systems in developing countries should be considered [27, 28]. However, most analyses were targeted at farm scale [28, 27]. Scenarios that involve different management strategy below farm scale have so far rarely been considered [28]. The links between agricultural energy inputs, yields, economic returns, land requirements and land-use change need further research [11, 29]. The information which could be obtained using existing methods could much more be useful if land-use and land management are integrated in a standardized energy analysis methodology. An overall advantage of integrating land-use and land management would be that energy efficient management and land-use strategies can be recommended as benchmark when formulating agricultural policies. Also, most of the currently applied methods ignore the regional interplay of energy fluxes which is so decisive for sustainable rural development in developing countries. Finally, existing methods of farm energy efficiency use different approaches and subsequently produce different results [15 p.356]. Furthermore, there are difficulties in comparing different agricultural systems using existing methods, because of the non-uniformity in the units in which energy efficiency is measured [23 p.123].

3. Methodological framework

To further develop the concept of energy efficiency analysis, we suggest combining the eMergy approach by Odum [16] and a technique in Data Envelopment Analysis (DEA) pioneered by Farrell [7] and later improved by Charnes *et al*., [3]. EMergy is a concept to better allocate and account for energy influxes (both inputs and outputs) in a production system. Its broader perspective of environmental inputs, direct connection to economics, and internal optimising principle [8] are a plus in analysis especially as energy, economics, and the environment are considered mutually dependent [26, 14]. Using transformity coefficients the influxes are converted into their energy equivalents measured in Solar eMergy Joule (SeJ), and subsequently analysed using DEA to process information in a way that enhances decisions making and energy efficiency oriented policies in agriculture. DEA is a non-parametric linear programming methodology through which it becomes possible to compare the productivity of different agricultural land use practices by considering a system of inputs and outputs. The best practice is benchmarked and the relative energy efficiency that can be improved in the peer land uses that are not benchmarked can be calculated. Another advantage is that different land use schemes are considered in the DEA analysis. The application of DEA is also useful to obtain result that is informative as much as possible even when there are constraints in the data [2].

For this study, the scarcity of data will be minimised by using a combination of data from primary and secondary sources. Rainfall is critical to agriculture in Africa, because rainfed agriculture is dominant in Africa. As such, data on rainfall and other renewable energy inputs from nature will be accounted. Table 2 shows exemplarily the energy influxes in a non-mechanised agricultural system. Table 3 shows the agronomic land use characteristics which are commonly practiced in non-mechanised agricultural systems in Ghana, representating a developing country in West Africa. Figure 3 shows our suggested overall framework for assessing energy efficiency. It is equipped with the capabilities to account for input resources which are difficult to account, and particular animal and human labour in African agricultural systems.

Renewable energy inputs from nature	**Non-renewable energy inputs from nature**	**Purchased energy Inputs**	**Service energy inputs**	**Biomass energy outputs**
Solar energy for photosynthesis Wind (kinetic energy) for pollination Rain for rain-fed irrigation Earth for geothermal/ geochemical input	Topsoil loss associated with agricultural land use & farming practices Seeds/ seedlings for sowing	Fertilizers Pesticides Other chemicals	Human labour Draft animal labour	e.g. crop yield

Table 2: A list of exemplary energy inputs and outputs in a non-mechanised agricultural system

Farming system	Farming practice	Effect of soil
Rotational bush burning	Slash & burn. Fallow period with or without fertilizer	Destruction of vegetative cover, Expose soil to erosion, Leaching of soil nutrients.
Permanent tree crop system	Slash & burn but presence of tree canopy	Minimal soil loss by erosion due to tree canopy.
Compound farming system	Slash & burn with or without fertilizer/ manure. Livestock grazing	Soil loss due to erosion, leaching of nutrients, Soil compaction due to livestock.
Mixed farming system	Slash & burn with or without fertilizer/ manure	Soil erosion & nutrient depletion.
Special horticultural farming system	Slash & burn with fertilizer/ manure & chemical application	Soil erosion, eutrophication & acidification due to fertilizer & chemical application.

Table 3: Characteristics of agronomic land use schemes in Ghana
Source: [4 p.4]

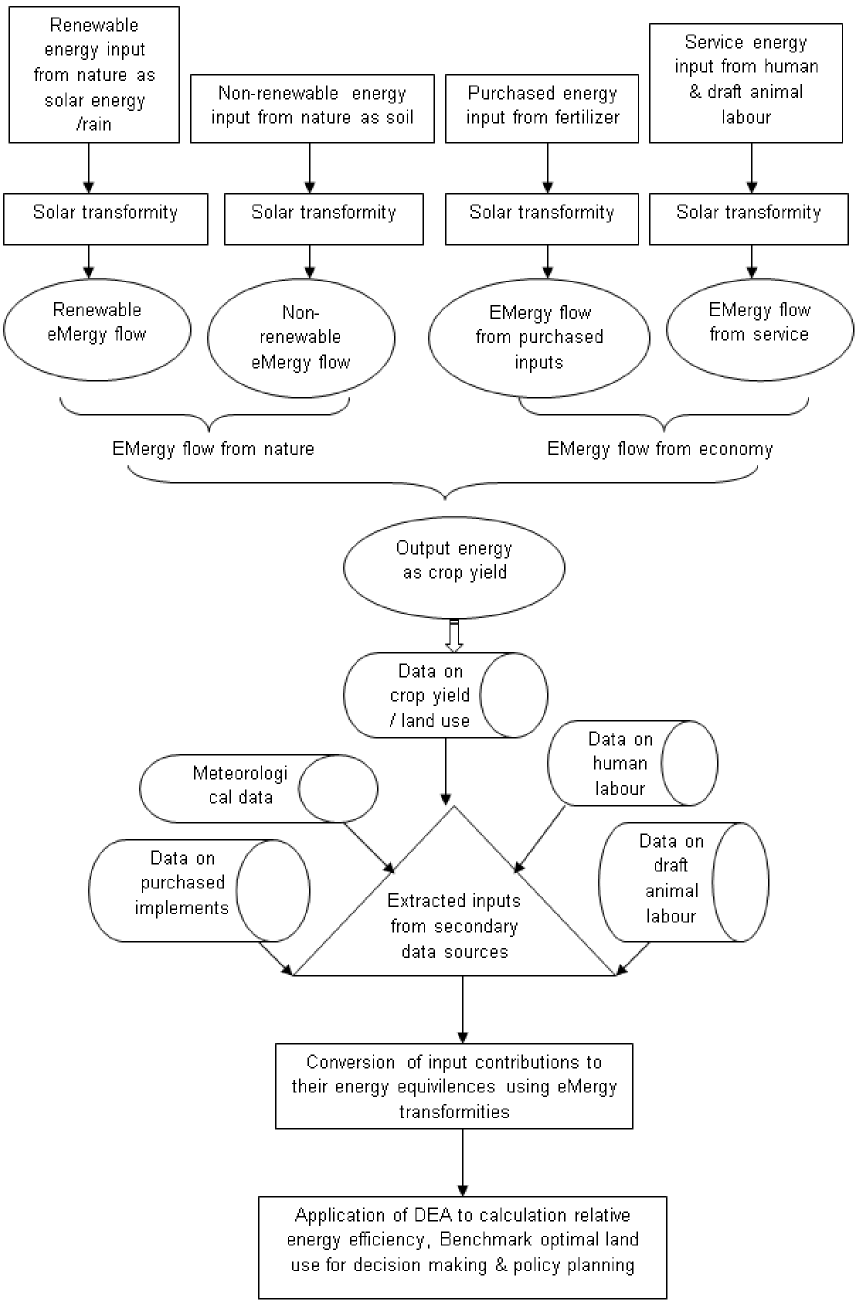

Figure 3: Conceptual framework

The eMergy component of the framework accounts for the various energy inputs to the production process in a given system. The energy use of the unit processes in the production system sum up to produce the output (yield). The inputs and outputs are converted to their energy values using transformity coefficients in eMergy. These energy values including their corresponding land-use schemes are fed into the DEA model component of the framework. The land-use schemes are the decision making units (DMUs). DEA uses a total factor productivity ratio to calculate the efficiency by attributing virtual weights to the input and output resources. The performance of entities is then calculated using a linear optimisation process, which maximises the ratio of each entity by finding the best set of weights for the inputs and outputs. The optimisation is constrained by the fed data such that each entity is compared against the best observed performance. In this way, the best land-use could be benchmarked. This could be used when making decision such as in policy planning that aims at optimising energy use in agriculture.

In 1995, the FAO [5] had already highlighted the complexity involved in assessing energy efficiency in non-mechanised agricultural systems which use human and draft animal power as input sources. In view of this complexity, our system boundary pays greater attention to direct inputs, and the produced outputs delivered at the farm gate. Unlike in mechanised system where the embodied energy of machines is standard and energy is consumed only when a machine is at work, the energy consumption of living systems (humans and draft animals) is continuous during their life span. More so, humans and animals need to be fed even when they are not momentarily expending energy at work. For this reason, we further consider pasture land for animal grazing to be within the confinement of the system boundary in order to minimise the dependence of draft animals on the output energy (i.e. crops excluding residue). Figure 4 shows a sketch of an exemplary system boundary of a non-mechanised agricultural system.

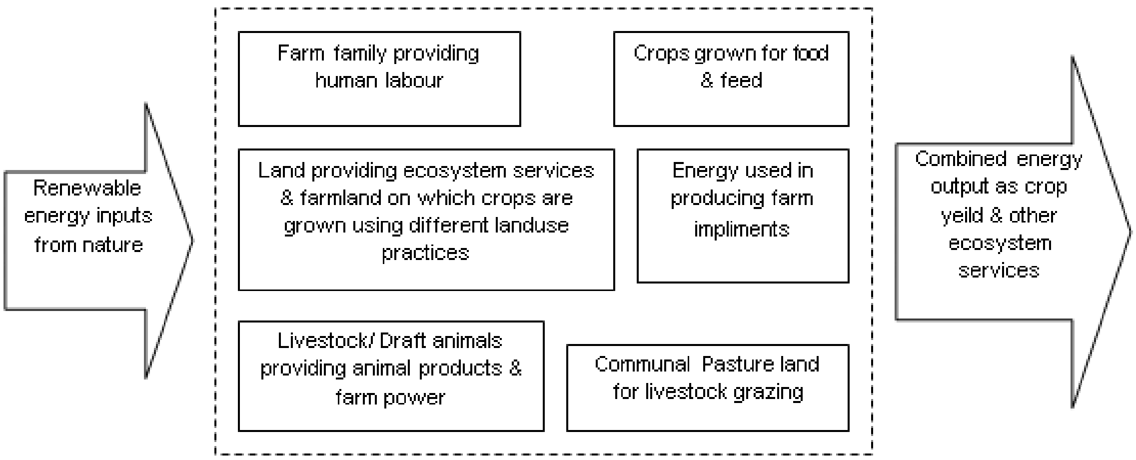

Figure 4: Sketch of system boundary

4. Discussion and conclusion

Following the oil crisis in the 1970s, the relationship between agriculture and energy (in this case fossil fuel) became vividly clearer and scholars have become increasingly aware of the dependence of agriculture on energy [20]. Since then, the analysis of energy use in agriculture has gained much momentum as many scholars have shown interest in the subject [26]. The main objective of a good energy analysis is to determine how much energy is actually needed to produce a given product or get a service done. But a more fundamental challenge is to decide on a logical and consistent system boundary, because different boundaries may lead to different results and conclusions [28].

The single ratio of output energy to input energy which defines energy efficiency obscures the visualisation of all the possible options through which the efficiency of a system whose output depends on multiple inputs could be improved [2]. The method and framework in this paper present a unique approach that combines eMergy and DEA to account for farm energy efficiency in non-mechanised systems, and support for policy making from a sustainable development perspective. The eMergy component of the method and framework ensures that all fluxes are accounted in the total energy use [26]. It further considers input energy contributions from natural resources (sun, rain, wind) to man-made agricultural systems for the benefit of the farmer, and considers ecosystem services in agriculture. The DEA component of the framework increases the number of assessable alternative approaches which could be used to improve on efficiency by incorporating data from both renewable and non-renewable energy inputs including land-use. More so, the framework is scale sensitive in order to support assessment at different scales. An assessment at regional scale will be useful in relating energy fluxes and balance to ecosystem services from both associated agricultural and naturally occurring ecosystems. The reference unit, i.e. SeJ further provides a means to compare different production systems in both quantitative and qualitative approaches.

Our future research tasks include fine-tuning the framework, and adapt it for assessing agricultural energy efficiency at regional scale, as well as to improve on the followsing previewed weaknesse. For example, the paucity in reliable data on agricultural land use, crop yields, human and draft animal labour. Data are scantily documented in most developing African countries. DEA is a data oriented analysis approach. It does not require any prior assumptions on the underlying functional relationships in converting inputs into outputs. However, the advantage of not requiring such prior assumption could pose a weakness when over specialisation is required. This can lead to a situation whereby some inputs and outputs could be ignored [12]. Another current weakness may be related to the limits of the system boundary as defined above. However, assessment at multiple levels minimises the problem of defending a particular system boundary [28].

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A Holistic Method of Assessing Efficiency and Sustainability in Agricultural Production Systems

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Abstract

Until now, no single universally adaptable method exits for complete assessment of efficiency and sustainability of agricultural production systems. Existing methods are limited for analyzing agricultural systems. This paper presents the Emergy-Data Envelopment Analysis method; which we built from aggregating Emergy Analysis (EMA) and Data Envelopment Analysis (DEA) into a framework, to provide improved accounting of resource and energy use efficiency including absolute and relative sustainability of agricultural production systems. The method of assessment is as follows. An emergy diagram of the production system is drawn to visually represent the system. Inputs and outputs of the system are estimated on an annual base in their standard physical units of measurement. The available energy content (exergy) of input and output resources are calculated respectively using appropriate methods of calculating exergy for each given input and output. This is done assuming the concept of energy memory. Using Microsoft excel, the emergy of the input and output resources are calculated as the mathematical product of resource exergy and unit emergy value (UEV). The refined procedure of emergy calculation by Brown and Ulgiati (2016) is applied, and it leads to the retainment of selected inputs and outputs of various resource types. The emergies of the selected resource inputs and outputs from comparative peer systems of production (decision making units - DMUs) are concatenated into a table (.csv format), and imported into a model of DEA. The optimization function in DEA applies Pareto efficiency to estimate the relative technical efficiency (rTE) scores among peer units. The score value is a proxy indicator for relative sustainability. The calculated UEV of a product equates to eco-efficiency, and it is applied to evaluate the resource and energy use efficiency. Selected emergy-based indicators of proven reliability are applied for the evaluation of absolute sustainability. The composition of the evaluation outcomes provides improved accounting information that contributes to completeness of assessed efficiency and sustainability of agricultural systems as a whole.

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1 Introduction

Global agriculture (crop production, livestock, forestry and other land use) was the second most significant source that accounted for 24% of greenhouse gas emissions in 2010 (IPCC, 2014). In addition, 70% fresh water and 37% land area were used for growing agricultural produce (Searchinger et al., 2013). Such rate of environmental impacts is a cause for concern. Thus, production systems with improved efficiencies and minimal impacts for global sustainability are a passionate goal (Tilman, 1999). This requires assessment methods which could provide more accounting information that could contribute to better understanding of agricultural production systems' efficiencies. Since management decision on selecting a particular system is influenced by the measured efficiency and sustainability (Clark and Tilman, 2017). Methods that could lead to complete assessments of agricultural systems could contribute to the goal of global food security, through the selection of systems whose efficiency could contribute better to the expected 50-70% increase in agricultural productivity in 2030 (Alexandratos and Bruinsma, 2012).

The efficiency of a production system is an expression of how much output is produced from a given input relative to the observed standard for the given system type (Black, 1930). Knowing the efficiency of a system compared to other systems is useful for supporting decisions on the resource management practice which could contribute to optimal productivity while exerting minimal impacts on the environment (Keating et al., 2010). This is important especially given the current growth rate of global population, it would imply more food has to be produced using systems with improved efficiencies in order to achieve food security (FAO, 2003; 2017; Edgerton, 2009; Alexandratos and Bruinsma, 2012). Reliable assessment of sustainability would also ensure that effort to grow sufficient amount of food is being achieved with minimal impacts on the environment (Giovannucci et al, 2012; McLaughlin and Kinzelbach, 2015). Since the last green revolution, the demand for energy including other resources needed by global agricultural production systems to sustain productivity has being increasing (Pimentel et al., 1999; Woods et al., 2010; Blum, 2013; Pellegrini and Fernández, 2018). This situation can not continue indefinitely because some natural resources are finite in supply (Glavič and Lukman, 2007). Therefore, it is obvious that the efficiency of resource and energy use in agriculture must be improved in order to increase agricultural productivity in a manner that would be sustainable (Spiertz and Ewert, 2009).

The measurement of efficiency is an important task in management particularly because it provides relevant information for making informed decisions. It provides a means to compare the productive capability of a management practice relative to peer practices, so as to make decisions which could lead to better planning in the agriculture sector for effective contribution towards sustainable development (FAO, 2016). It is also clear that resource and energy use efficiency are criteria of importance in agricultural production because they affect the economic and environmental sustainability (Alluvione et al., 2011). Subsequently, the concept of economic-ecological efficiency (commonly referred to as eco-efficiency) is a pragmatic approach to sustainability evaluation. Furthermore, by analogy eco-efficiency relates the economic value of products or services to the environmental pressure that had been exerted by a given production system while producing the said products or services (Schaltegger, 1996; Huppes and Ishikawa, 2005a; United Nations, 2009; Huysman et al., 2015).

So far existing methods of energy efficiency are limited for analyzing all energy input types that are invested as resources into the processes of production in agriculture (Jones, 1989). In particular, considering energy that is put into production through labor by humans and animal traction as in smallholder systems in developing countries (FAO, 1995). Implying that when all the energy fluxes that contribute to the ensued measured efficiency of a given system are not quantitatively accounted in the assessment process, that could lead to compromising decisions because every input and output has an impact on the measured efficiency.

The term "energy efficiency" (Patterson, 1996) refers to energy return on energy invested (EROI) in a production process (Murphy and Hall, 2010). In connection to agricultural production systems, the EROI is the ratio of output energy to input energy (Rehman, 2003; Murphy and Hall, 2010; Jordan, 2013). In other words, the metabolisable energy of a biomass yield (delivered at the farm gate) to the energy which had been invested to produce the given output (Black, 1971). The principal motivation for assessing the efficiency of a production system is to avoid compromises in productivity and sustainability (De Koeijer et al., 2002; Lin and Shao, 2006; Gomes et al., 2009, Chen et al., 2015). Until now, no single universally adaptable method exists for assessing energy efficiency (Jones, 1989, Blancard and Martin, 2012) neither is there a unique method of assessing sustainability of agricultural production systems (Schindler et al., 2015).

Without an adequate quantification of all resource inputs which energize the process of production in an agricultural system, assessment of efficiency will be in incomplete. Some insightful gaps identified in the existing literature worth noting are for example; "due to this complexity in managing semi-open systems [agriculture and forestry], usually their efficiency is measured incompletely" (Alvarenga et al., 2013). Moreover, "to obtain an energy efficiency indicator, it is generally necessary to have information about energy content of inputs. Several techniques exist to assess these energy contents but no single best source has been found". Therefore, one of the challenges has being "how to take this uncertainty or incomplete information into account when measuring energy efficiency of farms" (Blancard and Martin, 2014). The quest to make better informed decisions on agricultural production systems based on their measured efficiency implies the need for a methodic approach which could be comprehensive on the accounting of resources as a whole.

We aggregate Emergy Accounting (EMA) and Data Envelopment Analysis (DEA) methods into a framework (Mwambo and Fürst, 2014) that leads to the Emergy-Data Envelopment Analysis (EM-DEA) method is presented here as a novel approach for assessing resource and energy use efficiency including sustainability in agricultural production systems. This aims at making a contribution towards a better accounting of resources in order to provide more information when assessing agricultural systems. The rationale of our method builds on the fact that resource use, the energy driving the processes of production, the ensued efficiency and sustainability are interrelated in any given system of production (De Wit, 1979). All processes of production in agriculture use up environmental resources from nature and human economy (Odum, 1984). Implying resources which are used up are the inputs which provide the necessary energy for processes of production which eventually yields biomass output as a form of stored energy (Brüll, 2015). Challengingly, most input resources are limited in supply (Meadows et al., 1972; Neumayer, 2000). Therefore, the technical efficiency (TE) at which peer systems of production (using similar input resources but differ in management practices) would be capable to produce a given output under the constraint of limited availability of input resources, would be a proxy indicator for assessing relative sustainability of peer systems of production (Gomes et al., 2009).

EMA is applied for environmental accounting of resource use and output in production systems. This choice was made because EMA provides flexibility of quantitative accounting of environmental input resources from nature as well as from human economy (which include human labor and draft animal traction) which contribute to the processes of production in agricultural systems (Odum, 1967). Therefore, EMA is the tool which provides information on the energy content of inputs that take part in a production process (Campbell et al., 2014). On the other hand, DEA is applied to evaluate the sustainability efficiency of comparative peer systems of production. This choice was made because DEA's ability to evaluate the relative efficiencies of peer units simultaneously as a batch. This is helpful for supporting management decision when the selection of a particular system for implementation is dependent on the measured efficiency and sustainability (Gomes et al., 2009; Ren et al., 2013). The goal of this paper is to illustratively present the methodic synthesis of the innovative synergy between EMA and DEA which leads to the EM-DEA method. This paper is organized as follows: Section 1 is an overview of this paper. Section 2 explains the methods that are synthesized into the EM-DEA method. Followed by a narrative on the assessment of resource and energy use efficiency, as well as absolute and relative sustainability respectively. Section 3 reviews the synthesized method and the indicators. Section 4 highlights the key points in a conclusion.

2 Methods

2.1 Emergy accounting method

The theory of emergy is a well established method of environmental accounting (Odum, 1967; 1984; 1996; Odum and Odum, 1983; Brown and Ulgiati, 2004a). On the assumption that solar energy is the ultimate source of energy (besides deep earth heat and tidal energies) which drives processes on earth, emergy is defined as *"the energy of one type previously used up directly and indirectly to make a product or deliver a service*" (Odum, 1996; 1988; Odum and Odum, 2000). Thus, EMA is a useful tool for environmental sustainability assessment (Odum, 1996; Brown and Ulgiati, 1997; 2016). Closely associated with emergy method is the concept of transformity (Odum, 1988; Brown and Ulgiati, 2004b, Brown et al., 2004). Odum (1996) states that, "*energy flows of the universe are organized in an energy transformation hierarchy*". Adding that, "*the position in the energy hierarchy is measured with transformity*". By definition, solar transformity is "the solar emergy required to make 1 J of a service or product" (Odum, 1996). Therefore, by analogy transformity is the unit emergy value (UEV) which is the total amount of emergy used per functional unit of product produced by a given system (Ingwersen et al., 2014). This concept is applied for the quantification of material and energy into emergy on the premise of "energy memory" (Scienceman, 1987). The embodied energy is represented as a "memory" of the solar energy which had been used previously to produce a given product or service (Brown and Herendeen, 1996). In other words, the cumulative work done by nature including the processing by humans through labor, in transforming the environmental input resources into output resources which are the yield by a given system of production. Thus, emergy assessment provides the most comprehensive means to value human labor inputs (Kamp et al., 2016). More so, emergy method is a useful means to present meaningful accounting of natural, as well as human-made capital (Brown and Ulgiati, 1999; Campbell and Brown, 2012; Mellino et al., 2014; 2015).

Therefore, emergy methodology has been adopted here as the means to account for resources (in nature and human economy) which are used up (demand side) and produced (supply side) during an agro-ecological production in a given system. Thus, accounting for energy which can be obtained from a resource during a production process (Brown and Ulgiati, 2016). Therefore, given that energy is "t*he universal natural agency by means of which work is done*" (Garver, 1916), emergy becomes useful for expressing energy quality as well as quantity by comparing different energy forms relative to the energy of the primary source (the sun) which is measured in solar emergy joule (sej) as the common base (Brown and Ulgiati, 2004b).

Emergy analysis "is a systematic approach to consider environmental and economic sustainability at a systems level" (Daley, 2013). Emergy accounting as the quantitative evaluation of the contributions of energy and material inputs to processes of production in a system is in accordance with the concept of energy hierarchy (Odum, 2002). To calculate the emergy of producing a given output, the annual inputs resources required to produce a given output are estimated in their standardized measurable physical units. The available energy content (exergy) of a measured resource input is quantified in Joule. The energy content is transformed into its emergy by calculating the mathematical product of the resource exergy and transformity (or UEV) as given in Eq. (1).

$$Emergy_{resource} = exergy_{resource} * \tau_{resource} \tag{1}$$

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 UEV; measured in sej/unit.

2.2 Date envelopment analysis method

Data Envelopment Analysis (DEA) is a nonparametric linear programming based technique for estimating the relative efficiency of similar entities (commonly referred to as decision making units - DMUs) (Toloo and Nalchigar, 2009; Wen, 2015). First built by Farrell (1957) on the basis of relative efficiency, DEA has been improved further with different models of estimating efficiency and performance among peer entities. The estimation of efficiency is through mathematical optimization which operates as a linear programming function. Two basic envelopment models are distinguished. On the one hand, the constant return-to-scale (CRS) model of DEA which assumes a change in input leads to a correspondingly proportionate change in output. Thus, the marginal rate of transformation between inputs and outputs is fixed (Charnes et al., 1978). On another hand, the variable return-to-scale (VRS) model of DEA assumes the transformation constraint relating inputs to outputs changes for every given case (Banker et al., 1984).

Accordingly, by definition "efficiency" is the ratio of the observed and optimal values of output and input of a production system (Lovell, 1993). Given a production system as in agriculture, similar inputs are used to produce common outputs. However, differences in the management practices (DMUs) could lead to differences in outputs and eventually the measured efficiency. In DEA, the productive efficiency is estimated as relative technical efficiency (rTE) scores. In other words, the ratio of productive efficiency of each DMU relative to the productive efficiency of the most productive DMU (best-practice) for a given batch of peer units. In this light, the productive efficiency of the "best-practice" is treated as the standard observed efficiency for the given peer DMUs -on the assumption that it is by analogy the observed standard efficiency for the given systems type. In a system of production as in agriculture that consumes multiple inputs to produce multiple outputs, the productive efficiency (Ep) of a DMU is estimated as the ratio of output to input (Farrell, 1957). However, during the optimization process in DEA, different weights are assigned to the various inputs and outputs so as to obtain Pareto efficiency for each DMU among the given peers. Subsequently, Ep becomes the ratio of the weighted sum of outputs to the weighted sum of inputs. The linear programming function in DEA reduces this ratio into that of a single virtual output as the numerator and single virtual input as denominator respectively as given in Eq. (2). The ratio of the single virtual output to single virtual input for each DMU relative to that of the most performing unit leads to the estimate of rTE scores (Hartwich and Kyi, 1999; Kao, 2014).

$$E_P = \frac{u_1y_1 + u_2y_2 + u_3y_3 + u_4y_4 + u_my_m}{v_1x_1 + v_2x_2 + v_3x_3 + v_4x_4 + v_nx_n} = \frac{\sum_{o=1}^{m} u_{o1}y_{o1}}{\sum_{i=1}^{n} v_{i1}x_{i1}} \tag{2}$$

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.

The rTE scores indicate how much each DMU is efficient compared to the best performing DMU among the given peers. The management practice of a DMU is described as technically efficient if it minimizes the use of inputs at a given level of outputs, or it maximizes outputs at a given level of inputs. Thus, an efficient DMU would produce a certain amount of outputs or more outputs from a given amount of inputs, or uses the same amount of inputs or less inputs to produce a given amount of outputs when compared to its peers. Subsequently, an inefficient DMU is denoted by a score <1, while an efficient DMU is denoted by a score of 1; symbolizing it is 100% efficient and lies on the efficiency frontier. The programming function in DEA provides a linear convex frontier, thereby "enveloping" data points of lesser efficiency as purported by the nomenclature of this analysis tool. As illustrated in Fig. 1, the efficient DMUs: A, C, E, and G lie on the frontier which envelops the inefficient DMUs: B, D, and F. An inefficient DMU could attain efficiency through one of the two optimization oriented models. In an input oriented model, efficiency could be attained through a reduction of input to a level which would have been required if the given inefficient DMU were to be projected unto the efficiency frontier, while maintaining its level of output. For example, when B which is currently inefficient is to become efficient through an input oriented optimization process as in B′, there would have to be a reduction in input level from I_1 to I_2, while maintaining the output level at O_1 (see also Fig. 1). Alternatively, an output oriented optimization would seek to maximize the output of B to a level which would project B unto the frontier, while maintaining its level of input as in B″. An increase in output level from O_1 to O_2, while maintaining its input level at I_1 (see also Fig. 1).

Advantages of using DEA include the following. Prior knowledge or assumption on the relationship between inputs and outputs (parameter) is not a prerequisite for the estimation of efficiency (Cooper et al., 2007). Several DMUs including multiple inputs and outputs can be assessed as a batch. The units of measurement of inputs and outputs could be different. These features make DEA a suitable analysis tool which provides decision makers

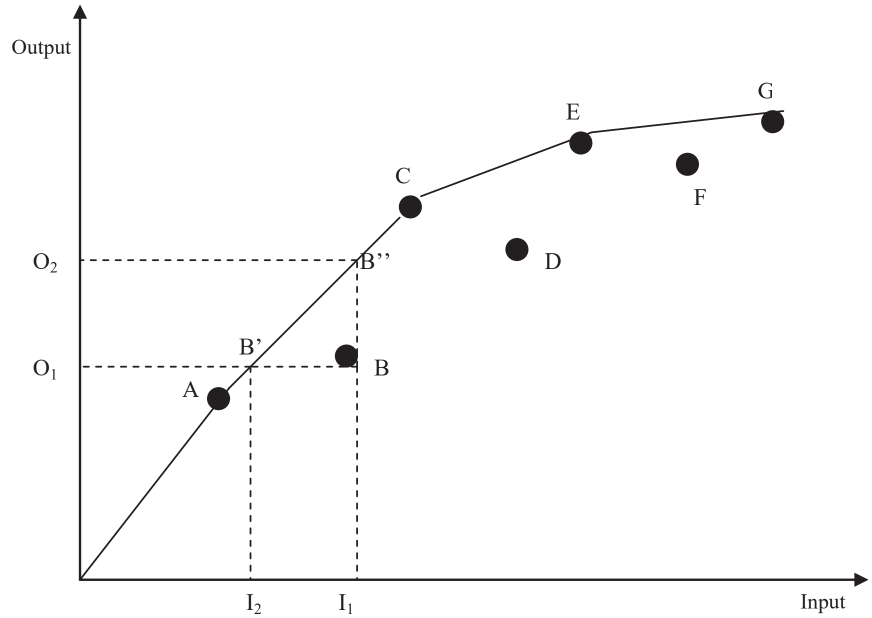

Fig. 1 A hypothetical example to illustrate the creation of an efficiency frontier in DEA (Source: authors' creation).

useful information using fewer data when compared to most other analyses tools (Sarkis, 2000). Therefore, the adoption of DEA here achieves the following objectives.

(i) To estimate rTE scores of different peer units of production. Hence, the rTE score is treated as a proxy indicator of relative sustainability of peer units of production.

(ii) To provide benchmarking of peer production units on the basis of the most performing unit. Thus, to differentiate between efficient and inefficient systems. On a relative scale, such differentiation coupled with the rTE scores provide an idea on how much is the efficiency disparity between the most productive unit and the inefficient peer units which have to be improved.

2.3 Synthesis of the emergy-data envelopment analysis method

The aggregation of Emergy Accounting and Data Envelopment Analysis methods into a framework (Mwambo and Fürst, 2014) leads to the innovative synergy – the Emergy-Data Envelopment Analysis (EM-DEA) method. The EM-DEA method is as follows. The assessment procedure starts by way of identifying the main components (e.g. energy sources, pathways of energy and material flow, producer, processes of production, output, storage, and boundary) which make up a given production system. A given system of production is represented graphically using energy systems diagram for the purpose of visualization, and this further eases the process of accounting. Emergy analyses of a system follow a top-down approach (Brown et al., 2000). The annual input and output resources are estimated in their standardized measurable physical units (e.g. grams for material weight). As illustrated in Table 1, the input and output resources are itemized, and their quantities estimated on an annual base. The available energy content (exergy) of each estimated resource is appropriately calculated in Microsoft Excel; which also serves as the tool for mathematical operations on the datasets. The calculated exergy of a resource is measured in Joule (J). The energy content of each resource is transformed into its corresponding emergy equivalence; which is the mathematical product of a resource exergy and transformity (or UEV) as stated in Eq. (1). The calculated emergies are summed up categorically in accordance with the refined emergy accounting approach provided by Brown and Ulgiati (2016). The basic categories are (i) local renewable sources (R: e.g. sunlight, rain, wind), (ii) local non-renewable sources (N: e.g. soil loss), (iii) imported sources from outside the system (F: e.g. fertilizer, animal labor), (iv) labor and services (L&S: e.g. direct human labor on the farm, services include all other human endeavors from outside the system but contributing directly to crop production on the farm), and (v) yield (Y: e.g. agricultural biomass produce) (see also Table 1). The refined approach is useful for avoiding double counting of resources during the accounting procedure. The adoption of the refined approach leads to a retainment of selected resources from the basic pool of resources as exemplified in Table 1. Hereafter, the selected resources become the short listed variables for subsequent evaluation of efficiency and sustainability as illustrated below. Eqs. (3) and (4) show illustrations of the refined approach for the calculation of input emergy for the production of a given output by considering nature resources (raw material), as well as nature and human economy (complete economy) respectively.

$$Total\,emergy\; U_{\substack{without\\ L\&S}} = Max\left[A_{exe}A_{UEV} + B_{exe}B_{UEV} + C_{exe}C_{UEV},\ \max\left(D_{exe}D_{UEV}, E_{exe}E_{UEV}\right)\right] + F_{exe}F_{UEV} + G_{exe}G_{UEV} + H_{exe}H_{UEV} + \max\left(I_{exe}I_{UEV}J_{exe}J_{UEV}\right), \tag{3}$$

$$Total\,emergy\, U_{\substack{with\\ L\&S}} = Max\left[A_{exe}A_{UEV} + B_{exe}B_{UEV} + C_{exe}C_{UEV},\ \max\left(D_{exe}D_{UEV}, E_{exe}E_{UEV}\right)\right] + F_{exe}F_{UEV} + G_{exe}G_{UEV} + H_{exe}H_{UEV} + \max\left(I_{exe}I_{UEV}, J_{exe}J_{UEV} + K_{exe}K + L_{exe}L_{UEV}\right). \tag{4}$$

The selected resource outputs, inputs, and their respective nominal peer systems of production are concatenated into a table (Table 2), and imported as a file (in "comma delimited" format; .csv) into a model of DEA. The nominal peers of the imported data by analogy represent the batch of decision making units (DMUs) in a model of DEA.

During the process of running the model to achieve optimization, the linear programming function in DEA applies different weights to the imported data so as to achieve Pareto efficiency. DEA assumes the least square regression method (Kuosmanen and Johnson, 2010); which is illustrated here using a multiple ordinary least square regression whose general formula is given in Eq. (5). DEA calculates the relative productive efficiency (E_p) as a function of the selected inputs and outputs for each of the entities (DMUs) that constitute the given system of peers as given in Eq. (2). The rTE scores are generated from the calculation of relative productive efficiency as an expression of the ratio of E_p of each peer to E_p of the best performing entity of the given batch (Gomes et al., 2009).

$$\gamma_i = \beta_0 + \beta_1\chi_1 + \beta_2\chi_2 + \beta_3\chi_3 + \beta_4\chi_4 + \beta_5\chi_5 + \beta_6\chi_6 + \beta_7\chi_7 + \beta_n\chi_n + \mu_i \tag{5}$$

where, γ_i = yield or resource output, β_0 = coefficient of the intercept, $\beta_1, ..., \beta_n$ = slope or coefficient of selected resource inputs (variables), $\chi_1, ..., \chi_n$ = selected resource inputs (variables), μ_i = slacks (residuals).

Note: The agricultural output yield (Y) is a product of multiple input variables (which in this case are the emergy values of the selected resource inputs).

The estimated rTE scores lie in the interval $0 \leq score \leq 1$. The score of an efficient production entity is 1, while the score of an inefficient production system is <1 respectively. The rTE score is by analogy a measure of the productive efficiency of each DMU when compared to the most performing entity (best practice unit) for the given batch of peer units of production. On this basis, an efficiency frontier is constructed as illustrated in Fig.1.

In the EM-DEA method, the eco-efficiency concept is applied for the assessment of resource and energy use efficiency. Absolute sustainability is system based and is assessed by applying selected emergy-based indicators of proven reliability, while relative sustainability is assessed on the basis of comparison between peer entities (DMUs) by considering the estimated rTE scores as a proxy indicator -respectively. Consequently, the assessments are as follows.

2.3.1 Assessing efficiency

The EM-DEA method assesses efficiency using the eco-efficiency concept as the inversed ratio of environmental impact to economic value as given in *Eq*. (6). By analogy, the eco-efficiency is the calculated UEV of a product. Subsequently, the assessments of resource and energy use efficiency are expressed as eco-efficiency by resource use (EcoERU) and eco-efficiency by energy use (EcoEEU) as given in *Eqs*. (7) – (10) respectively.

$$Eco-Efficiency = \frac{Environmental\ \ pressure}{Economic\ \ value} = \frac{Total\ \ emergy\ \ U}{yield\ \ matter\ \ dry} \tag{6}$$

Table 1 Basic input and output resources emergies of a generalized non-mechanized system of agricultural production.

Note	Item	Unit	Data	Exergy (J)	UEV (sej/unit)	Emergy (sej/yr)
	Primary sources					
1	Sun	*J*	A	A_{exe}	A_{UEV}	$A_{exe}A_{UEV}$
2	Deep heat	*J*	B	B_{exe}	B_{UEV}	$B_{exe}B_{UEV}$
3	Gravity	*J*	C	C_{exe}	C_{UEV}	$C_{exe}C_{UEV}$
	Sum of primary sources					$A_{exe}A_{UEV}+B_{exe}B_{UEV}+C_{exe}C_{UEV}$
	Secondary sources					
4	Water/Rain /irrigation	*J*	D	D_{exe}	D_{UEV}	$D_{exe}D_{UEV}$
5	Wind	*J*	E	E_{exe}	E_{UEV}	$E_{exe}E_{UEV}$
	max. of secondary sources					$\max(D_{exe}D_{UEV}, E_{exe}E_{UEV})$
	Max. of Renewables (R)					$\mathrm{Max}[A_{exe}A_{UEV}+B_{exe}B_{UEV}+C_{exe}C_{UEV}, \max(D_{exe}D_{UEV},E_{exe}E_{UEV})]$
	Non-renewable sources (N)					
6	Topsoil loss	*J*	F	F_{exe}	F_{UEV}	$F_{exe}F_{UEV}$
	Imported sources (F)					
7	NPK fertilizer	*g*	G	G_{exe}	G_{UEV}	$G_{exe}G_{UEV}$
8	Seeds	*g*	H	H_{exe}	H_{UEV}	$H_{exe}H_{UEV}$
9	Animal labor	*hr/yr*	I	I_{exe}	I_{UEV}	$I_{exe}I_{UEV}$
10	Manure	*g*	J	J_{exe}	J_{UEV}	$J_{exe}J_{UEV}$
	Labor & Services (L&S)					
11	Human labor (L)	*yr*	K	K_{exe}	K_{UEV}	$K_{exe}K_{UEV}$
12	Services (S)	*$*	L	L_{exe}	L_{UEV}	$L_{exe}L_{UEV}$
	Total Emergy (U) without L&S					[*Eq*. 3]
	Total Emergy (U) with L&S					[*Eq*. 4]
	Yield (Y)					
	(Without L&S)					
13	Edible biomass	*g*	M		[Eq.3]/M	
	Edible biomass	*J*	M*LHV		[Eq.3]/[M*LHV]	
14	Biomass by-products	*g*	N		[Eq.3]/N	
	Biomass by-product	*J*	N*LHV′		[Eq.3]/[N*LHV’]	
	(With L&S)					
13	Edible biomass	*g*	M		[Eq.4]/M	
	Edible biomass	*J*	M*LHV		[Eq.4]/[M*LHV]	
14	Biomass by-product	*g*	N		[Eq.4]/N	
	Biomass by-product	*J*	N*LHV′		[Eq.4]/[N*LHV′]	

where,

A,.., N = resources estimated in their physical unit of measurement (e.g. *J* for Joule,*g* for grams)

A_{exe} = exergy of the resource “A”

A_{UEV}= UEV of the resource “A”

[a] = reference of the UEV of resource “A”

(L) = human Labor; all forms of physical labor on the farm (e.g. land preparation, sowing, weeding, harvesting)

(S) = Services; other forms of physical & technical labor done outside the farm but directly contribute to production on the farm (e.g. industrial manufacture of agrochemicals, transportation of inputs to farm).

LHV = lower heating value of edible biomass

LHV′ = lower heating value of biomass by-product

[Eq.3]/M = calculated UEV of product (without including L&S)

[Eq.4]/M = calculated UEV of product (with L&S)

Table 2 Table showing emergies of their selected outputs and inputs of a system and its peers.

DMUs	Output	Output	Input	Input	Input	Input
Production system 1	$M_{exe}M_{UEV}1$	$N_{exe}N_{UEV}1$	(R) 1	(N) 1	(F) 1	(L&S) 1
Production system 2	$M_{exe}M_{UEV}2$	$N_{exe}N_{UEV}2$	(R) 2	(N) 2	(F) 2	(L&S) 2
Production system 3	$M_{exe}M_{UEV}3$	$N_{exe}N_{UEV}3$	(R) 3	(N) 3	(F) 3	(L&S) 3
Production system 4	$M_{exe}M_{UEV}4$	$N_{exe}N_{UEV}4$	(R) 4	(N) 4	(F) 4	(L&S) 4
Production system 5	$M_{exe}M_{UEV}5$	$N_{exe}N_{UEV}5$	(R) 5	(N) 5	(F) 5	(L&S) 5
Production system *n*	$M_{exe}M_{UEV}n$	$N_{exe}N_{UEV}n$	(R) *n*	(N) *n*	(F) *n*	(L&S) *n*

where,

DMUs = peer production systems; 1, ..., *n*

Note:

Cell values are calculated emergies of output and input resources of the peer systems. See also Table 1 showing exemplified items in (R), (N), (F) and (L&S) categories.

$$EcoERU_{(without\ L\&S)} = \frac{U_{(without\ L\&S)}}{yield\ \ matter\ \ dry} = \frac{[Eq.3]}{yield\ \ matter\ \ dry_{(g)}} \tag{7}$$

$$EcoERU_{(with\ L\&S)} = \frac{U_{(with\ L\&S)}}{yield\ \ matter\ \ dry} = \frac{[Eq.4]}{yield\ \ matter\ \ dry_{(g)}} \tag{8}$$

$$EcoEEU_{(without\ L\&S)} = \frac{U_{(without\ L\&S)}}{yield\ \ exergy_{(J)}} = \frac{[Eq.3]}{yield\ \ matter\ \ dry_{(g)} * LHV} \tag{9}$$

$$EcoEEU_{(with\ L\&S)} = \frac{U_{(with\ L\&S)}}{yield\ \ exergy_{(J)}} = \frac{[Eq.4]}{yield\ \ matter\ \ dry_{(g)} * LHV} \tag{10}$$

where, U= Total emergy of a system, $L\&S$ = Labor and Services, g= mass of yield matter dry measured in grams, J= available energy content of yield matter dry measured in Joule, LHV= lower heating value of yielded agricultural biomass product.

2.3.2 Assessing sustainability

The measured sustainability relies on the evaluation of suits of indicators because sustainability is multidimensional. Consequently, no single indicator contains sufficiently enough information on all the dimensions of sustainability. More so, the assessment is further sub-divided into absolute and relative sustainability (Jin and High, 2004). Absolute sustainability is system focused while relative sustainability focuses on a comparison between the given peer entities.

2.3.2.1 Absolute sustainability

The suits of indicators for assessing the absolute sustainability include the following emergy-based indicators: Total emergy (U), Emergy Yield Ratio (*EYR*), Environmental Loading Ratio (*ELR*), Emergy Sustainability Index (*ESI*), and Percentage Renewability (*%REN*) which have been proven through emergy related studies (Brown and Ulgiati, 2004a; Ulgiati et al., 2011; Dong et al., 2014; Viglia et al., 2017). Consequently, when L&S are not considered in an assessment, the indicators are evaluated as follows.

$$Total\ emergy\ U = [Eq.\ 3] \tag{11}$$

$$EYR = \frac{(R+N+F)}{F} = \frac{(\mathrm{Max}[\mathrm{A_{exe}A_{UEV}} + \mathrm{B_{exe}B_{UEV}} + \mathrm{C_{exe}C_{UEV}}, \max(\mathrm{D_{exe}D_{UEV}}, \mathrm{E_{exe}E_{UEV}})]}{[(\mathrm{G_{exe}G_{UEV}}) + (\mathrm{H_{exe}H_{UEV}}) + (\mathrm{I_{exe}I_{UEV}})]} + \frac{(\mathrm{F_{exe}F_{UEV}}) + (\mathrm{G_{exe}G_{UEV}}) + (\mathrm{H_{exe}H_{UEV}}) + (\mathrm{I_{exe}I_{UEV}}))}{[(\mathrm{G_{exe}G_{UEV}}) + (\mathrm{H_{exe}H_{UEV}}) + (\mathrm{I_{exe}I_{UEV}})]} \tag{12}$$

$$ELR = \frac{(N+F)}{R} = \frac{[(F_{exe}F_{UEV}) + (G_{exe}G_{UEV}) + (H_{exe}H_{UEV}) + (I_{exe}I_{UEV})]}{[\mathrm{Max}[A_{exe}A_{UEV} + B_{exe}B_{UEV} + C_{exe}C_{UEV}, \max(D_{exe}D_{UEV}, E_{exe}E_{UEV})]]} \quad (13)$$

$$ESI = \frac{EYR}{ELR} = \frac{[Eq.\ 12]}{[Eq.\ 13]} \quad (14)$$

$$\%REN = \frac{1}{(1+ELR)} = \frac{1}{(1+[Eq.\ 13])}. \quad (15)$$

Alternatively, when labor and services are taken into consideration, the indicators are evaluated as follows.

$$Total\ emergy\ U = [Eq.\ 4] \quad (16)$$

$$\begin{aligned} EYR &= \frac{(R+N+F+L+S)}{(F+L+S)} \\ &= \frac{(\mathrm{Max}[A_{exe}A_{UEV} + B_{exe}B_{UEV} + C_{exe}C_{UEV}, \max(D_{exe}D_{UEV}, E_{exe}E_{UEV})]}{[(G_{exe}G_{UEV}) + (H_{exe}H_{UEV}) + (I_{exe}I_{UEV}) + (K_{exe}K_{UEV}) + (L_{exe}L_{UEV})]} \\ &\quad + \frac{(F_{exe}F_{UEV}) + (G_{exe}G_{UEV}) + (H_{exe}H_{UEV}) + (I_{exe}I_{UEV}) + (K_{exe}K_{UEV}) + (L_{exe}L_{UEV}))}{[(G_{exe}G_{UEV}) + (H_{exe}H_{UEV}) + (I_{exe}I_{UEV}) + (K_{exe}K_{UEV}) + (L_{exe}L_{UEV})]} \end{aligned} \quad (17)$$

$$\begin{aligned} ELR &= \frac{(N+F+L+S)}{R} \\ &= \frac{[(F_{exe}F_{UEV}) + (G_{exe}G_{UEV}) + (H_{exe}H_{UEV}) + (I_{exe}I_{UEV}) + (K_{exe}K_{UEV}) + (L_{exe}L_{UEV})]}{[\mathrm{Max}[A_{exe}A_{UEV} + B_{exe}B_{UEV} + C_{exe}C_{UEV}, \max(D_{exe}D_{UEV}, E_{exe}E_{UEV})]]} \end{aligned} \quad (18)$$

$$ESI = \frac{EYR}{ELR} = \frac{[Eq.\ 19]}{[Eq.\ 20]} \quad (19)$$

$$\%REN = \frac{1}{(1+ELR)} = \frac{1}{(1+[Eq.\ 20])} \quad (20)$$

where, U = Total emergy of a system, $L\&S$ = Labor and Services, g = mass of yield matter dry measured in grams, J = available energy content of yield matter dry measured in Joule, LHV = lower heating value of yielded agricultural biomass product.

2.3.2.2 Relative sustainability

The assessment of relative sustainability is by comparing the relative productive efficiencies (otherwise the relative technical efficiency - rTE) of the peer entities (DMUs) in DEA. The emergy-based data of the peer entities (Table 2) are imported into DEA. The rTE are calculated by DEA which applies Pareto efficiency using *Eqs*. (5) and (2) respectively for the evaluation of the rTE. The relative sustainability is interpreted as a score given in the interval $0 \leq score \leq 1$. The score is generated for each of the DMUs as the ratio of the productive efficiency (E_p) of each unit to the (E_p) of the most efficient unit of production.

3 Discussion

EMA and DEA methods have being existing for quite some time, and often applied separately for environmental accounting (Odum, 1967; Odum and Odum, 1983; Odum, 1988; Odum, 1996; Ulgiati and Brown, 1997; 1998), and assessment of relative efficiency (Charnes et al., 1978; Førsund and Sarafoglou, 2002; Cooper et al., 2007; 2011) in a variety of system types – respectively. The combination of both methods into a common methodic framework (Mwambo and Fürst, 2014) to improve the accounting information on resource and energy efficiency, including absolute and relative sustainability assessment in agricultural systems as illustrated in this paper is quite new.

The capability to quantitatively measure resource inputs and outputs is provided by EMA which provides flexibility for evaluating energy and material resources as the input energy fluxes that contribute to processes of production in a system including the accounting of the output resources. The accounting is in accordance with the concept of energy hierarchy (Brown and Ulgiati, 2004b). Thus, EMA considers both the energy quality and quantity which had been used previously to produce a product. In addition, EMA values non market inputs which otherwise can not be valued monetarily. The sej as the common unit of measurement allows all resource inputs and outputs to be compared fairly on a common base. Furthermore, DEA permits peers to be compared simultaneously, by assessing the rTE as a ratio of the E_p of each peer to E_p of the most productive peer of a given batch. This approach provides a fair score showing peers that are relatively efficient (denoted by score =1) and peers that require improvement (denoted by score <1). This score is treated as a proxy indicator for relative sustainability.

Even though generally there are no precise criteria or indicators for sustainability in agriculture (Park and Seaton, 1996; Hayati et al., 2010), the selected indicators for the assessment of efficiency and sustainability are meaningful and provide relevant information about a given system. For example;

(1) Total emergy U provides a measure of a given system in terms of demand for environmental support by biosphere. The smaller this demand the more sustainable is a give system.

(2) Calculated UEV expresses the eco-efficiency of a product expressed in terms of (i) resource use and, (ii) energy use efficiency respectively. The smaller the calculated UEV is, the higher the eco-efficiency of the given product.

(3) EYR expresses a system's reliance on local resources. The higher the EYR imply the better the sustainability of the given system.

(4) ELR provides an upper limit to the carrying capacity. In other words, the limit to which the production may not cause alteration in the ecological, economic and social patterns.

(5) %REN expresses the fraction of renewability of the product from a given system. The higher the value of % REN, the more ecological is a given system and the derived product.

(6) ESI is a composite ratio of EYR to ELR. It is an expression of the environmental sustainability. The ESI evaluates the higher yield per unit of lower environmental loading. Consequently, it provides a long term perspectives of a given system.

Therefore, these indicators provide relevant information for informed decision making about a given system (Brown and Ulgiati, 1997; 2001).

In several aspects, the EM-DEA method is founded on well established methods, integrates meaningful concepts, and sizes up to existing methods of assessing efficiency and sustainability. For example, the concept of "eco-efficiency" which implies "creating more value with less environmental impact" (WBCSD, 2000) as in "producing more agricultural output from less resources" (Keating et al., 2010). The description by WBCSD on the means to achieve eco-efficiency reads as follows;

"*Eco-efficiency is achieved by the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the earth's estimated carrying capacity*" (WBCSD, 2000).

This description distinguishes economic value and environmental impact as the determinants of eco-efficiency. This description also objectively reflects the commonly accepted dimensions of sustainability –which are: environmental/ecological, economic, and social (Hueting and Reijnders, 1998). The eco-efficiency concept could be interpreted as the ratio between the economic value to environmental impact (WBCSD, 2000). An alternate interpretation to this is the inversed ratio of impact to value (United Nations, 2004; Kortelainen & Kuosmanen, 2004). The application of eco-efficiency in the EM-DEA method is that of the latter approach which equates eco-efficiency to the calculated UEV of a product by assessing the ratio of impact to value (see also Eq. (6) and the derived equations that follow). Consequently, the smaller the magnitude of the calculated UEV implies the more eco-efficient is a product expressed here in terms of EcoERU and EcoEEU respectively.

The adoption of eco-efficiency into this method of assessment is useful as a pragmatic concept in sustainability assessment in terms of resource and energy use. An assessment based on this concept could empower a decision maker with relevant information to provide answers to questions such as, why a particular agricultural management practice could be a wise choice that could guarantee high productivity while minimizing impacts on environment? Such an approach in sustainability is rational on the basis of the value derived and impact on the environment (Huppes and Ishikawa, 2005b). Hence, a sustainable agricultural production system implies one that achieves sufficient agricultural biomass production, for the socio-economic benefits that could contribute to human wellbeing, while minimizing the impacts on the environment through efficient use of resources in the long term (Sydorovych and Wossink, 2008; Keating et al., 2010; Reytar et al., 2014).

When the EM-DEA method is compared to some existing methods, to an extent it is similar to the method of assessing energy efficiency with imprecise energy content information (Blancard and Martin, 2012), and the method of assessing sustainability of agricultural systems (Gomes et al., 2009) – which both use DEA models. However, the EM-DEA method has the following strengths over some existing methods. Flexibility to quantitatively account for inputs (as well as outputs) from both nature and human economy, and the capacity to have all resources measured in sej, which is the common base for comparison. The relative measure of performance given as rTE scores is a useful proxy for assessing relative sustainability of agricultural production systems. Weaknesses of the method include the following. All inputs and outputs must be quantitatively measured, and valid. Any invalid measurement will bias the assessment. When interpreting the results on relative sustainability, one should bear in mind that the relative sustainability of a given production system is in comparison with the peers that constitute a given batch.

The use of an improved method to assess resource and energy use efficiency in agriculture is important, because farm management decision making that could lead to desirable development objectives such as sustained productivity to enhance food security, economic profitability for farmers and minimal impacts on the environment should be based on reliable information from measured efficiency and sustainability (Bojnec and Latruffe, 2008). The EM-DEA method is emergy-based and provides a means of accounting resource use by quantification of the energy content of all input and output energy fluxes of a production system. Such accounting could provide improved information on resources which could ultimately contribute to comprehensive assessment of a production system as a whole. Given that emergy is a derivative of exergy, implies emergy-based analysis could provide an improved evaluation of the energy content of resources, and this could ultimately contribute to completeness of resource and energy use efficiency. In particular, exergy is a useful concept in resource accounting (Wall, 1977).

It should be noted that in as much as the upper limit to crop productivity is set by the climatic conditions as well as the genetic potential of a given crop variety (Doorenbos and Kassam, 1979; Steduto et al., 2012), however, the farmer is the manager of the crop production system. Consequently, resource management practices by the farmer would to a lesser extent influence crop productivity and availability of resources in a system. For this reason and much more, the consideration of DMUs in this paper focused on farmer's management practices, and how the adoption of the EM-DEA method could be useful in increasing the amount of meaningful information that could be available to the farmer in order to support his decision to enhance both crop productivity and the overall sustainability of an agricultural production system.

4 Conclusion

This paper illustrates the novelty of the EM-DEA method in achieving comprehensive assessment of efficiency and sustainability in agricultural production systems as a whole. This method is synthesized from EMA and DEA methods. EMA provides the means for quantitative accounting of resources that are used from nature and human economy. Using the refined emergy accounting approach, selected fluxes are retained for the analysis. A table of the retained input and output fluxes for comparative production systems (also referred to as decision making units of production-DMUs) in ".csv" format makes the emergy-based data. The calculated UEV of products is interpreted as eco-efficiency and used as the means to evaluate resource and energy use efficiency of comparative production systems. Selected emergy-based indicators of proven reliability are applied for the evaluation of absolute sustainability. DEA provides nonparametric treatment of the imported emergy-based data of DMUs for comparative sustainability efficiency analyses which leads to rTE scores that are interpreted as proxy indicator for relative sustainability. Therefore, the composition of the results from the assessments would provide relevant accounting information of resources in terms of relative sustainability, absolute sustainability, resource and energy use efficiency. This paper has to be considered as a first attempt to build an adaptable method to better assess energy efficiency of agricultural production systems as a whole. In particular, in assessing small-scale systems in developing countries. In order to improve further the EM-DEA method as presented here, the method must be widely tested and criticized.

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

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ABSTRACT

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

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Despite the limitation caused by scarcity of data, the use of the EM-DEA approach led to inclusive information on RUE and sustainability of the DMUs. Hence, the EM-DEA approach represents a way forward to better assess energy footprint in agricultural land use as a whole.

1. Introduction

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

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

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

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

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

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

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

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

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

2. Materials and methods

2.1. Study area

The study area is Bolgatanga and Bongo Districts located in the Upper East Region, Ghana, SSA[1] (Fig. 1). The area is about 1217 km^2, situated within latitudes 10° and 11° N, and longitudes 0° and 1° W. The natural vegetation is a mosaic of Sudan and Guinea savanna woodland, characterized by scanty stunted trees which form an open canopy over grasses as the understorey (Bagamsah, 2005). The area is drained by the Volta River, and the climate is sub-arid. The rainfall ranges between 800 and 1100 mm (Callo-Concha et al., 2013; GSS, 2014), while the annual mean rainfall is about 1044 mm (Badmos et al., 2015). The annual mean temperature is 29 °C (Badmos et al., 2015), maximum is 34 °C, and minimum is 15 °C (Faulkner et al., 2008). The annual rainy season lasts between April/May and September/October, and the distribution is unimodal. The length of the growing period is between 90 and 165 days (Mdemu, 2008). Small-scale agriculture is the major economic activity in this area. The fertility of the soil is low, except alluvial plains (Mdemu, 2008). The area is impacted by climatic and environmental stress factors (Amikuzino and Donkoh, 2012; Issahaku et al., 2016). This situation is exacerbated by pressure from agro-pastoral activities which are carried out by a growing population (Akolgo, 2011). The complex combination of these natural and man-made constraints contribute in land degradation (Callo-Concha et al., 2013), and this situation aggravates the cycle of poverty (GSS, 2015; Cooke et al., 2015) as well as the risks of food insecurity (Abane, 2015; Alhassan, 2015). Considering that smallholder farmers in semi-arid Africa are in an increasingly vulnerable situation due to the direct and indirect effects of climate change, demographic pressure and resource degradation (Tittonell et al., 2012), as well as a likely increase in the demand for cereals in the Sudano-Sahelian zone in the coming decades (Ringler et al., 2010), this area represents a typical situation in the Sudan savanna zone.

2.2. Data sources and data processing

The data for this study were derived from primary and secondary sources. The primary data focused on farmers' practices including agricultural land use and resource management in small-scale maize systems. Using the snowball sampling method, in total $n = 56$ personal interviews of small-scale maize farmers were conducted in Bolgatanga and Bongo Districts in 2015. The data were

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

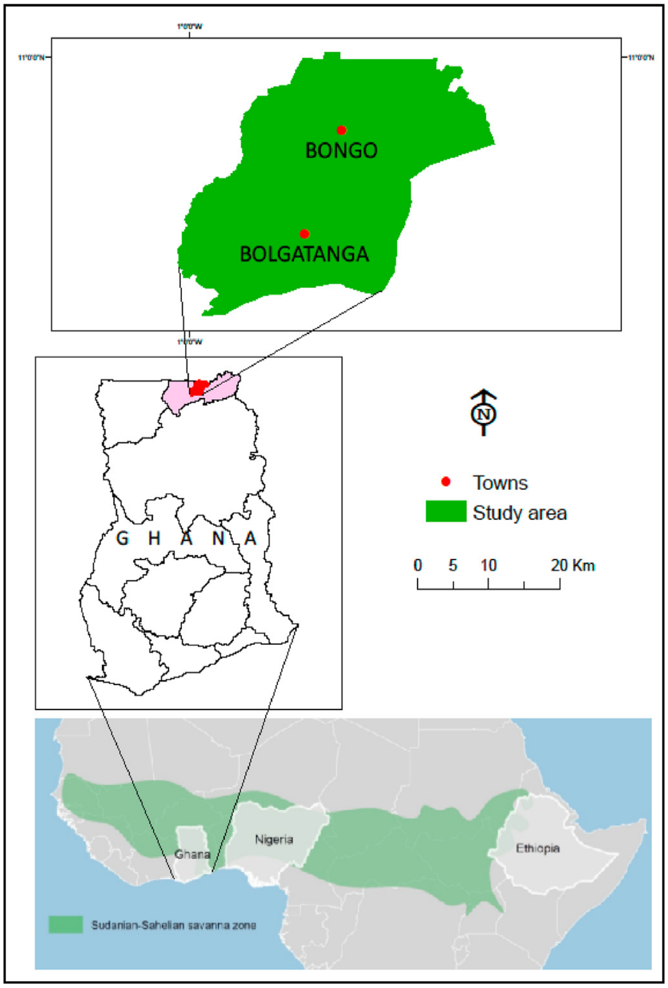

Fig. 1. Study area.

collected using semi-structured questionnaire. Local varieties were the most cultivated. The farm labor (L) inputs were as follows: land preparation, sowing, fertilizer/manure application, weeding, harvesting, and threshing. The following services (S) were considered: cost of purchased inputs (seeds, NPK/urea fertilizer, solar powered pump for irrigation, draft animal, animal feed, stable, phytosanitary care, and a shadow price for farm labor). The data were processed using standard statistical tools in Microsoft Excel (2007). The data are presented in Table 1.

The majority of the interviewees could not present farm records during the interview survey, and hence the primary data were based on estimates. The representativeness of the primary data was checked using statistical comparison between the mean yield (Table 1) and the mean yield based on production data for Bolgatanga and Bongo Districts during the period 2003–2011 (Ghanaian Ministry of Food and Agriculture, MoFA) (Appendix E). The statistical difference between both means was small. The primary data (Table 1) was enhanced further by substituting the mean yield which was based on estimates (Table 1) with the mean yield which was based on recorded production data (Table 17).

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

$$\begin{aligned}&Estimated\ residue,\ i.e. stover\ (ton\,/\,acre)\\&= Grain\ yield\ (bushel\,/\,acre)*56/2000,\end{aligned} \tag{1}$$

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

$$Estimated\ residue\ (ton/ha) = \left[\left(Grain\ yield*14.86*\frac{56}{2000}*2.25\right],\right. \tag{2}$$

The primary data (Table 1) were supplemented with the simulated data, and complemented with biophysical data from reliable and published secondary sources (Table 2). These consolidated datasets were used to model five land use and resource management scenarios to represent practices in smallholder maize systems in Ghana, SSA. The scenarios were synthesized by combining land use and resource management options (Table 3). The scenarios were the decision making units (DMUs). The data on GHG emissions and carbon stocks in maize systems were derived from reliable and published secondary sources (Table 4).

2.3. Assessment methods

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

2.3.1. Explanation of the Emergy Accounting (EMA)

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

Table 1
Primary data.

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

Source: Field survey in Bolgatanga and Bongo Districts (2015). *1 man day = 6 h, **1 animal day = 4 h.

Table 2
Biophysical data.

Data	Value	Reference
Grain yield	1.2 ton/ha	[Table 16][a]
Rainfall in study area during 2003–2011	0.911 m/yr	MoFA (2012)
Manure input	29.25 kg/ha	Dadson et al. (2016)
Moisture content in manure	0.70	Sonko et al. (2016)
Solar insolation	1.20E+21 J/m^2/yr	CEP (2012)
Albedo	0.15	Arku (2011)
Subsurface heat	42 mW/m^2	Beck and Mustonen (1972)
Wind speed	2.6 m/s	(World Weather Online)
Fraction of evapotranspiration water	0.73	Nurudeen (2011)
Soil erosion	0.1291 ton/ha/yr	Badmos et al. (2015)
Soil organic matter (OM) content	0.0129%	Amegashie (2009)
Moisture content in OM	0.012%	Dawidson and Nilsson (2000)
Cost of NPK (15 15 15) fertilizer	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 (1.5hp) 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	

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

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

where.

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

2.3.2. Explanation of the Data Envelopment Analysis (DEA)

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

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

where.

E_P = *productive efficiency of a DMU*
μ_0 = *weight allocated to output o*
v_i = *weight allocated to input i*
y_o = *amount of output o from a DMU*
x_i = *amount of input i allocated to a DMU*

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

The EM-DEA approach is an assessment framework that aggregates EMA and DEA (Mwambo and Fürst, 2014), and the concept

Table 3
Land use and resource management practices.

Scenario	Description	External inputs	Biomass output
Extensive0	Zero external input to maize system. Maize and other non-leguminous crops could be grown in an intercropping system.	Water as rain, 0 kg/ha/yr urea fertilizer, ±29.25 kg manure.	1.17 t/ha (grain, wet matter)° 0.93 t/ha (grain, dry matter) 0.93 t/ha (residue, wet matter) 0.88 t/ha (residue, dry matter)
Extensive12	Low external input to maize systems. Maize and other non-leguminous crops could be grown in an intercropping system.	Water as rain, 12 kg/ha/yr NPK (15 15 15), ±29.25 kg manure.	1.2 t/ha (grain, wet matter)§ 0.96 t/ha (grain, dry matter) 0.96 t/ha (residue, wet matter) 0.90 t/ha (residue, dry matter)
Intercrop20	Maize-legume (cowpea -*Vagna unguiculata,* ground nuts -*Arachis hypogaea* or soybean −*Glycine max*) intercropping system. Modest external input to maize system.	Water as rain, 20 kg/ha/yr urea fertilizer, ±29.25 kg manure.	1.88 t/ha (grain, wet matter)° 1.5 t/ha (grain, dry matter) 1.41 t/ha (residue, wet matter) 1.17 t/ha (residue, dry matter)
Intensive50	Moderate external input to maize system. Maize is grown in a monoculture system.	Water as rain including supplemental irrigation from a surface source (0.18 m/ha/yr), 50 kg/ha/yr urea fertilizer.	2.75 t/ha (grain, wet matter)° 2.20 t/ha (grain, dry matter) 2.20 t/ha (residue, wet matter) 2.06 t/ha (residue, dry matter)
Intensive100	High external input to maize systems. Maize is grown in a monoculture system.	Water as rain including supplemental irrigation from a surface source (0.18 m/ha/yr), 100 kg/ha/yr urea fertilizer.	2.81 t/ha (grain, wet matter)° 2.25 t/ha (grain, dry matter) 2.25 t/ha (residue, wet matter) 2.11 t/ha (residue, dry matter)

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

of eco-efficiency is integrated to assess the RUE and sustainability of agricultural production systems as a whole (Mwambo and Fürst, 2019). In this study, the EM-DEA approach was applied as follows.

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

2.3.3.1. Mathematical evaluation of the relative sustainability. The names of the DMUs, as well as the corresponding emergy values of the retained outputs, i.e. grain yield (dry matter) and emergy values of the retained input resources were concatenated using Microsoft Excel, and the file was saved in comma delimited format (*.csv*). This was imported into an Open Source Data Envelopment Analysis (OSDEA)[2] model. The Charnes Cooper Rhodes input (CCR_I) oriented model of DEA (Charnes et al., 1978) was

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

Table 4
Data for carbon emissions and stocks.

Type	Description	Conversion factors/units	Reference
Emission	Emission factor for industrial production of NPK (15 15 15), and when applied as nutrient	1.61 (production), 10.71 (application) kg CO_2 e/kg	[a]
Emission	Emission factor for industrial production of Urea mineral, and when applied as nutrient	5.15 (production), 11.19 (application) kg CO_2 e/kg	[a]
Emission	Shipment of NPK (15 15 15)	2389 nautical mile (nm) [c]	[b], [c]
	Assumption: NPK (15 15 15) was imported (from Agadir, Morocco to Takoradi, Ghana)[b]	≈ 4424.43 km	
		8 g CO2 e/ton-km	ECTA and Cefic (2011)
Emission	Shipment of urea mineral	4569 nautical miles (nm) [c]	[b], [c]
	Assumption: urea mineral was imported (from Ambarli, Turkey to Takoradi, Ghana) [b]	≈ 8461.79 km	
		8 g CO2 e/ton-km	ECTA and Cefic (2011)
Emission	Transportation of NPK/urea by road from Takoradi to study area	832.9 km	[d]
		62 g CO_2	ECTA and Cefic (2011)
Emission	Emission from compost manure (production & application)	368.4 ± 18.5 kg CO_2/Mg manure	Hao et al. (2004)
Emission	Soil Organic Carbon (SOC) loss during plowing	4 ± 1.9 kg C e/ha	Lal (2004)
Emission	Emission caused by human labor	12.1–14.4 MJ/day	(Bleiberg et al., 1980; Brun et al., 1981; Houshyar et al., 2015)
		0.36 kg CO_2/MJ	
Stock	Carbon content in the above ground biomass	43.6% of above ground biomass (dry matter)	Latshaw and Miller (1924)

[a] https://www.fertilizerseurope.com/fileadmin/user_upload/publications/agriculture_publications/carbon_footprint_web_V4.pdf.
[b] https://www.infoafrica.it/wp-content/uploads/2018/02/Ghana-Fertilizer-Statistics-Overview-2016.pdf.
[c] https://sea-distances.org/.
[d] https://www.google.com/maps/dir/Sekondi-Takoradi,+Ghana/Bolgatanga.

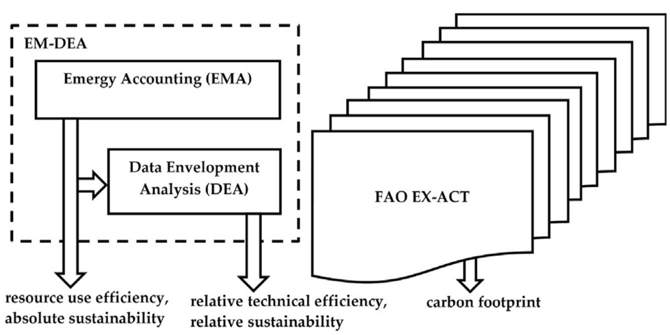

Fig. 2. Methodological framework.

applied in order to calculate the relative Technical Efficiency (rTE) scores. The optimization function in DEA assumes the multiple ordinary least squares regression as stated in *Eq.* (5) (Kuosmanen and Johnson, 2010), and applies Pareto efficiency to select the weights for the imported data. The DEA model uses the imported data and applies *Eq.* (4) to calculate the rTE scores (Table 15).

$$\gamma_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7 + \mu_i \, , \quad (5)$$

where.

γ_i = yield or output produced by the i^{th} practice
β_0 = coefficient of the intercept
$\beta_1, \ldots \beta_7$ = slopes or coefficients of selected input resources, i.e. $x_1, \ldots x_7$
x_1 = evapotranspired water
x_2 = topsoil loss
x_3 = NPK or urea application intensity
x_4 = draft animal labor (plowing)
x_5 = maize seeds
x_6 = human labor
x_7 = services
μ_i = slacks (residuals) of the i^{th} practice
Note : $x_1, \ldots x_7$ were the selected input resources, (see also, Table 11)

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

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

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

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

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

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

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

where.

F = Imported resources
N = Non-renewable resources
R = Renewable resources
U = Total emergy of a system
L&S = Labor and Services
g = mass of dried grain yield measured in grams
J = available energy content of dried grain yield measured in Joule
LHV = lower heating value of dried grain yield
Note: Details on F, N, R, U, L, S, g, J, & LHV are stated in Table 12.

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

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

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

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

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

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

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

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

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

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

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

where.

F = Imported resources
N = Non-renewable resources
R = Renewable resources
U = Total emergy of a system
L&S = Labor and Services
Note: Details of F, N, R, U, L, S, g, J, & LHV are stated in Table 12.

2.3.4. Application of the EX-ACT to evaluate the carbon footprint

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

On that note, the EX-ACT was adaptively applied to assess the carbon footprint of the various scenarios representing the DMUs in small-scale maize systems in Ghana, SSA as follows. The emergy systems diagrams (Fig. 8, Fig. 9 and Fig. 10) were used to define the system boundaries. By considering intensification as a strategy for improving productivity in small-scale maize systems, it was assumed that *Intensive100* was the reference scenario against which the following farm scenarios: *Extensive0*, *Extensive12, Intercrop20*, and *Intensive50* were compared (see also the trade-off analysis, Table 8). The carbon emissions and stocks were quantified in ton CO_2 e/ha/yr. The following sources of GHG emissions were quantified: industrial production of NPK and urea fertilizer as well as the transportation, on-farm application of NPK and urea fertilizer or organic manure, loss of soil carbon during plowing, and emissions by human during farm labor. The GHG emissions were

Table 5
Analysis of RUE and sustainability.

Indicator	*Extensive0*		*Extensive12*		*Intercrop20*		*Intensive50*		*Intensive100*	
	without L&S	*with L&S*	without L&S	with L&S	without L&S	with L&S	without L&S	With L&S	without L&S	with L&S
Total emergy U (E+15 *sej*/ha yr)	0.273	5.35	0.396	5.87	0.385	4.64	0.611	8.85	0.904	9.55
UEV_R (E+9 *sej*/g d.m.)	0.292	5.72	0.412	6.12	0.256	3.09	0.278	4.02	0.402	4.25
UEV_E (E+5 ***sej/J***)	0.195	3.81	0.275	4.08	0.171	2.06	0.185	2.68	0.268	2.83
EYR	6.60	1.05	2.42	1.05	2.49	1.05	1.83	1.03	1.44	1.03
ELR	0.19	22.27	0.72	24.54	0.67	19.19	1.22	31.18	2.28	33.73
ESI	34.97	0.05	3.35	0.04	3.70	0.05	1.50	0.03	0.63	0.03
%REN	84	4	58	4	60	5	45	3	30	3
rTE	100		64.7		100		100		100	
$UEV_{currency}$ (E+12 sej/Gh')	1.30		1.30		1.30		1.30		1.30	

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

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

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

Sample study/Method of assessment	Technical Efficiency (%)
Addai and Owusu (2014) Translog Stochastic Production Frontier Function was used in estimating the TE of small-scale maize farmers in Forest, Transitional, and Savanna Zones in Ghana. The sample size $n = 453$. The results of the TE were as follows: 79.9, 60.5, and ***52.3***%, respectively. The mean was 64.1%. Note: In this cited study, only the TE for the Savanna Zone was considered for its close similarities to the mix Guinea and Sudanian savannas in northern Ghana.	52.3
(This study) The EM-DEA method was used for measuring the rTE of five practices for cultivating maize in small-scale systems in the mix Sudanian and Guinea savannas in northern Ghana. The sample size consists of interview with 56 farmers, simulations using APSIM and extensive secondary data sources.	64.7
Abdulai et al. (2013) The Stochastic Frontier Approach (SFA) was used in estimating the TE of maize farmers in northern Ghana (Northern-, Upper East-, and Upper West- Regions). The sample size $n = 360$.	74
Abdulai et al, (2018) Data Envelopment Analysis (DEA) was used in estimating the TE of maize farmers in northern Ghana (Northern-, Upper East-, and Upper West- Regions). The sample size $n = 360$.	77
Mean efficiency of sample studies (excluding this study)	*67.76*
Mean efficiency of sample studies (including this study)	*67*
Difference between the calculated means of efficiency values (with and without this study)	*0.76*
Standard deviation (SD) of efficiency distribution of the given sample studies	*11.1*
Number of SDs of rTE for Extensive12 from the mean efficiency value of the sample studies	*−0.21*
95% Confidence Interval	*56.12 −77.88*

calculated using *Eq.* (21). Maize crop was the carbon sink, and the carbon stock was calculated using *Eq.* (22). The annual carbon balance was the difference between the sum of GHG emissions and sum of carbon stocks, and this was calculated using *Eq.* (23). This net emissions value per unit of farmland was considered as the carbon balance, i.e. net carbon emissions per hectare (ton CO_2 e/ha/yr). This being the metric which was used to quantify the net GHG emissions in crop production while focusing on environmental health. Using *Eq.* (24), the carbon balance associated with per tonne of grain produced, i.e. carbon balance per tonne grain (ton CO_2 e/ton grain) was quantified. This being the metric which was used to emphasize both emissions during the production of a crop as well as the products (grain yield) associated with per unit of emission.

$$GHG\ emissions = activity\ data * GHG\ emission\ factor \tag{21}$$

$$carbon\,stock = above\,ground\,biomass * carbon\,stock\,exchange\,factor, \tag{22}$$

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

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

2.4. Validation methods

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

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

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

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

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

Legend:

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

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

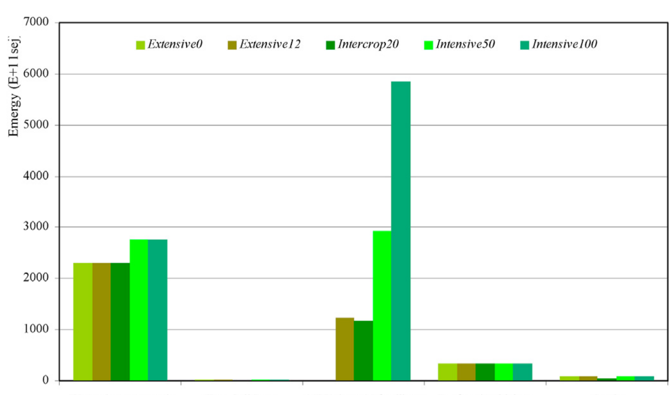

Fig. 3. Input raw materials per hectare.

where.

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

3. Results

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

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

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

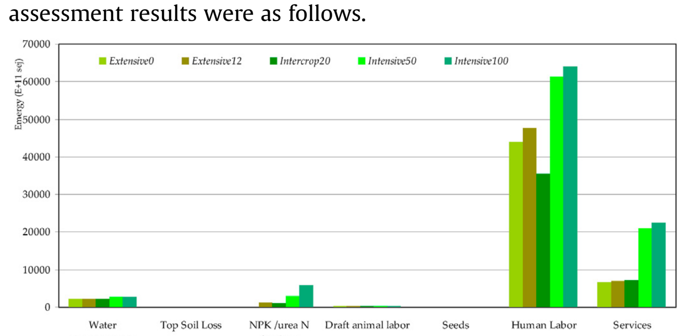

Fig. 4. Input raw materials including labor and service per hectare.

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

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

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

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

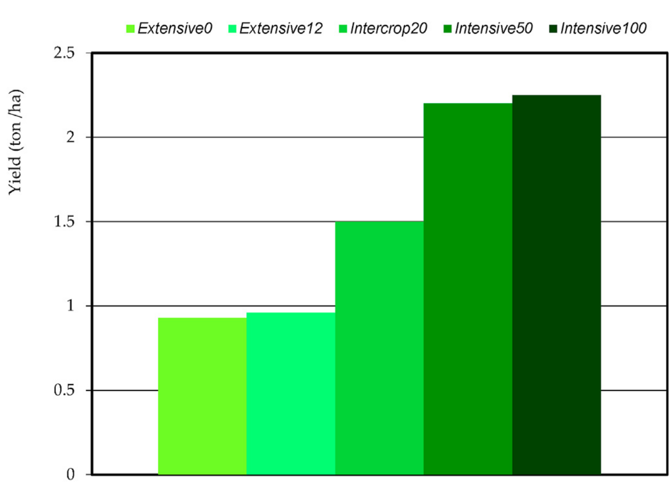

Fig. 5. Dry matter yield.

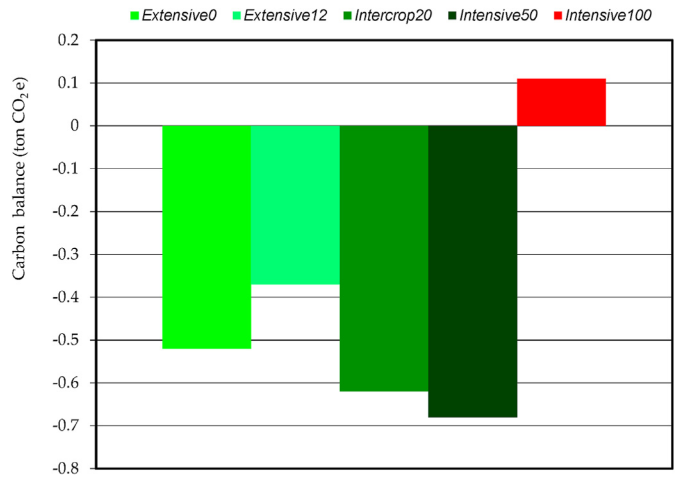

Fig. 6. Carbon balance per unit of farmland.

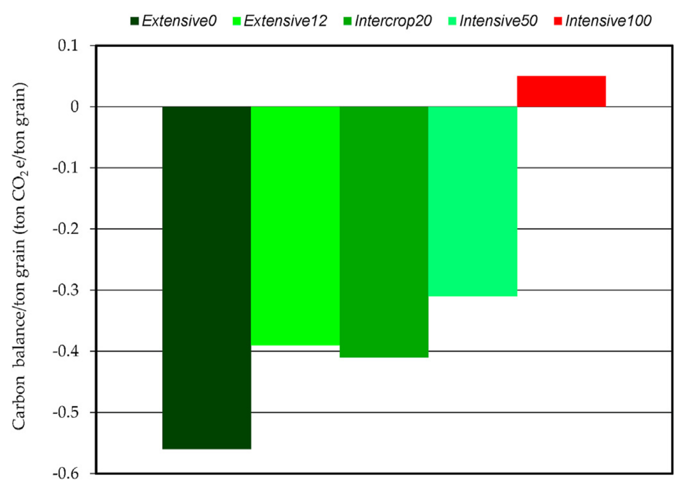

Fig. 7. Carbon balance per tonne grain.

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

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

The Percentage Renewability (%REN) is the fraction of renewability of the product, i.e. the fraction of the product (yielded grain delivered at the farm-gate) that originated from renewable input resources. The greater the %REN, implies that the product was produced using more renewable resources, and hence the more sustainable the given system would be. The sequence of the scenarios based on the %REN, from high to low was as follows: *Extensive0*, *Intercrop20*, *Extensive12*, *Intensive50* and *Intensive100*. As such, *Extensive0* achieved the greatest fraction of renewability of product by using more renewable input resources, while *Intensive100* achieved the least fraction of renewability of the product by using more non-renewable input resources. In other words, *Extensive0* relied on 84% of renewable resources to produce the grain yield as compared to *Intensive100* which relied on 30% of renewable resources to produce the gain yield, respectively.

3.2. RUE and absolute sustainability based on the inputs from the whole economy

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

3.3. Relative sustainability

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

3.4. Carbon footprint

The GHG emissions increased with increase in NPK or urea intensity. Both the carbon balance per unit of farmland and carbon balance per unit of product (grain yield) showed similar trends (Fig. 6 and Fig. 7). The assessment results (Table 6), showed that the field-to-farm gate carbon balance ranged between −0.680 and 0.114 ton CO_2 e/ha/yr, while the carbon balance per tonne grain ranged between −0.563 and 0.051 ton CO_2 e/ton grain, respectively. The impact of the various scenarios based on the carbon balance per unit of farmland, from low to high were as follows: *Intensive50*, *Intercrop20*, *Extensive0*, *Extensive12*, and *Intensive100*. When the carbon balance per unit of product was considered, the impact caused by the various systems, from low to high were as follows: *Extensive0*, *Intercrop20*, *Extensive12*, *Intensive50*, and *Intensive100*. In both metrics, the impacts caused by *Intensive100* were greatest when compared to the peer systems. The source attributed with the greatest emission was industrial production of NPK and urea fertilizer. The detailed analysis of the carbon footprint of the various scenarios are presented in Appendix D.

3.5. Holistic view of the aggregated results

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

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

4. Discussion

4.1. Validation of the results for RUE

The validation was by comparing our results for the RUE to the results of another empirical study that was assessed using another method. In this study, *Extensive12* was the "business-as-usual" scenario, because it was based on primary data. While *Extensive0, Intercrop20, Intensive50,* and *Intensive100* were the "contrasting"" scenarios, because they were based on simulations (Table 3). The use of the EM-DEA approach in this study showed that the relative Technical Efficiency (rTE) score which was achieved by *Extensive12* was 64.7% (Table 5). This value was compared to the Technical Efficiency (TE) of small-scale maize farmers in the Sudanian and Guinea savanna, Ghana (Wongnaa, 2016). The TE was assessed using the stochastic frontier production function (Aigner et al., 1977; Meeusen and van den Broeck, 1977). The observed TE was 61.2% (Wongnaa, 2016). This value is statistically comparable to 64.7%, which was derived using the EM-DEA approach in this study. The comparability between both values which were derived using different methods in assessing the efficiency in similar production systems located in an identical agroecological zone, demonstrates the validity of our results for RUE.

4.2. Uncertainty of the results for RUE

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

The calculated Z-score was about −0.21, and this implies that the rTE value for *Extensive12* was 0.21 times below the mean efficiency value reported by the sample of studies (Table 7). To further confirm that the uncertainty was statistically small, the difference between the mean efficiency values reported by the sample of studies (including and excluding this study) was calculated. The difference was 0.76, which is statistically small. Thus, the uncertainty of the rTE value which was derived using the EM-DEA approach was small and allowable. The following assumptions were applied: (i) the efficiency values of the sample of studies formed a normal distribution (Table 7), (ii) the values of the TE reported by the three empirical studies were representative of the TE of small-scale maize production systems in Ghana, SSA, (iii) the mean efficiency value reported by the sample of studies approximated to the true mean efficiency value for small-scale maize production systems in Ghana, SSA.

4.3. Reliability of the results for RUE

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

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

$$SD = \sqrt{\frac{\sum\left(X - \overline{X}\right)^2}{n-1}}, \quad (26)$$

$$Z-score = \frac{X - \overline{X}}{SD}, \quad (27)$$

$$95\%CI = \overline{X} - \pm Z\frac{SD}{\sqrt{n}}, \quad (28)$$

where.

SD = *standard deviation*
X = *TE value reported by an empirical study*
$\overline{X}$ = *mean of the TE values*
n = *sample studies*
$Z - score$ = *number of SDs of the rTE value for Extensive*12 *from mean TE value of sample studies*

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

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

4.4. Validation of the results for carbon footprint

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

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

4.5. Comparison of results to other existing empirical studies

First, this study was compared to an empirical study on maize yield response to fertilizer input in the Guinea savanna zone, Nigeria, SSA. The results of the empirical study showed that intensive land use systems treated with 100 kg/ha urea N as the base intensity, produced a yield that was suboptimal relative to systems that were treated with fertilizer input intensities that were less than 100 kg/ha urea N. The greatest yield was observed in fields

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

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

[P] projection using the data for *Extensive0*
[P] projection using the data for *Extensive0.*

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

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

Third, this study was compared to an empirical study on the carbon footprint of maize production as affected by synthetic nitrogen input intensity (100, 200 kg/ha N) to continuous monoculture and maize-legume (alfalfa -*Medicago sativa*, red clover -*Trifolium pratense*, or soyabean -*Glycine max*) rotation systems in North America. The results of the reported field experiment showed that high application of N increased both the GHG emissions and carbon footprint across all rotation systems. Although the GHG emissions were high in the rotation systems, however, the carbon footprint was lesser due to the improved yield in the maize that follows the legume crop cycle. More so, the GHG emissions and carbon footprint of the maize-legume rotation systems were lesser when compared to the emissions and footprint of the monoculture systems (Ma et al., 2012). The results of the reported experiment are similar to the results of this study. For instance, the GHG emissions and carbon footprint of *Intercrop20* were lesser relative to the GHG emissions and carbon footprint of *Intensive50* and *Intensive100*. More so, although the total GHG emissions emitted by *Intercrop20* was greater than the total GHG emissions emitted by *Extensive12,* however, the carbon footprint (carbon balance per tonne grain) of *Intercrop20* was lesser relative to the carbon footprint (carbon balance per unit tonne grain) of *Extensive12* (Appendix D). The similarities between our results and the results obtained by Wang et al. (2015), and Ma et al. (2012), confirm that our results conform to trends that have been observed in maize systems with similar cropping pattern and input resources in other regions of the world.

4.6. Trade-off analysis

The total emergy (U), carbon balance per tonne grain, and grain yield were the proxies for analyzing the trade-offs among resource saving, carbon saving and yield gap, respectively. In this trade-off analysis, it was assumed that *Intensive100* was the "reference scenario", while *Extensive0*, *Extensive12*, *Intercrop20* and *Intensive50* were the "farm scenarios", respectively. *Extensive0* and *Extensive12* demanded for fewer resources and the productivities were lower relative to the other scenarios. The yield gap was much wider when compared with *Intensive100* (Table 8). More so, food provision by *Extensive0* and *Extensive12* was lower (Mwambo et al., 2020). As such, the risk of converting more naturally occurring ecosystems into farmland in order to grow more food could likely occur in *Extensive0* than in the other systems, and this could lead to increase in GHG emissions (Table 9). Hence, *Extensive0* and *Extensive12* were less attractive, because of the wider yield gap. *Intensive100* produced the greatest yield, but the urea input intensity and GHG emissions were also greatest. Although the yield gap was null, however, the resources and carbon saving were least relative to the various scenarios. As such, *Intensive100* was not a preferable practice, because of the environmental impacts (Table 8).

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

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

4.7. Empirical evidence and policy recommendations

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

The majority of small-scale maize production systems in SSA are rainfed (Edreira et al., 2018). Water (evapotranspiration) was the most demanded input from nature (Fig. 3). Water is a scarce resource. Climate change is aggravating water scarcity (Oyebande and Odunuga, 2010; Kabo-Bah et al., 2016; Mancosu et al., 2015; Amisigo et al., 2015), and this could affect future maize yield (Jones and Thornton, 2003; Lobell et al., 2011; Cairns et al., 2013). As such, supplemental irrigation could become relevant to boost productivity in small-scale maize systems in SSA (Rosegrant et al., 2002).

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

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

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

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

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

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

4.8. Strengths and weaknesses of the assessment approaches

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

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

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

5. Conclusions and outlook

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

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

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CRediT authorship contribution statement

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

Declaration of competing interest

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

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Appendix A. Supplementary data

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Appendices to Mwambo et al. 2021

Appendix A: Emergy diagrams

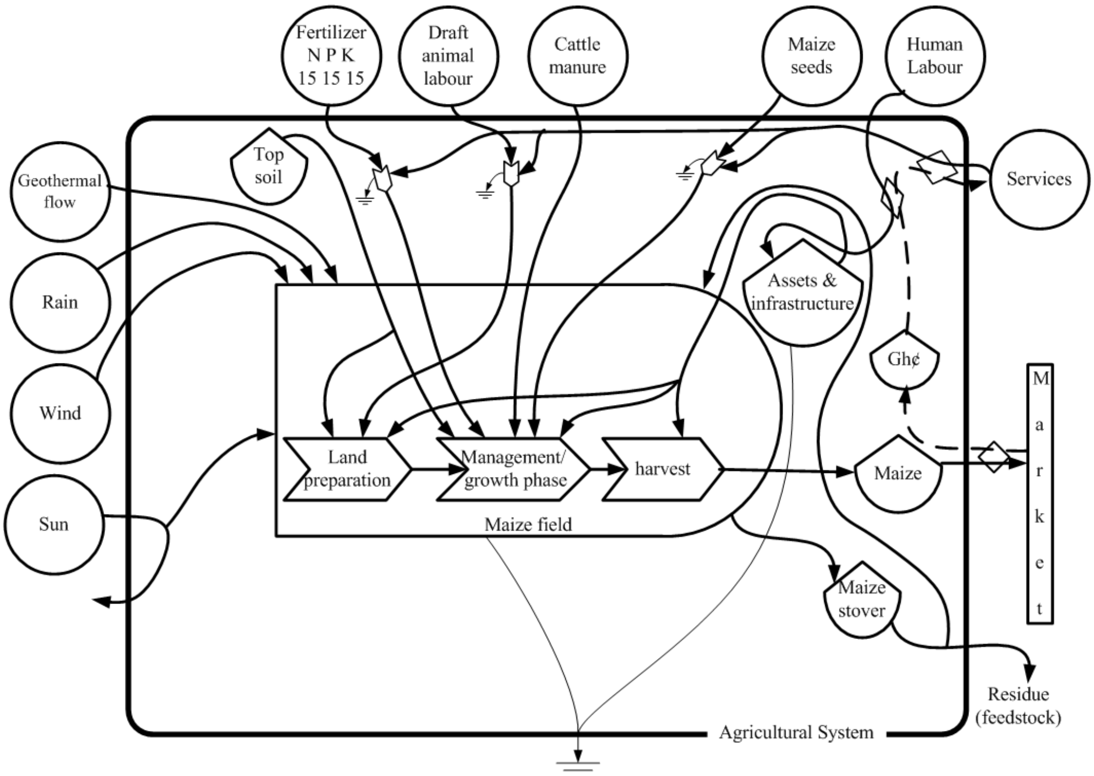


Figure 1. A simplified emergy diagram of *Extensive12* and *Extensive0*

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

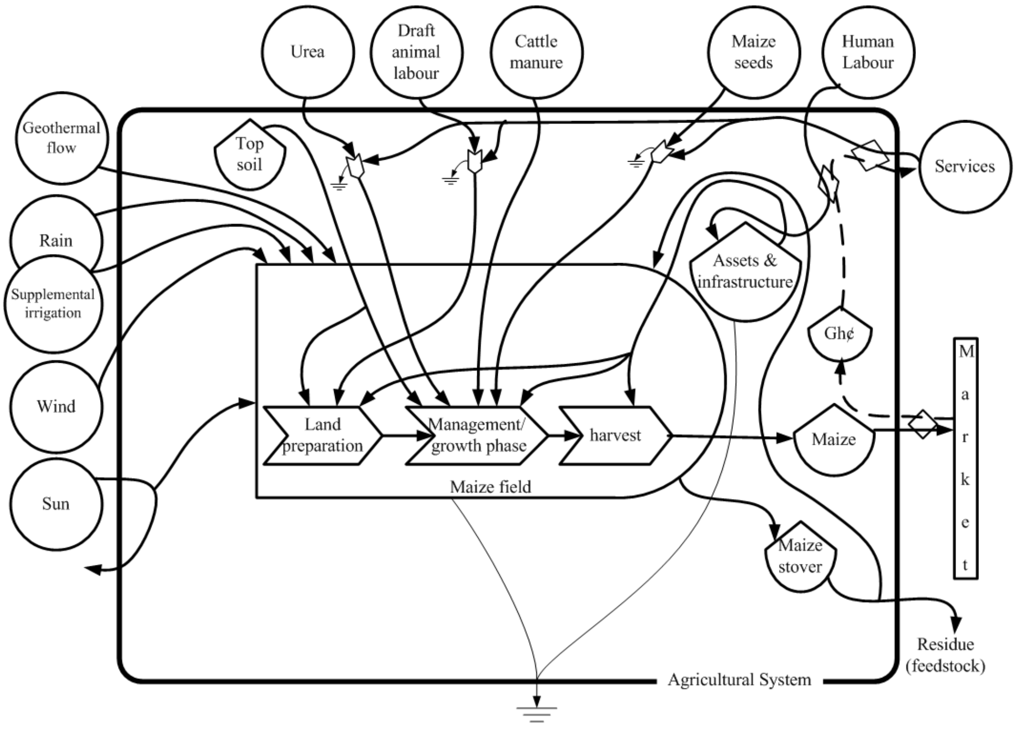


Figure 2. A simplified emergy diagram of *Intensive50* and *Intensive100*

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

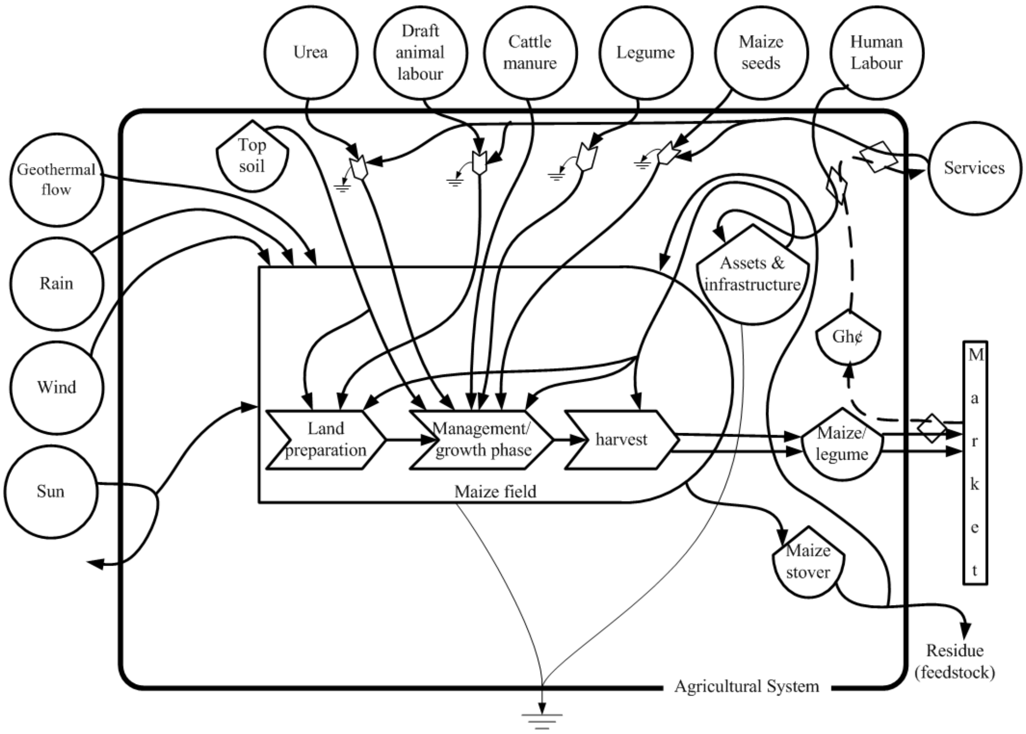
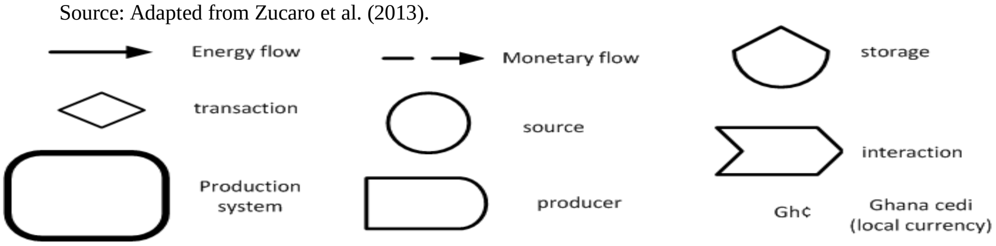


Figure 3. A simplified emergy diagram of *Intercrop20*

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



Source: Energy systems symbols from Odum (1996).

Table 1. Distinction between emergy diagrams

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

Appendix B: Emergy data and accounting

Table 2. Emergetic data of selected resource inputs and outputs for import into DEA model

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

Table 3. Emergy evaluation of annual inputs and outputs normalized at 1ha of land

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

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

Table 4: Definition of sources

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

1. **Solar energy**:

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

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

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

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

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

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

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

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

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

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

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

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

2. **Deep heat**:

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

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

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

Energy (J) = (land area, 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 (normalized to 1ha)

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

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

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

Drag coeff. = 2.50E−03 (estimate)

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

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

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

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

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

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

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

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

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

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

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

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

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

Evapotranspiration rate = 73% (Nurudeen, 2011)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5 **Topsoil, soil erosion**:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

6 **NPK/urea**:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

7 Animal labor:

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

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

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

8 **Maize seeds**

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

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

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

= 1.60E+04 g (*Extensive12*)

=8.00E+03 g (*Intercrop20*)

= 1.60E+04 g (*Intensive50*)

= 1.60E+04 g (*Intensive100*)

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

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

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

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

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

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

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

Unit cost of seeds = 1.00E+00 Gh¢/kg

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

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

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

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

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

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

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

9 **Human labor**

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

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

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

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

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

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

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

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

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

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

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

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

UEV = 1:30E+12 sej Gh¢$^{-1}$

10 **Services**

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

Services for seeds (purchase of seeds

Services for fertilizer (purchase cost)

Services for draft animals (forage, water, others)

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

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

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

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

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

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

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

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

UEV = 1.30E+12 sej Gh¢$^{-1}$

11 **Grains**

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

12 **Residue (stover)**

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Table 5. Specifications of the OSDEA model

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

Appendix C: Assessment of RUE & sustainability indicators

Efficiency assessment *(UEV$_R$ ≡EcoERU, UEV$_E$ ≡EcoEEU)*

Extensive0

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

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

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

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

Extensive12

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

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

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

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

Intercrop20

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

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

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

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

Intensive50

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

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

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

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

Intensive100

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

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

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

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

Sustainability assessment

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)**

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

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

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

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

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

***Intensive100* (without L&S)**

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

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

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

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

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

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

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

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

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

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

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

Table 6. Relative Technical Efficiency scores

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

Source: calculated using OSDEA

Appendix D: Assessment of carbon footprint

Table 7. Carbon budget

Carbon (C) source / stock	**Conversion factor**	**Unit**	***Extensive0***	***Extensive12***	***Intercrop20***	***Intensive50***	***Intensive100***	**Unit of emitted C**	**Ref.**
Fertilizer/urea dosage			0	12	20	50	100	kg/ha	[this study]
NPK (15 15 15)	12.32	kg CO_2 e/kg	/	0.148	/	/	/	ton CO_2 e/ha/yr	[a]
Urea (CH_4N_2O)	16.34	kg CO_2 e/kg	0	/	0.327	0.817	1.634	ton CO_2 e/ha/yr	[a]
Shipment NPK/urea	8	g CO_2/ton-km							ECTA, 2011
Morocco - Ghana	2389 ≈ 424.43	nautical mile ≈ km	/	0.00043	/	/	/	ton CO_2 e/ha/yr	[b]
Turkey - Ghana	4569 ≈ 8461.79	nautical mile ≈ km	0	/	0.0014	0.0034	0.0068	ton CO_2 e/ha/yr	[b]
Transport NPK/urea by road	832.9	(Tkd. – Bolga.) km							[c]
Road transport	62	g CO_2/ton-km	0	0.00062	0.0010	0.0023	0.00516		ECTA, 2011
Applied manure		kg/ha/yr	29.25	29.25	29.25	0	0		[this study]
Composting	368.4	kg CO_2 e/Mg	0.10776	0.10776	0.10776	0	0	ton CO_2 e/ha/yr	Hao 2004
C loss after plowing	4	kg C e/ha	0.004	0.004	0.004	0.004	0.004	ton C e/ha/yr	Lal, 2004
C due to human labor	14.4 , 0.36	MJ/day, kg CO_2/MJ	0.251	0.272	0.202	0.35	0.365	ton CO_2 e/ha/yr	[d]
Total GHG emissions			**0.266**	**0.436**	**0.546**	**1.177**	**2.015**	ton CO_2 e/ha/yr	
C stock in above ground biomass	43.6	%							[e]
Vegetative biomass (residue)			0.88	0.899	1.17	2.06	2.11	ton/ha/yr	[this study]
Carbon stock in residue			0.384	0.392	0.510	0.898	0.920	ton C	
Grain biomass			0.93	0.96	1.5	2.2	2.25	ton/ha/yr	[this study]
Carbon stock in grain			0.405	0.419	0.654	0.959	0.981	ton C	
Total Carbon Stocks			**0.789**	**0.811**	**1.164**	**1.857**	**1.901**	ton C/ha/yr	
Carbon balance			**- 0.523**	**- 0.374**	**- 0.618**	**-0.680**	**0.114**	ton CO_2 e/ha/yr	
Carbon balance / ton grain			**- 0.563**	**- 0.390**	**- 0.412**	**-0.309**	**0.051**	tonCO_2e/ton grain	
Index of sustainability (I_s)			**2.97**	**1.86**	**2.13**	**1.58**	**0.94**		

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

4 Carbon emission from compose/manure

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

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

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

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

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

5 Carbon loss due to plowing and cultivation of soil

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

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

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

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

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

6 Emission from human labor

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

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

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

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

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

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

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

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

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

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

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

Carbon stock in the above-ground biomass

= carbon stock in residue + carbon stock in gain

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

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

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

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

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

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

Carbon balance

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

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

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

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

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

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

Average C emission from the five scenarios

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

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

Appendix E: Production data for Bolgatanga and Bongo

Table 8. Maize yield for Bolgatanga and Bongo for the years 2003 - 2011

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

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

Appendix F: Trade-off calculations

1a Resource saving (without L&S)

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

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

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

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

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

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

1b Resource saving (with L&S)

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

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

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

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

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

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

2 Carbon saving

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

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

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

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

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

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

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

3 Yield gap

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

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

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

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

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

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

4 Yield, area cultivated & C emission

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

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

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

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

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

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

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

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

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

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

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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).

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).

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).

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).

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 secrity 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

[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]

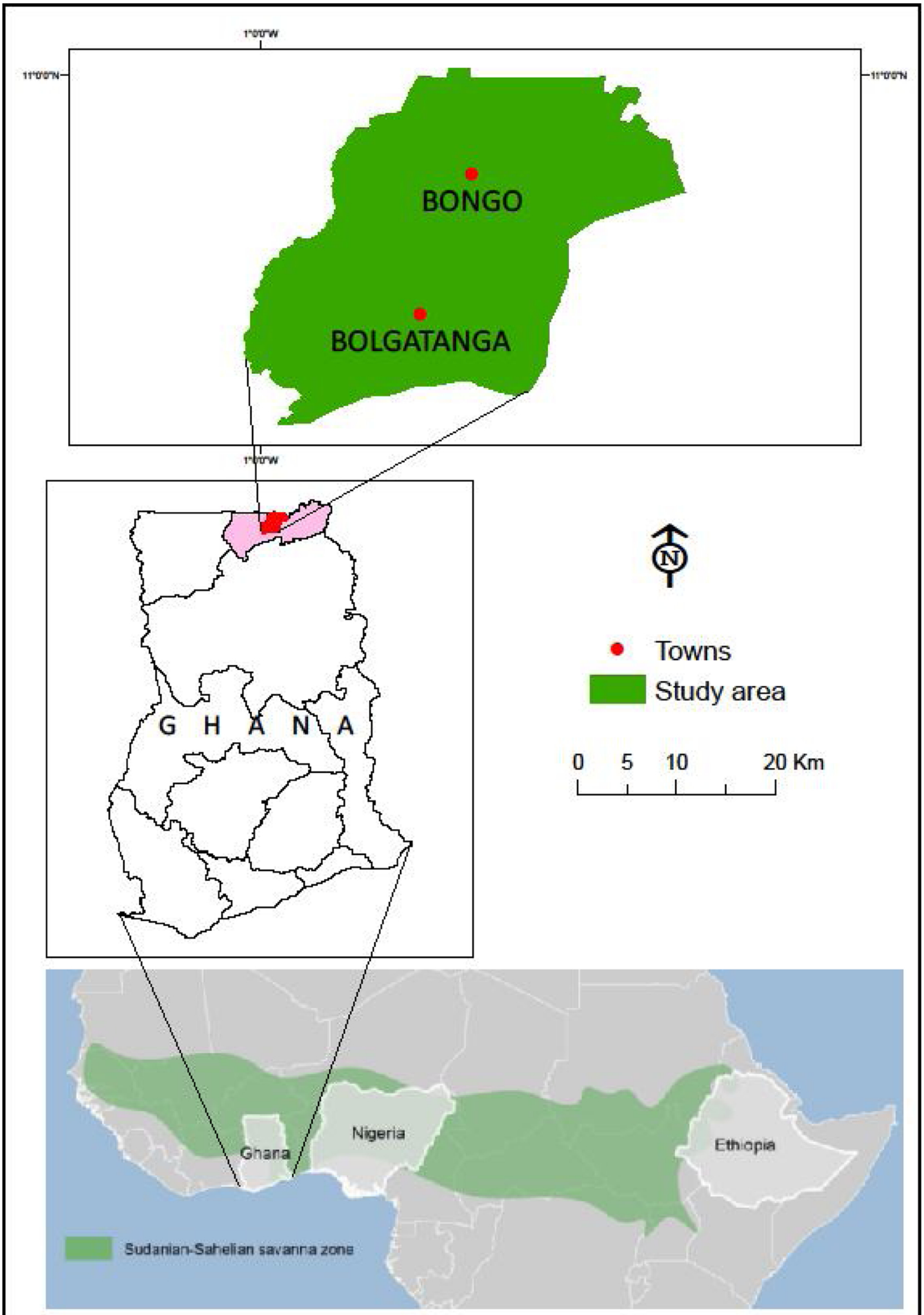

Fig. 1. Study area.

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.

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

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

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).

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

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

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

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

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).

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

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

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

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

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

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]

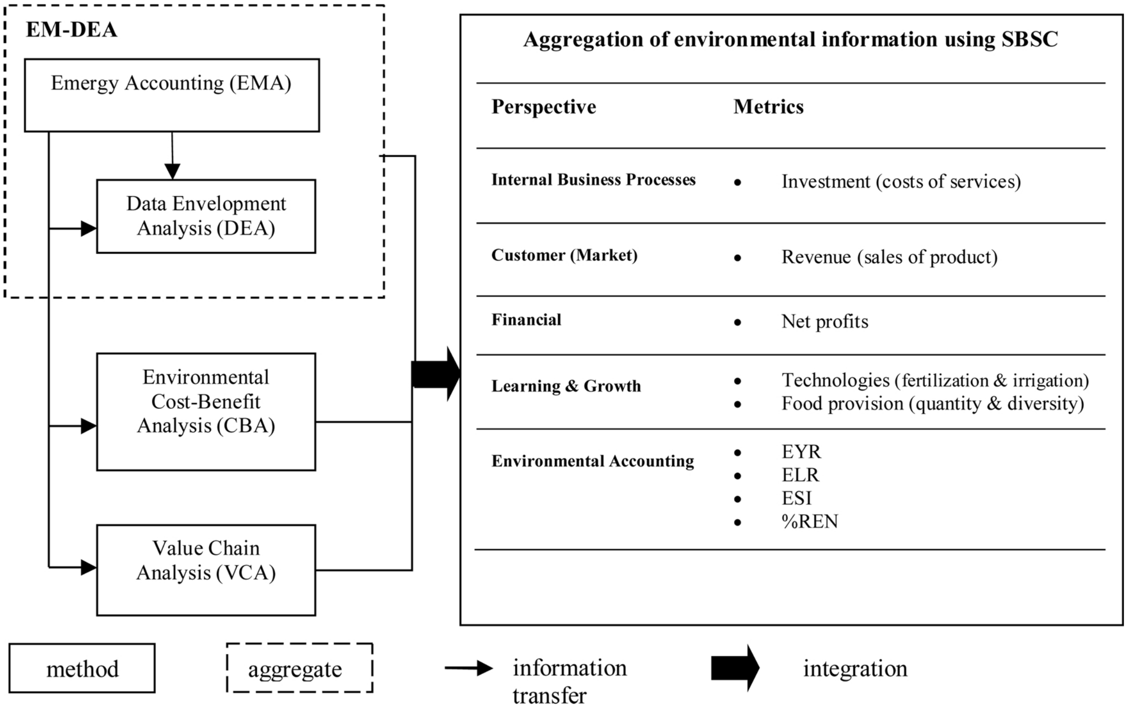

Fig. 2. Framework showing the integration of methods.
Note: See also the explanation of the metrics in the footnotes[7]

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	Moderate	High
<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 *Exten.0*	Counterpart system Mexico *Trad. low intensity*	This study Ghana *Exten.12*	This study Ghana *Inter.20*	Counterpart system Brazil *Hybrid 2009*	This study Ghana *Inten.50*	Counterpart system Argentina *Hybrid 1986*	This study Ghana *Inten. 100*	Counterpart system Argentina *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 sei/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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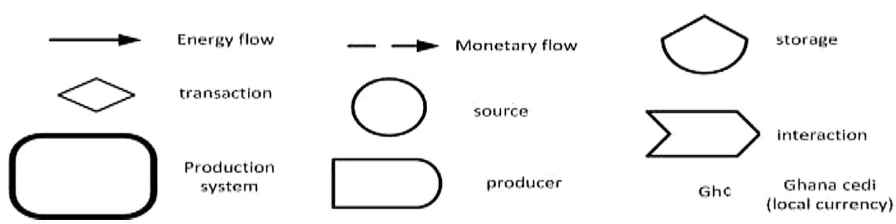
Appendix A. Other data and Emergy diagrams



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	

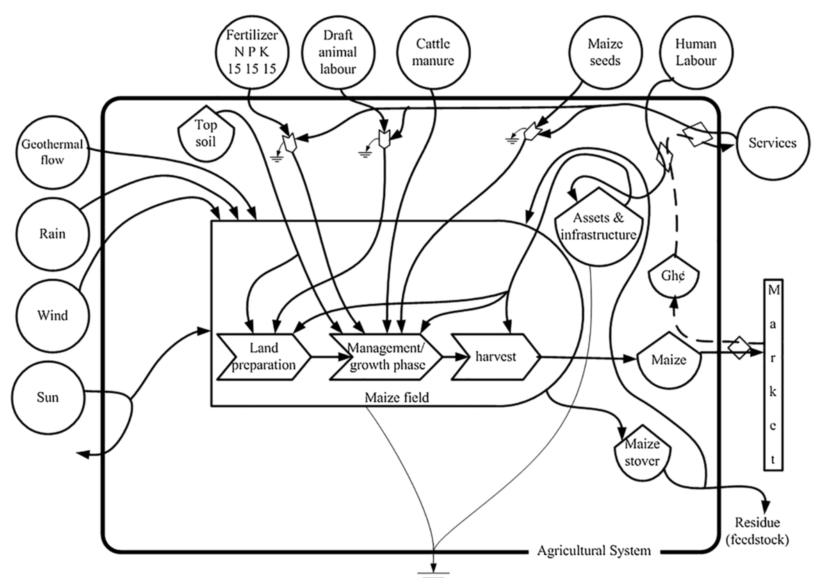


Fig. A1. A simplified emergy diagram of *Extensive12* and *Extensive0*.
Note: Manure is provided for free or produced locally, and therefore no service is associated.
Source: Adapted from Zucaro et al. (2013).

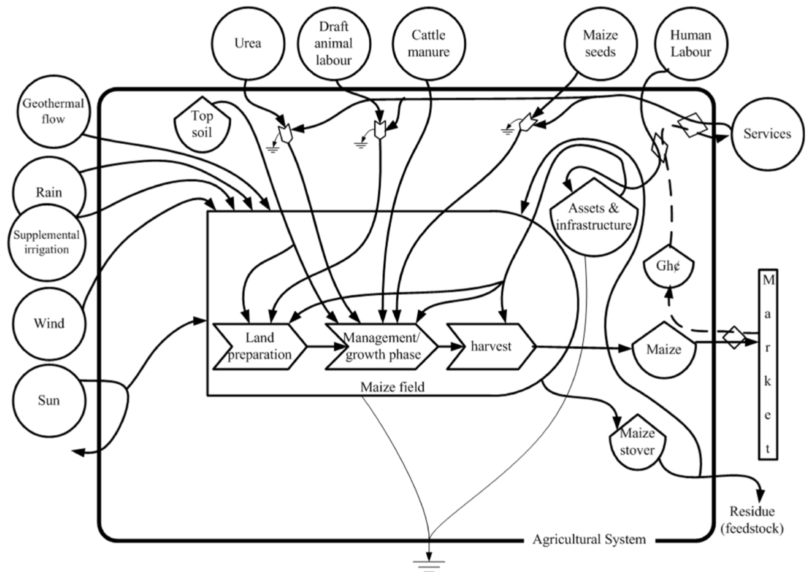


Fig. A2. A simplified emergy diagram of *Intensive50* and *Intensive100*.
Note: Manure is provided for free or produced locally, and therefore no service is associated.
Source: Adapted from Zucaro et al. (2013).

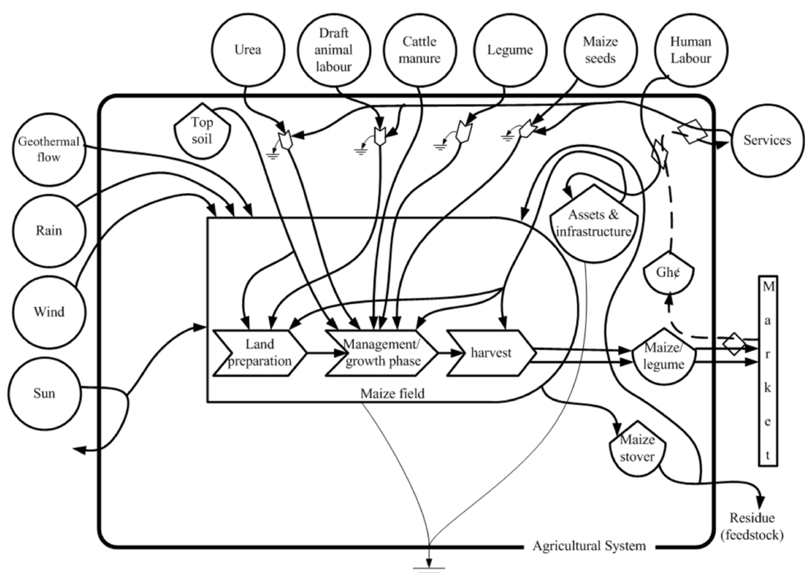


Fig. A3. A simplified emergy diagram of *Intercrop20*.
Note: Manure is provided for free or produced locally, and therefore no service is associated.
Source: Adapted from Zucaro et al. (2013).

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

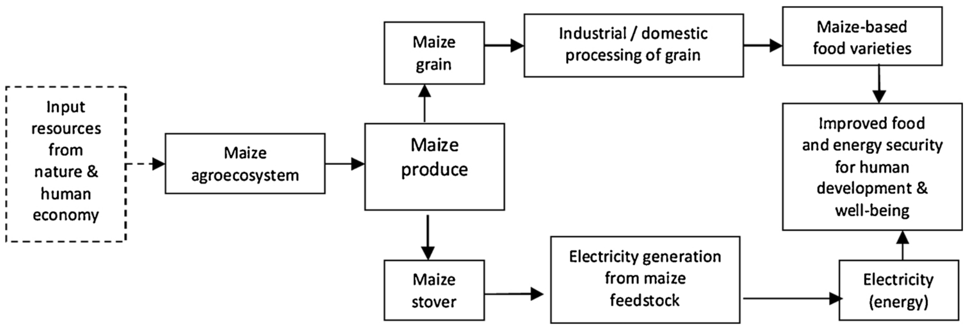


Fig. B1. A schematic value chain model to fit *Extensive12*, *Extensive0*, *Intensive50* and *Intensive50*.

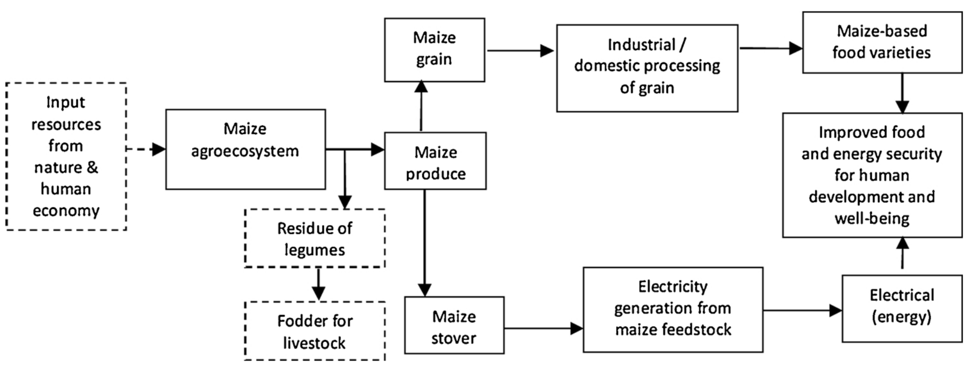


Fig. B2. A schematic value chain model to fit *Intercrop20*.

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)**

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

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

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

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

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

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

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

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

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

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

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

***Intensive50* (without L&S)**

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Extensive12

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

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

Intercrop20

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

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

Intensive50

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

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

Intensive100

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

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

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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APPENDICES

Appendix I: Questionnaire for primary data collection during the field survey

ID	Date of data collection, and author of the data	Name and contact of farmer, Years of experience as a farmer	Location/ District (Tick the box applicable)
	....	....	☐ Bolgatanga ☐ Bongo

(1) What crop(s) is/ are grown by the farmer?

....

(2) What is the percentage of the area cultivated with maize relative to the area cultivated with other crops and/ or fallow land with respect to the total farmland? (Please, see Appendix II illustrating the estimation of farmland area during the field survey)..

....

(3) What cropping/ farming system is practiced by the farmer? Provide a brief explanation of the farmer's practice to grow maize?

....

....

(4) Considering that in recent times, climate variability is an issue of concern. Is this phenomenon affecting maize cultivation locally? If yes, what are the farmer's strategy for adaptation – if any? (Provide a succinct summary of the farmer's own words).

....

....

(5) What are the farmer's estimate of the following input resources:

a. time spend on land preparation (e.g. ploughing using animal or tractor)?
b. time spend on sowing/ method of sowing (direct seeding or seedling)?
c. time spend on weeding (manual, shallow ploughing or use of herbicide)?
d. quantity of seeds sow/ variety (local/ improved)?
e. quantity & type of fertilizer/ manure/ compost or any other input applied?

....

....

....

(6) What is the maize yield? What percentage of the maize yield is used for household consumption and/ or traded for income? What is the residue used for?

....

....

(7) Is there any other data or remark that has not been captured in (1) – (6), which is of relevance as far as land use and/ or maize cultivation is concern that the farmer wishes to express? (This could be narrative, descriptive, qualitative or quantitative)

....

....

....

Appendix II: An illustration of land use data collection during the field survey

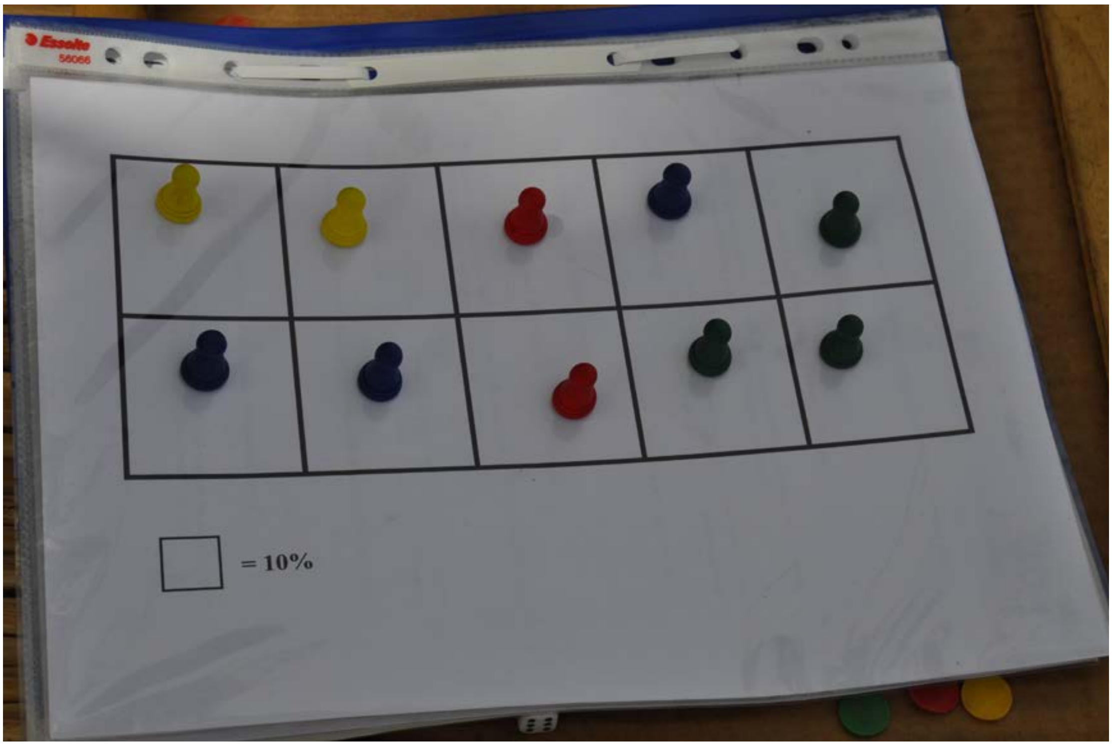

Fig. 4: An illustration of how percentages and areas of land uses were estimated.

The assumption was that the total farmland owned by a farmer was equal to 10 squares of equal areas. Each square represents 10% of a farmer's total farmland. During the field survey, the farmers were given mini wooden chess pegs of different colors, and they were asked to place 1 peg per square to illustrate the land use while considering different colors to represent different land uses or crops. The author of the data then used the illustration coupled with the explanation given by a farmer, to estimate the percentages and areas of farmland that were associated with the various land uses.

Appendix III: Emergy analysis to support the empirical studies

Appendix III presents the emergy analysis (Mwambo 2021), which was derived from using the primary data that was collected through field survey (Mwambo 2020) and in combination with geophysical data from published secondary sources.

Mwambo, F. M. (2021). Emergy analysis of maize production in Ghana. https://daten.zef.de/#/metadata/0b40d479-d6dd-41e0-abd9-cc7e8e2a4240.

Multi-method analysis

Material Flow Accounting, Embodied Energy Analysis and Emergy Analysis for maize production in Ghana, Africa (Mwambo et al. 2020, 2021)

Total land area of Ghana	2.30E+07	ha	2.30E+11	m²	[https://knoema.com/atlas/Ghana/topics/Land-Use/Area/Surface-area]
Total area cropped with maize in Bolga. & Bongo Districts (20	3.31E+03	ha	3.31E+07	m²	MoFA, 2012
Unit area for analysis in this study	1.00E+00	ha	1.00E+04	m²	This study

Item	Value	Unit	Variation	Reference
Sun insolation	1.20E+21	J/m²/yr		[http://www.cep.ees.ufl.edu/nead/data.php?country=74&year=247#]
Wind velocity	2.6	m/s		[worldweatheronline.com]
Rainfall	0.911	m/yr		MoFA, 2012
Fraction evapotranspired water	0.73			Nurudeen (2011)
Supplemental irrigation	0.179	m/yr		Adams et al, (2014)
Cost of supplemental irrigation	8.00E+02	Gh¢/ha		[Dey & Avumegah, 2016]
Deep heat (average heat flow per area)	4.20E+01	mW/m²		[Beck & Mustonen, 1972]
Soil erosion	1.29E+01	g/m²/yr		[Badmos et al., 2015]
	6.46E+00	g/m²/yr		[This study]
Fertilizer				
NPK (15 15 15)	1.20E+01	kg/yr		This study; [Inventory survey]
NPK (15 15 15) price	2.30E+00	Gh¢/kg		MoFA, Facts & Figures, 2016
urea N	0.00E+00	kg/yr		This study
	2.00E+01	kg/yr		This study
	5.00E+01	kg/yr		This study
	1.00E+02	kg/yr		This study
urea N price	2.10E+00	Gh¢/kg		[MoFA Ghana, Facts & Figures 2016]

Human labour							
land preparation (ploughing) based on this study	6.00E+00	days/yr					
sowing	1.05E+01	days/yr	5.00E+00				
application of NKP/urea N fertilizer	6.00E+00	days/yr	0.00E+00				
application of manure	1.10E+01	days/yr	0.00E+00				
weeding (2 cycles per crop season)	3.20E+01	days/yr	3.00E+01	2.20E+01	4.50E+01	4.80E+01	
harvesting	9.50E+00	days/yr	1.15E+01	1.80E+01	2.10E+01		
threshing	5.00E+00	days/yr	5.50E+00	6.50E+00	1.65E+01	1.80E+01	
Total days of human labour	7.40E+01	days/yr	8.05E+01	8.15E+01	7.90E+01	8.35E+01	
Daily wage for farm labour	7.00E+01	Gh¢/day					
Total annual cost on human labour	5.18E+03	Gh¢/yr	5.64E+03	5.71E+03	5.53E+03	5.85E+03	Gh¢/yr
	2.24E+03		2.10E+03	1.54E+03	3.15E+03	3.36E+03	
Use per capita for Ghana = Av. Of use per capita of Kenya & Iv	5.50E+15	sej/capita		[http://www.cep.ees.ufl.edu/nead/]			
emergy to cedi ratio	1.30E+12	sej/Gh¢		This study			
Draft anaimal labour							
Draft animal labour (ploughing)	2.40E+01	hr/ha		[estimated after Houssou et al. (2013); Sims & Kienzle (2016)]			
Service for draft animal	497.5	Gh¢		[This study]			
emergy to draft animal labour ratio	1.39E+12	sej/hr		[This study]			
Seeds							
Planted maize seeds	1.60E+01	kg/ha		This study			
	8.00E+00	kg/ha		This study			
Maize seeds price	1.00E+00	Gh¢/kg		[http://www.ghanabusinessnews.com/2013/04/17/ghana-subsidizes-fertilizer-seed-prices-for-2013/]			

Manure				
Applied manure	2.93E+01	kg/yr	0.00E+00	[Awunyo-Vitor et al., 2016]
Biomass products				
Maize grain yield	1.17E+03	kg/yr		This study
	1.20E+03	kg/yr		This study
	1.88E+03	kg/yr		This study
	2.75E+03	kg/yr		This study
	2.81E+03	kg/yr		This study
Economic value of maize grain	5.60E-01	Gh¢/kg		[https://knoema.com/FAORWP2015Jul/fao-retail-and-wholesale-prices-2015-july?tsId=1004330], price for 2013
stover residue	8.76E-01	ton/yr		[This study; estimated from the grain dry matter yield using equation by Lang (2002)]
	8.99E-01	ton/yr		[This study; estimated from the grain dry matter yield using equation by Lang (2002)]
	1.41E+00	ton/yr		[This study; estimated from the grain dry matter yield using equation by Lang (2002)]
	2.06E+00	ton/yr		[This study; estimated from the grain dry matter yield using equation by Lang (2002)]
	2.10E+00	ton/yr		[This study; estimated from the grain dry matter yield using equation by Lang (2002)]

	CALCULATION	Extensive0	units	Ref.	Extensive12	units	Ref.	Intercrop20	units	Ref.	Intensive50	units	Ref.	Intensive100	units	Ref.
	N.B. The inventory data refers to primary input data for analysis. The collection of inventory data was done by															
	means of farmer interviews using semi-structured questionnaires that were administred during the field survey.															
	The survey was conducted in Bolgatanga and Bongo Districts located in Upper East Region of Ghana. The inventory															
	data were complemented with secondary data from other sources. Referenes have been provided where necessary.															
	The inventory data were normalised using standard statistical methods. Considered in this study were the mean															
	values of input variables of the inventory data. Also the cropped area was normalised to 1 hectare = 10000m².															
	Area of analysis	1.00E+04	m²	[Inventc	1.00E+04	m²	[Inv	1.00E+04			1.00E+04			1.00E+04	m²	[Inventory survey]
Renewable Inputs (locally available)																
1	**Sun insolation**															
	Average insolation	1.20E+21	J/yr	[http://v	1.20E+21	J/yr	[http	1.20E+21	J/yr		1.20E+21	J/yr	[htt	1.20E+21	J/yr	[http://www.cep.ees.ufl.edu/nead/data.php?c
	solar energy received = (average insolation, J/m²/yr)(area, m²) = (1.2E+21)(1.0E+4)	5.22E+13	J/yr		5.22E+13	J/yr		5.22E+13			5.22E+13	J/yr		5.22E+13	J/yr	
	Albedo	0.15		[Arku, 20	0.15		[Ark	0.15			0.15		[Ark	0.15		[Arku, 2011]
	solar energy recieved =	**4.43E+13**	J/yr		**4.43E+13**	J/yr		**4.43E+13**			**4.43E+13**	J/yr		**4.43E+13**	J/yr	
2	**Wind**															
	Wind energy = (air density,kg/m³)(drag coeff.,)(geostrophic wind velo., m/s)³(area,															
	Air density =	1.15	kg/m³		1.15	kg/m³		1.15	kg/m³		1.15	kg/m³		1.15	kg/m	[Assumption: same wind speed in the area]
	Wind velocity (2015) =	2.6	m/s	[worldw	2.6	m/s	[wo	2.6			2.6			2.6	m/s	[worldweatheronline.com]
	Geostrophic wind velocity =	4.0	m/s		4.0	m/s		4.0			4.0			4.0	m/s	
	Drag Coeff. =	2.50E-03			2.50E-03			2.50E-03			2.50E-03			2.50E-03		
	Time frame (sec/yr)	3.15E+07			3.15E+07			3.15E+07			3.15E+07			3.15E+07		
	Wind energy on land	**5.87E+10**	J/yr		**5.87E+10**	J/yr		**5.86E+10**			**5.87E+10**			**5.87E+10**	J/yr	

3	**Rainfall**															
	Rain (average temperate areas) =	0.911	m/yr	MoFA, 2	0.911	m/yr	MoF	0.911	m/yr	MoF	1.09	m/yr	[Rai	1.09	m/yr	[Rainfall plus supplementary irrgat
	Water density =	1.00E+06	g/m^3		1.00E+06	g/m^3		1.00E+06	g/m^3		1.00E+06	g/m^3		1.00E+06	g/m^3	
	Mass of rainfall water =	9.11E+09	g/yr		9.11E+09	g/yr		9.11E+09	g/yr		1.09E+10	g/yr		1.09E+10	g/yr	
	Fraction of water that is evapotranspired =	0.73		[Nurude	0.73		[Nur	0.73		[Nur	0.73		[sar	0.73		[Nurudeen, 2011]
	Evapotranspired rain water =	0.66503	m/yr		0.66503	m/yr		0.66503	m/yr		0.7957	m/yr		0.7957	m/yr	
	Mass of evapotranspired water =	6.65E+09	g/yr		6.65E+09	g/yr		6.65E+09	g/yr		7.96E+09	g/yr		7.96E+09	g/yr	
	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	[Odum,	4.94	J/g	[Od	4.94	J/g		4.94	J/g	[Od	4.94	J/g	[Odum, 1996]
	Energy of evapotranspired rain	**3.29E+10**	J/yr		**3.29E+10**	J/yr		**3.29E+10**	J/yr		**3.93E+10**	J/yr		**3.93E+10**	J/yr	
4	**Deep Heat**															
	Heat flow through the earth crust contributing to uplift replacing	4.20E+01	mW/m	[Beck &	4.20E+01	mW/m	[Bec	4.20E+01	mW/	[Bec	4.20E+01	mW/	[Bec	4.20E+01	mW/	[Beck & Mustonen, 1972]
	Average heat flow per area	1.32E+06	J/m2/yr		1.32E+06	J/m2/yr		1.32E+06	J/m2/yr		1.32E+06	J/m2/yr		1.32E+06	J/m2/yr	
	Energy (J/yr) = (land area, m^2) * (heat flow per area, $J/m^2/yr$) =	**1.32E+10**	J/yr		**1.32E+10**	J/yr		**1.32E+10**	J/yr		**1.32E+10**	J/yr		**1.32E+10**	J/yr	

Non-Renewable Inputs (locally available)																
5	**Soil erosion**															
	Erosion rate =	1.29E+01	g/m²/	[Badmo	1.29E+01	g/m²/	[Bac	6.46E+00	g/m²/	[Ass	1.29E+01	g/m²,	[Bac	1.29E+01	g/m²,	[Badmos et al., 2015]
	Net loss of topsoil = (farmed area,m²)*(erosion rate, g/m²/yr)	1.29E+05	g/yr		1.29E+05	g/yr		6.46E+04	g/yr		1.29E+05	g/yr		1.29E+05	g/yr	
	Average % organic matter in soil	0.0129		[Amega	0.0129		[Am	6.45E-03			0.0129		[Am	0.0129		[Amegashie, 2009]
	Organic matter in topsoil used up = (total mass of topsoil)(%organic) =	1.67E+03	g/yr		1.67E+03	g/yr		4.16E+02	g/yr		1.67E+03	g/yr		1.67E+03	g/yr	
	Water content in organic matter =	4.00E-05		[Dawids	4.00E-05		[Dav	2.00E-05			4.00E-05		[Dav	4.00E-05		[Dawidson & Nilsson, 2000]
	Dry organic matter lost with erosion	1.67E+03	g/yr (d.m)		1.67E+03	g/yr (d.m)		4.16E+02	g/yr (d.m)		1.67E+03	g/yr (d.m)		1.67E+03	g/yr (d.m)	
	Energy content of dry organic matter	5.00	kcal/g d.m.		5.00	kcal/g d.m.		5.00	kcal/g d.m		5.00	kcal/g d.n		5.00	kcal/g d.m.	
	Energy loss = (loss of dry organic matter)(5kcal)(4186J/kcal) =	**3.49E+07**	J/yr		**3.49E+07**	J/yr		**8.71E+06**	J/yr		**3.49E+07**	J/yr		**3.49E+07**	J/yr	
6	**cattle manure**															
	Manure applied (kg)	2.93E+01	kg/ha	[Awunyo	2.93E+01	kg/ha,	[Awu	2.93E+01	kg/ha	[Awu	0.00E+00	kg/ha/yr		0.00E+00	kg/ha/yr	
	Manure applied	2.93E+04	g/ha/yr		2.93E+04	g/ha/yr		2.93E+04	g/ha/yr		0.00E+00	g/ha/yr		0.00E+00	g/ha/yr	
	moisture content	0.70		[Sonko e	0.70		[Sor	0.70		[Sor	0.7			0.7		
	Dry organic matter applied =	8.78E+03	g/ha/yr		8.78E+03	g/ha/yr		8.78E+03	g/ha/yr		0.00E+00	g/ha/yr		0	g/ha/yr	
	Energy content of dry organic matter	5.00	kcal/g d.m.		5.00	kcal/g d.m.		5.00	kcal/g d.m		5.00	kcal/g d.n		5.00	kcal/g d.m.	
	Energy gain= (applied dry manure)*(5kcal)*(4186J/kcal)	**1.84E+08**	J/yr		**1.84E+08**	J/yr		**1.84E+08**	J/yr		**0.00E+00**	J/yr		**0.00E+00**	J/yr	[assumption: no need for manue
	UEV of manure (calculated in ths	4.96E+08	sej/g	[This stu	4.96E+08	sej/g	[Thi	4.96E+08	sej/g	[Thi	4.96E+08	sej/g	[Thi	4.96E+08	sej/g	[This study]
	Average water consumed by cow in	1.64E+04	l/yr	[Lukuyu	1.64E+04	l/yr	[Luk	1.64E+04				l/yr	[Lukuyu et al., 20		l/yr	[Lukuyu et al., 2012]
	forage	4.38E+03	kg/yr	[http://v	4.38E+03	kg/yr	[http	4.38E+03							kg/yr	[http://www1.agric.gov.ab.ca/$de
	emergy of water consumed in 1yr	1.15E+16	sej/yr		1.15E+16	sej/yr		1.15E+16							sej/yr	
	emergy of forage	5.78E+12	sej/yr		5.78E+12	sej/yr		5.78E+12							sej/yr	
	manure produced by year	7.35E+03	kg/yr		7.35E+03	kg/yr		7.35E+03							kg/yr	
	UEV of manure (calculated in ths	**4.96E+08**	sej/g	[This stu	**4.96E+08**	sej/g	[Thi	**4.96E+08**	sej/g						sej/k	[This study]

Labour Inputs																
10	**Human Labour**															
	Fraction of labour directly contributing to yield	4.85E+01	days/ha/yr		5.25E+01	days/ha/yr		3.90E+01	days/ha/y		6.75E+01	days/ha/		7.05E+01	days/ha/yr	
	Daily wage of labour	7.00E+01	Gh¢/day		7.00E+01	Gh¢/day		7.00E+01	Gh¢/day		7.00E+01	Gh¢/day		7.00E+01	Gh¢/day	
	Total cost of labour	3.40E+03	Gh¢/yr		3.68E+03	Gh¢/yr		2.73E+03	Gh¢/yr		4.73E+03	Gh¢/yr		4.94E+03	Gh¢/yr	
	emergy to Cedi ratio)	1.30E+12	sej/Gh¢													
	% of labour intensive task to fraction of lab.	0.00			6.00E+00			6.00E+00			6.00E+00			6.00E+00		
	la	0.00			420.00			420.00			420.00			420.00		
	emergy of lab	0.00			5.46E+14											
11	**Draft animal labour**															
	Total hour of ploughing by draft	2.40E+01	hr/yr		2.40E+01	hr/ha/yr		2.40E+01	hr/ha/yr		2.40E+01	hr/ha/yr		2.40E+01	hr/ha/yr	
	Emergy to draft animal labour	1.39E+12	sej/hr		1.39E+12	sej/hr		1.39E+12	sej/hr		1.39E+12	sej/hr		1.39E+12	sej/hr	
	Total cost of animal labour	3.32E+13	Gh¢/yr		3.32E+13	Gh¢/yr		3.32E+13	Gh¢/yr		3.32E+13	Gh¢/yr		3.32E+13	Gh¢/yr	
Products (locally produced)																
12	**Maize grain biomass**															
	grain yield	1.17E+03	kg/yr	[MoFA]	1.20E+03	kg/yr	[Thi	1.88E+03	kg/yr	[Thi	2.75E+03	kg/yr	[Thi	2.81E+03	kg/yr	[This study]
	Estimated mass of maize grain harvested	1.17E+06	g/yr		1.20E+06	g/yr		1.88E+06			2.75E+06	g/yr		2.81E+06	g/yr	[simulated in APSIM]
	Estimated moisture content in maize grain	0.20		[Aggrey,	0.20		[Agg	0.20			0.20			0.20		[Aggrey, 2015]
	Estimated mass of maize grain (dry matter)	9.36E+05	g/yr		9.60E+05	g/yr		1.50E+06	g/yr		2.20E+06	g/yr		2.25E+06	g/yr	
	Estimated mass of mass grain (d.m.) in kg)	9.36E+02	kg/yr		9.60E+02	kg/yr		1.50E+03			2.20E+03			2.25E+03	kg/yr	
	Energy content of maize grain =	1.47E+04	J/g	[Ulgiati,	1.47E+04	J/g	[Ulg	1.47E+04			1.47E+04	J/g		1.47E+04	J/g	[Ulgiati, 2001]
	Energy content of maize grain	1.38E+10	J/yr		1.41E+10	J/yr		2.21E+10			3.23E+10	J/yr		3.30E+10	J/yr	
13	**Maize stover biomass (dry matter)**															
	stover	8.76E+05	g/yr		8.99E+05	g/yr		1.41E+06	g/yr		2.06E+06	g/yr		2.10E+06	g/yr	

Transformities and their emergy intensities					
#	Item	Value	Unit	Variation	Ref.
	Renewable Inputs (Locally available)				
1	Sun	1.00E+00	sej/J		[By definition, Odum 1996]
2	Wind (kinetic energy of wind used at the surface)	7.90E+02	sej/J		[Brown & Ulgiati, (2016)]
3	Rainfall (chemical potential)	7.00E+03	sej/J		[Brown & Ulgiati, (2016)]
4	Deep heat (geothermal heat)	4.90E+03	sej/J		[Brown & Ulgiati, (2016)]
5	Gravitational potential (gravity)	3.09E+04	sej/J		[Brown & Ulgiati, (2016)]
	Non-Renewable Inputs (Locally available)				
6	Top soil (estimated from erosion rate and turnover)	5.61E+04	sej/J		[https://cep.ees.ufl.edu/nead/data.php#]
7	Cattle Manure	4.96E+08	sej/g		[This study]
8	Seeds	5.12E+08	sej/g		Rotolo et al., (2015)
	Imported Inputs				
9a	NPK (15 15 15) fertilizer	1.02E+10	sej/g		Odum, 1996
9b	Urea N fertilizer	5.85E+09	sej/g		Odum, 1996
	Labour				
10	Human Labour	1.30E+12	sej/Gh¢		[This study]
11	Draft Animal Labour	1.39E+12	sej/hr		[This study]
13	Annual services to agricultural production	1.30E+12	sej/Gh¢		[This study]

Emergy flows			**Extensive0**				**Extensive12**				**Intercrop20**			**Intensive50**			**Intensive100**			
			Raw amount	UEV (sej/u	Ref	Emergy (sej	Raw amount	UEV (sej/u	Ref	Emergy (sej	Raw amount	UEV	Emergy (sej	Raw amount		Emergy (sej/	Raw amount		Emergy (sej/yr)	
#	Items	Units																		
(*)																				
Renewable Inputs (locally available)																				
1	Sun	J	4.43E+13	1.00E+00	[a]	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	
2	Deep Heat (geothermal heat)	J	1.32E+10	4.90E+03	[b]	6.49E+13	1.32E+10			6.49E+13	1.32E+10		6.49E+13	3.93E+10		1.93E+14	1.32E+10		6.49E+13	
3	Gravitational potential	J	0.00E+00	3.09E+04	[c]	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	
SUM of primary sources (tripartite)						1.09E+14				1.09E+14			1.09E+14			2.37E+14			1.09E+14	
Secondary renewabe sources																				
4	Wind (kinetic energy of wind used a	J	5.87E+10	7.90E+02	[d]	4.64E+13	5.87E+10			4.64E+13	5.86E+10		4.63E+13	5.87E+10		4.64E+13	5.87E+10		4.64E+13	
5	Rainfall (chemical potential)	J	3.29E+10	7.00E+03	[e]	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	
Maximum of secondary forces						2.30E+14				2.30E+14			2.30E+14			2.75E+14			2.75E+14	
Maximum of renewable sources (R)						2.30E+14				2.30E+14			2.30E+14			2.75E+14			2.75E+14	
Non-renewable Inputs (locally available) (N)																				
6	Top soil	J	3.49E+07	5.61E+04	[f]	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	
Imported Inputs (F)																				
7	Fertilizer (NKP 15 15 15) / Urea for II	g	0.00E+00	5.85E+09	[g]	0.00E+00	1.20E+04	1.02E+10	[h]	1.22E+14	2.00E+04		1.17E+14	5.00E+04		2.93E+14	1.00E+05		5.85E+14	
8	Draft animal labour	hr	2.40E+01	1.39E+12	[i]	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	
9	Cattle manure	g	2.93E+04	4.96E+08	[j]	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	
10	Maize seeds	g	1.60E+04	5.12E+08	[k]	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	

Labour & Services (L & S)																		
11	Human labour L	Gh¢/yr	3.40E+03	1.30E+12	[l]	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
12	Services S	Gh¢	5.14E+02	1.30E+12	[m]	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
	Total Emergy without Labour and Services					**2.73E+14**			**3.96E+14**			**3.85E+14**			**6.11E+14**			**9.04E+14**
	Total Emergy with Labour and Services					**5.35E+15**			**5.87E+15**			**4.64E+15**			**8.85E+15**			**9.55E+15**
Yield, also including the emergy of L&S																		
13	Grain yield (dry matter) 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	
	Grain yield (dry matter) 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	
14	stover residue (d.m.) 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	
	stover residue (d.m.) with L&S	J	1.31E+10	4.07E+05			1.35E+10	4.36E+05		2.11E+10	2.20E+05		3.09E+10	2.87E+05		3.16E+10	3.03E+05	
Yield, without including the emergy of L&S																		
13	Grain yield (dry matter) 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	
	Grain yield (dry matter) 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	
14	stover residue (d.m.) 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	
	stover residue (d.m.) 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	

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

Indicators	*Extensive0*	*Extensive12*	*Intercrop20*	*Intensive50*	*Intensive100*	Unit
Assessment without labour and services (L&S)						
Total Emergy (U without L&S)	2.73E+14	3.96E+14	3.85E+14	6.11E+14	9.04E+14	sej/ha
Unit Emergy Value in term of resource use (UEV_R)	2.92E+08	4.12E+08	2.56E+08	4.02E+09	4.02E+08	sej/g
Unit Emergy Value in term of exergy use (UEV_E)	1.95E+04	2.75E+04	1.71E+04	1.85E+04	2.68E+04	sej/J
Emergy Yield Ratio (EYR)	6.60	2.42	2.49	1.83	1.44	ratio
Environmental Loading Ratio (ELR)	0.19	0.72	0.67	1.22	2.28	ratio
Emergy Sustainability Index (ESI)	34.97	3.35	3.70	1.50	0.63	ratio
Percentage Renewability (R%), then multiple by 100	0.84	0.58	0.60	0.45	0.30	percent
Emergy to money ratio, i.e. Unit Emergy Value to currency (UEV_C)	1.30E+12	1.30E+12	1.30E+12	1.30E+12	1.30E+12	sej/Gh¢

Assessment with labour and servives (L&S) included						
Total Emergy (U)	5.35E+15	5.87E+15	4.64E+15	8.85E+15	9.55E+15	sej/ha yr
Unit Emergy Value in term of resource use (UEV_R)	5.72E+09	6.12E+09	3.09E+09	2.78E+08	4.25E+09	sej/g
Unit Emergy Value in term of exergy use (UEV_E)	3.81E+05	4.08E+05	2.06E+05	2.68E+05	2.83E+05	sej/J
Emergy Yield Ratio (EYR)	1.05	1.05	1.05	1.03	1.03	ratio
Environmental Loading Ratio (ELR)	22.27	24.54	19.19	31.18	33.73	ratio
Emergy Sustainability Index (ESI)	0.05	0.04	0.05	0.03	0.03	ratio
Percentage Renewability (R%)	0.04	0.04	0.05	0.03	0.03	percent
Emergy to money ratio, i.e. Unit Emergy Value to currency (UEV_C)	1.30E+12	1.30E+12	1.30E+12	1.30E+12	1.30E+12	sej/Gh¢

Calculations of the UEV for manure obtained from draft animal (i.e. this study)								
item	**amount**	**unit**	**UEV (sej/unit)**	**emergy (sej/yr)**				
Forage eaten by animal	4.38E+03	kg/yr	1.32E+09	5.78E+12				
Water intake by animal	16425	l/yr	6.99E+11	1.15E+16				
Cost of phytosanitry services (animal welfare)	497.5	Gh¢	1.2993E+12	6.46E+14				
Total				1.21E+16				
				3.32E+13	sej/day			
				1.39E+12	sej/hour			
services of animal	27.524	Gh¢						
							4.96E+11	4.96E+08
Manure	7.35E+03	kg/yr	4.96E+11					
Groundnut			7.16E+04					
Use/ capita								
sej/Country currency (emergy to dollar ratio) i.e emergy to cedi ratio						1.3E+12		
Forage intake by cow	4272							
water intake by cow	16425							
manure produced by cow	7345							
				1504000				
References								
tbs= https://www.thebeefsite.com/articles/3154/								
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