The emergy-data envelopment analysis (EM-DEA) approach handbook

An illustrated guide on how to use the EM-DEA approach to assess resource- and energy-use efficiency and the sustainability of agricultural and forestry ecosystems

Francis Molua Mwambo

OCCASIONAL PAPER 1

Occasional Paper 1

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DOI: 10.17528/cifor-icraf/008793

Mwambo FM. 2023. *The emergy-data envelopment analysis (EM-DEA) approach handbook: An illustrated guide on how to use the EM-DEA approach to assess resource- and energy-use efficiency and the sustainability of agricultural and forestry ecosystems*. Occasional Paper 1. Bogor, Indonesia: CIFOR (Center for International Forestry Research); and Nairobi, Kenya: World Agroforestry (ICRAF).

Photo by Kate Evans/CIFOR
Aerial view of the landscape around Halimun Salak National Park, West Java, Indonesia.

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Abbreviations and acronyms

CCR	Charnes Cooper Rhodes (i.e., the surnames of the three authors who developed the DEA model)
CIFOR	Center for International Forestry Research
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
EUE	Energy-use efficiency
EYR	Emergy yield ratio
F	Imported sources
L	Labour
LHV	Lower heating value
N	Non-renewable sources
NPK	Nitrogen Phosphorus Potassium
OSDEA	Open-source data envelopment analysis
%REN	Percentage renewability
R	Renewable source
rTE	Relative technical efficiency
RUE	Resource-use efficiency
S	Services
SE	Sustainability efficiency
TE	Technical efficiency
U	Total emergy
UEV	Unit emergy value

Glossary

Abiotic	The physical and non-living parts of an ecosystem.
Agricultural system *or* **Agroecosystem**	A community of plants and animals interacting with social, political and economic components as well as environment and nature (i.e., biotic and abiotic components) through physical and chemical interactions that have been modified by man to produce food, feed, fibre, fuel and other products for human consumption and industrial use.
Agroforestry system	Agroforestry is a land-use management system in which agricultural and forestry practices are deliberately combined to create productive and sustainable land use that provides multiple ecosystem services to meet socioecological needs. An agroforestry system is an example of an agroecosystem.
Biotic	The physical and living parts of an ecosystem.
Ecosystem	A community of organisms that interact with their physical environment (biotic and abiotic).
Emergy	The energy of one type previously used up directly and indirectly to make a product or deliver a service.
Forestry system	A land dominated by trees (including biotic and abiotic components), often managed for the provision of timber, fuelwood, non-timber forest products and ecosystem services.
Imported sources	Fraction of used emergy purchased from outside the system.
Labour	Human endeavour that contributes directly towards production inside a system.
Non-renewable sources	Resources that are extracted and used faster than they are being replaced.
Pareto efficiency *or* **Pareto optimality** *or* **allocative efficiency**	The state of allocative efficiency occurs when resources are so allocated that it is not possible to make anyone better off without making someone else worse off.
Renewable sources	Resources that are being replaced faster than they are extracted.
Services	Purchased resources that come from outside a system and enable production.
Solar transformity *or* **Specific emergy unit emergy value** (UEV)	The emergy per unit of available energy (exergy), which is measured in solar emjoule/Joule (sej/J), i.e., energy from the sun required to form a unit mass or solar emjoule.
Yield	The output resource of a production system.

Acknowledgments

Support for this study was provided through CGIAR Research Initiative on Low-Emission Food Systems. We would like to thank all funders who supported this research through their contributions to the CGIAR Trust Fund. We also appreciate additional funding that was provided by the CGIAR Research Program on Forests, Trees and Agroforestry (CRP-FTA), with financial support from the donors contributing to the CGIAR Fund, to cover a stipend for the author. This study is also part of CIFOR's Global Comparative Study on REDD+ (www.cifor.org/gcs). The funding partners that have supported this research include the Norwegian Agency for Development Cooperation (Norad), the Australian Department of Foreign Affairs and Trade (DFAT), the European Commission (EC), the International Climate Initiative (IKI) of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), the United Kingdom Department for International Development (UKAID), and FTA.

The EM-DEA approach was developed with technical advice from Christine Fürst, Christian Borgemeister, Sergio Ulgiati, Christopher Martius, and Benjamin Nyarko.

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Executive summary

With global challenges like food security, climate change and environmental degradation, there is a rational call for action that could contribute to halting the situation. There is also increasing environmental awareness of public calls for reliable methods to assess ecological systems (natural and man-made), and that such methods should provide quantitative details about the impacts of human activities. At the same time, improved reporting standards are frequently being called for.

As the world transitions to becoming a global bioeconomy, agricultural, forestry and agroforestry systems are greatly important for human and economic development. Yet, they are also at risk of environmental degradation – especially as food security is still a major global challenge. Human activities that cause deforestation and emissions are equally a threat to the long-term sustenance of some forest ecosystems and their biodiversity. Assessing agricultural, forestry and agroforestry systems is therefore critical so that these resources can be used wisely, and so that these systems are both efficient and sustainable.

This guidebook was developed based on empirical studies carried out as part of the BiomassWeb Project. These studies serve as evidence-based research on the development and applicability of the emergy-data envelopment analysis (EM-DEA) approach. The approach is an innovative tool for assessing resource- and energy-use efficiency (RUE and EUE), as well as the sustainability of agroecological systems. It could also be applied to other similar systems. The approach was developed by coupling emergy accounting (EMA) and data envelopment analysis (DEA) to form a holistic assessment framework, before integrating the concept of eco-efficiency into the framework, to develop the final EM-DEA approach. While EMA offers a way to account for various resources and land-use characteristics that might be involved in biomass production in such systems, DEA offers a way to compare the performance of multiple production systems that use similar inputs to produce similar outputs. Using this combination to assess a system provides quantitative analysis on environmental and economic accounting, measured using a common reference unit – the solar emjoule (sej).

This handbook is about using the EM-DEA approach as a tool that could have useful applications in forestry and agroforestry systems, and hence in the work of the Center for International Forestry Research (CIFOR) and World Agroforestry (ICRAF). Illustrations and detailed explanations make this handbook easy-to-use and self-explanatory, providing basic background for the concepts and theories that were used to frame the EM-DEA approach. The handbook provides step-by-step instructions on how to use the approach to assess RUE, EUE and sustainability of agroecosystems.

The handbook is organized into eight chapters. Definitions of terminologies and abbreviations are provided in the glossary and list of abbreviations at the front, so that users can become familiar with them before diving into the main chapters that follow. Expected learning outcomes are listed as a checklist at the end of each chapter. In this way, users can track their understanding of the EM-DEA approach as they progress. Links to online resources and suggested supplementary materials for further reading are included in the toolbox in Chapter 7. This provides extra support to users so they can develop a deeper understanding of the EM-DEA approach. These online materials demonstrate how the EM-DEA approach has been applied in empirical studies and how to manage data when using the EM-DEA approach. Users can therefore develop both a theoretical background and hands-on understanding to enable them to apply the EM-DEA approach effectively when analysing forestry and agroforestry systems.

1 Introduction

1.1 Why is this handbook needed?

Since the industrial revolution, the rate of environmental degradation occurring globally, especially in agriculture, forestry and other land uses (AFOLU), has accelerated with global population growth. More people means more demand for products and services to meet development needs. This exerts pressure on the earth's already scarce resources (i.e., non-renewable resources). The complex interactions between natural and man-made phenomena (e.g., climate change, population pressure, land use and natural resource extraction) occurring within AFOLU only worsen the situation. Considering how fragile most of our planet's ecosystems currently are, and yet how resilient nature is, there is a compelling reason for rational and strategic thinking to ensure an adequate and timely intervention (WCED 1987; IPCC 2018).

The coronavirus pandemic of 2019 (Covid-19) has further complicated the challenge of environmental degradation in many ways (UNEP 2020; United Nations 2020; UNCDP 2021). With global economic activities curtailed, sustainable development gains in some sectors deteriorated, while increased human pressure on the environment was seen as humans struggled for survival (Helm 2020; World Bank Group 2020). The advent of post-Covid-19 has been identified as an ideal time to build back better (OECD 2020), presenting an opportunity to strategically rethink on ways to foster resilience.

More than ever before, organizations need to build new capabilities at scale and make rational changes that could enable them to effectively contribute to resilience (Heldeweg 2021). For post-Covid economic recovery to be durable and resilient, a return to 'business-as-usual' means avoiding environmentally-destructive investment patterns and activities. A more resilient economy depends on shifting to more sustainable practices that can better contribute to sustainable development. For example, ensuring a food supply that uses fewer resources while causing fewer greenhouse gas (GHG) emissions. For such a paradigm shift to be effective, decision making needs to be based on reliable methods and approaches that support the intended outcome. This requires detailed environmental and economic accounting to improve reporting standards, human action and environmental impacts[1,2]. One example of this is the United Nations' recently-launched System of Environmental Economic Accounting – Ecosystem Accounting (SEEA-EA), which aims to integrate nature's contribution into the economy during the accounting process in a more structured way (UNSD 2021).

Biomass – organic material that comes from living organisms such as plants and animals or parts of what were living organisms in the recent past. Biomass is suitable for the provision of food, feed and fibre, and is a better substitute for most of the industrial feedstock needed for human and economic development. The concept of circular bioeconomy (herein defined as the "*economic space where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimized*")[3] is therefore an alternative pathway to linear economy. This could also be a means to decouple economic growth from fossil fuel-driven industries and eventually couples it to the Sustainable Development Goals defined by the United Nations. In this way, it is being widely adopted as a pathway which could

1 https://seea.un.org/events/building-back-better-natural-capital-accounting-green-recovery

2 https://ec.europa.eu/environment/news/biodiversity-ground-breaking-change-economic-reporting-accounting-natures-contribution-economy_de

3 https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52015DC0614andfrom=ES

contribute to solutions to environmental challenges such as waste reduction (Tan and Lamers 2021; Nagarajan et al. 2021; OECD 2020).

As two major sectors for the supply of food and other raw materials needed to sustain a bio-based economy, the world relies on its agricultural and forestry systems. To effectively manage the risk of environmental degradation in agriculture and forestry, it is fundamental to assess the efficiency and sustainability of these systems. Measuring the sustainability of these systems is complex, however, and limited methods exist to analyse the resource- and energy-use efficiency (RUE and EUE) of agricultural systems, in particular the small-scale systems that are commonly practiced in developing countries (Jones 1989; FAO 1995; Hayati et al. 2010; Schindler et al. 2015).

Considering the transition to bioeconomy, global environmental challenges like land degradation, and increased public awareness around environmental reporting standards, there is a need for reliable assessment methods which provide more detailed information. This level of detail could better inform decisions around sustainable development, minimizing environmental impacts without compromising productivity in agricultural and forestry systems.

The Center for International Forestry Research (CIFOR) and World Agroforestry (ICRAF) – the world's leading research and development organizations focused on forestry and agroforestry – are learning organizations committed to sustainable development through the prudent use of the earth's limited natural resources. In particular, forests, arable land, and their associated ecosystem goods and services. The emergy-data envelopment analysis (EM-DEA) approach could therefore be a key tool for the organizations in addressing their strategic goals for 2020–2030[4].

This handbook presents the recently-developed EM-DEA approach, and how it could be applied to assess resource-use efficiency (RUE), energy-use efficiency (EUE) and the sustainability of agricultural, forestry and agroforestry systems. The EM-DEA approach is the innovative coupling of emergy accounting (EMA) and data envelopment analysis (DEA) methods to form an assessment framework (Mwambo and Fürst 2014), while integrating the concept of 'eco-efficiency' into the framework allows users to assess resource- and energy-use efficiency (RUE and EUE) as well as the sustainability of agricultural production systems (Mwambo and Fürst 2019). This approach provides a flexibility to account for diverse resources, including nature, materials, energy, resource generation time, labour, economic and societal infrastructures, as well as other resources whose market values are too ambiguous to monetize (Odum 1996; Brown and Ulgiati 2011, 2016a; Campbell and Tilley 2014; Campbell et al. 2014). This approach has the capacity to assess multiple peer systems of production in a batch, and to provide assessment information obtained by means of quantitative measures on a common basis – i.e., the solar emjoule (sej). This provides an opportunity to explore this novel approach for assessing RUE, EUE and the overall sustainability of agricultural, agroforestry and forestry systems, in order to benchmark efficient and sustainable systems or to achieve a detailed life cycle assessment of these systems.

4 https://www.cifor.org/our-work/cifor-icraf-strategy/

1.2 How to use this handbook?

This stand-alone self-explanatory handbook provides a step-by-step guide on how to assess resource-use efficiency (RUE), energy-use efficiency (EUE) and the sustainability of agricultural, agroforestry and forestry systems using the emergy-data envelopment analysis (EM-DEA) approach. For a user to make the most out of this handbook, it is advisable that this handbook is explored alongside the following supplementary materials:

i. the sample Microsoft Excel file, which provides an example of the structure of basic data in spreadsheet form (Section 7.2 provides a link to this online data file, see Mwambo 2021a).
ii. the link to the open-source data envelopment analysis (OSDEA) file (https://opensourcedea.org/dea/). This is an executable file for the DEA, which can also be accessed through the CIFOR DataVerse or Toolbox site.

1.3 What to expect from the handbook?

At the end of this handbook, readers will have learned:

Learning outcome check: The EM-DEA approach as an innovative tool for assessing RUE, EUE and the sustainability of ecosystems.

- ✓ What the basic concepts and theories used to frame the EM-DEA approach are.
- ✓ How to curate data for analysis using the EM-DEA approach.
- ✓ How to implement the EM-DEA approach step-by-step.
- ✓ How to compile evaluation outcomes to present results logically.
- ✓ How to interpret results in non-technical language to support decision-making processes.
- ✓ Where to find recommended supplementary reading materials as additional support.
- ✓ How to use this handbook and supplementary materials to get a hands-on-experience of the EMDEA approach.
- ✓ A highlight of how EM-DEA approach could be applied to do environmental accounting, and how this could contribute to the work of CIFOR-ICRAF.

2 Background

2.1 Why the EM-DEA approach?

When assessing the efficiency and sustainability of a production system, it is key to access information that could help avoid compromises in productivity and minimize the impacts a production system could have on the resource base. Agricultural, forestry and agroforestry systems are multiple input and multiple output systems. Existing methods are limited in analysing energy efficiency in agricultural systems, because some inputs are difficult to measure (Jones 1989; FAO 1995; Blancard and Martin 2012, 2014). Until now most assessments of agricultural systems have been incomplete (Alvarenga et al. 2013), due to the challenge of analysing the input energy of humans and animals in small-scale agricultural systems, for example:

> *"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, 59).*

It is also complex and challenging to measure the sustainability of agricultural systems (Hayati et al. 2010; Schindler et al. 2015). It was this backdrop – where existing methods were unable to account for certain input resources in agricultural systems, and the complexity of measuring agricultural systems' sustainability presented similar challenges – that motivated the development of a holistic assessment approach for analysing agricultural systems as a whole.

2.2 Conceptualizing the EM-DEA approach

Having considered various concepts and theories (summarized in Table 1), emergy accounting (EMA), data envelopment analysis (DEA), and economic-ecological efficiency (eco-efficiency) emerged as prospective methods and concepts that could be helpful for developing a solution to the challenge stated in Section 2.1.

Emergy accounting (EMA) accounts for various material and energy flows in closed systems. EMA is therefore helpful in accounting for the fluxes of the various sources that contribute to production processes. This flexibility is useful in valorising nature and assessing environmental impacts in term of resource use. Accounted resources are measured using a common unit – solar emjoule (sej). This makes EMA suitable for quantifying various input and output resources; obtained assessment information also has a common base which makes it easier to compare different systems.

Data envelopment analysis (DEA) offers the means to compare the performance of multi-input and multi-output production entities in a batch. This makes it possible to compare the productive performance of multiple production systems using similar inputs to produce similar outputs. This makes DEA suitable for comparing different agricultural land-use production systems.

The EM-DEA approach was developed by coupling EMA and DEA methods to form an assessment framework (Mwambo and Fürst 2014), before the concept of eco-efficiency was integrated into this framework. The concept of eco-efficiency is based on the management strategy of doing more with less, combining attributes of efficiency and sustainability. The EM-DEA approach thus pools together the

Table 1. Concepts and methods considered in the development of the EM-DEA approach

Method / concept (study)	Review	Rationale for suitability / modification for EM-DEA
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 was adopted as a conceptual tool for accounting environmental resources (both inputs and biologically-produced outputs) in agricultural systems. EMA provides a means to define system boundaries, and 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, 1996)	The concept of energy memory (emergy) was founded by Odum in the 1980s after combining energetics and systems ecology. emergy accounting (EMA)'s first presentation in 1983 was used on the basis of embodied energy.	
Economic-ecological efficiency (eco-efficiency) (Jollands 2003; Kortelainen and 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 is adopted and applied for calculating resource-use efficiency (RUE), i.e., the eco-efficiency ratio is equated to unit emergy value (UEV) of product. Efficiency is further split into two 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 and Brown 1998; Brown and 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 sustainability-related information is illustrated. The studies provided a reliable basis upon which selected indicators were adopted into the EM-DEA method.	Absolute sustainability is assessed using the following indicators (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).
Data envelopment analysis (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 the relative efficiency of peer units (generally referred to as decision-making units, DMUs) of production, with multiple performance criteria.	DEA was adopted as a method of assessing the relative technical efficiency (rTE). Resources accounted for using EMA were quantified into emergies. The data were imported into open-source DEA (OSDEA). The non-parametric treatment of data, compatibility between a production system's emergetic data, and importation into DEA, mean it is possible 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.
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 to the TE under a constant return to scale model (TE_{CRS}). TE has a direct correlation with sustainability efficiency (SE). The TE is a suitable proxy for assessing relative sustainability.	
Land-use systems and 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 was applied in building the EM-DEA method to make it more synergistic for integrated assessments.

Source: Mwambo (2021b)

capabilities of EMA, DEA and eco-efficiency, with its overall strength being a synergetic, holistic assessment of RUE, EUE and the overall sustainability of agricultural systems (Mwambo and Fürst 2019). Chapter 3 goes into detail around the viability of the EM-DEA approach, covering both methodology and parameters to demonstrate how the EM-DEA approach is applicable as a method to assess RUE, EUE and sustainability using mathematical expressions to evaluate the various indicators involved in the evaluation process.

Learning outcome: The basic concepts and theories used to frame the EM-DEA approach.

The reader has learned the following:

- ✓ The limitations of existing methods.
- ✓ The motivation for developing the EM-DEA approach.
- ✓ The concepts and theories used to frame the EM-DEA approach.
- ✓ The development of the EM-DEA approach.

3 Methods and parameters

3.1 Developing the EM-DEA approach

3.1.1 Emergy accounting (EMA)

The EMA method is based on thermodynamics and systems theory. The concept of energy memory (emergy) is useful for environmental and economic accounting, because it provides the means to evaluate resources on the basis of the environmental work required to generate and make resources available in a system (Bonilla et al. 2016). EMA offers the flexibility to account for various resources in a system through the quantification of material and energy flows as emergy. Emergy is defined as "*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 means that the available energy (i.e., exergy or available energy content) of diverse resource types can be accounted for on the basis of their embodied energy (Scienceman 1987; Brown and Herendeen 1996). This enables accounting of all natural and socioeconomic inputs on a common metric (Bonilla et al. 2016). The emergy of a given resource is calculated as the mathematical product of the exergy and the unit emergy value (UEV) of a given resource, as stated in Equation 1. In this methodology, EMA is implemented using the EM-DEA approach (Mwambo and Fürst 2019). The following emergy baseline was used, as the most recent baseline for emergy-based calculations, i.e., 12.0E+24 *sej*/yr (Brown and Ulgiati 2016a).

$$Emergy_{resource} = exergy_{resource} * \tau_{resource} \qquad (1)$$

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 of a resource (measured in *sej/unit*)

3.1.2 Data envelopment analysis (DEA)

DEA is based on econometric analysis. DEA was originally developed as a technique for measuring the relative efficiency of a set of production entities (i.e., decision-making units – DMUs), when the price data for inputs and outputs are either unavailable or unknown (Farrell 1957). DEA is a non-parametric linear programming-based technique for estimating the relative performance of multiple production systems that use similar inputs to produce similar outputs (Toloo and Nalchigar 2009; Wen 2015). This is useful for comparing the relative efficiency of multi-input and multi-output production systems. Efficiency is calculated as the ratio of output to the observed input. Given a set of peer DMUs, the productive efficiency (E_p) is the ratio of the weighted sum of outputs to the weighted sum of inputs. 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 the denominator, as stated in Equation 2. The ratio of the single virtual output to the single virtual input for each DMU, relative to that of the most performing DMU, gives the relative technical efficiency (rTE) scores (Hartwich and Kyi 1999). In EM-DEA approach, these scores are considered the proxy indicator for expressing the relative sustainability of a set of DMUs. DEA is herein applied using the EM-DEA approach (Mwambo and Fürst 2019).

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

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

3.1.3 Linking EMA with DEA and integrating the concept of eco-efficiency

EMA offers a flexible approach to quantifying inputs and outputs as emergies, using a common unit – solar emjoule – so that the various sources involved in a multi-input multi-output production process can be considered. DEA offers a means to estimate the relative productive efficiencies (i.e., relative technical efficiencies) of peer DMUs (e.g., different land-use systems), by comparing the ability of the peer systems to convert inputs into outputs on a relative basis. By applying the refined procedure of emergy accounting to avoid double counting of inputs (Brown and Ulgiati 2016a), selected input and output emergies are retained from the basic pool of inputs and outputs. These retained input and output emergies, alongside the names of the DMUs, form the output-input data, which is then imported as a comma-separated values (CSV) file into DEA model. Emergy-based data being imported into DEA is how the two models are linked in the EM-DEA framework. The concept of eco-efficiency is then integrated into the framework, leading to the EM-DEA approach which provides detailed and holistic assessment of RUE, EUE and sustainability (Mwambo and Fürst 2019). This constitutes the methodological background on which the assessment will be based.

Eco-efficiency is defined as the ratio of environmental impact to the economic value added to agricultural produce (Kortelainen and Kuosmanen 2004; Pang et al. 2016). In EM-DEA approach, this ratio is equated to the unit emergy value (UEV) of product that is obtainable by a decision-making unit (DMU), as stated in Equation 3. The eco-efficiency was then subdivided to evaluate efficiency in terms of resource- and energy-use, to calculate: (i) UEV in terms of resource use (UEV_R), and (ii) UEV in terms of exergy use, i.e., the available energy content (UEV_E). The UEV_R and UEV_E are then further evaluated on the basis of input materials from nature ($UEV_{R(\text{without L\&S})}$ and $UEV_{E(\text{without L\&S})}$), as well as on the basis of input materials from nature, including labour and services from the human economy ($UEV_{R(\text{with L\&S})}$ and $UEV_{E(\text{with L\&S})}$), respectively. This distinction is important to better appreciate the impacts of a production system on: (i) the natural resource-base, and (ii) the whole economy. These evaluations are stated in Equations 4–7.

$$Eco-Efficiency = \frac{Environmental\ impact}{Economic\ value} = \frac{Total\ emergy\ U}{yielded\ product} = UEV_{(\text{product})} \tag{3}$$

$$UEV_{R\ (\text{without L\&S})} = \frac{U_{(without\ L\&S)}}{yielded\ product} = \frac{R+N+F}{yielded\ matter\ dry\ (g)} \tag{4}$$

$$UEV_{R\ (\text{with L\&S})} = \frac{U_{(with\ L\&S)}}{yielded\ product} = \frac{R+N+F+L+S}{yielded\ matter\ dry\ (g)} \tag{5}$$

$$UEV_{E\ (\text{without L\&S})} = \frac{U_{(without\ L\&S)}}{yielded\ exergy\ (J)} = \frac{R+N+F}{yielded\ matter\ dry\ (g) * LHV} \tag{6}$$

$$UEV_{E\ (\text{with L\&S})} = \frac{U_{(with\ L\&S)}}{yielded\ exergy\ (J)} = \frac{R+N+F+L+S}{yielded\ matter\ dry\ (g) * LHV} \tag{7}$$

Note: The environmental significance (i.e., impact) of the various indicators presented in Equations 3–7 is explained in Section 6.3, Indicators and what they mean.

DEA is applied to evaluate the relative technical efficiency (rTE), which is considered a proxy for the relative sustainability of peer DMUs (De Koeijer et al. 2002). Using a model like open-source data envelopment analysis (OSDEA), DEA applies Pareto efficiency (for definition, see the Glossary) to select weights for the input-output data. The optimization function in DEA assumes the multiple ordinary least square regression, as stated in Equation 8 (Kuosmanen and Johnson 2010). The DEA model uses input-output data and applies Equation 2 to calculate the relative technical efficiency (rTE) scores.

3.2 Evaluating indicators

3.2.1 Resource- and energy-use efficiency

The indicators for resource-use efficiency (RUE) and energy-use efficiency (EUE) are mathematically expressed in Equations 4–7. Equations 4 and 5 apply to RUE, while 6 and 7 apply to EUE.

3.2.2 Absolute sustainability

Absolute sustainability focuses on the environmental impacts of a particular system irrespective of its peers. Absolute sustainability is evaluated using 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). How these indicators are evaluated based on input materials from nature can be seen in Equations 9–13; while how these indicators are evaluated based on raw materials from nature, including labour and services from the human economy, is stated in Equations 14–18.

3.2.3 Relative sustainability

Relative sustainability focuses on relative ability of peer systems to convert inputs into outputs (Equations 2 and 8). Relative technical efficiency (rTE), which is the proxy for relative sustainability, is calculated by DEA after you run the model (Figure 10). Each indicator measures a specific parameter. Compiling the results of these indicators into a table of matrix as illustrated in Table 11 and exemplified in Table 12, respectively, provides a means to have a complete assessment of peer systems.

$$\gamma_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_n X_n + \mu_i \quad (8)$$

where,

γ_i	yield or resource output of the i^{th} DMU
β_0	coefficient at the intercept
$\beta_1, \dots, \beta_n$	slopes or coefficient
$X_1, \dots, X_n$	retained resources i.e., variables
μ_i	slack, i.e., residuals of the i^{th} DMU

$$\textit{Total emergy (U)} = R + N + F \quad (9)$$

$$EYR = \frac{(R + N + F)}{F} \quad (10)$$

$$ELR = \frac{(N + F)}{R} \quad (11)$$

$$ESI = \frac{EYR}{ELR} \quad (12)$$

$$\%REN = \frac{1}{(1 + ELR)} \quad (13)$$

$$\textit{Total emergy (U)} = R + N + F + L + S \quad (14)$$

$$EYR = \frac{R + N + F + L + S}{F + L + S} \quad (15)$$

$$ELR = \frac{(N + F + L + S)}{R} \quad (16)$$

$$ESI = \frac{EYR}{ELR} \quad (17)$$

$$\%REN = \frac{1}{(1 + ELR)} \quad (18)$$

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	Labour 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

Note: The environmental implications of the various indicators presented in Equations 9–18 is presented in Section 6.2.

Learning outcome: The methodological development of the EM-DEA approach and the mathematical equations used to assess RUE, EUE and overall sustainability.

The reader has learned the following:

- ✓ How the EM-DEA approach was developed.
- ✓ How various indicators are coded mathematically.
- ✓ The mathematical evaluation of indicators used to assess RUE.
- ✓ The mathematical evaluation of indicators used to assess EUE.
- ✓ The mathematical evaluation of indicators used to assess overall sustainability.

4 Curating data

4.1 Getting data

What data is needed to assess RUE, EUE and the sustainability of an ecosystem varies, depending on the ecosystem type (e.g., agricultural, forestry or agroforestry) and what the objective of analysis is. As an example of what data might be useful, raw primary field survey data – collated to assess RUE, EUE and the sustainability of manually-cultivated maize systems in Ghana (Mwambo 2020). This can be accessed via the link provided in Section 7.2. In general, this empirical data are described as follows:

- *production data:* these include the input materials (preferably an exhaustive list of inputs) including the land-use practices, farmer's practices (manual or mechanised labour input), and purchased services (e.g., farm implements).
- *output and yield data:* this includes ecosystem goods and services measured in quantitative units (preferably in metric units).

For illustrative purpose, the structural format for your data is shown in Table 2. For your understanding, empirical examples of data are provided in Chapter 5.

Transformity or unit emergy values (UEVs), for the resources that are being accounted, are needed for any assessment study. These values can be adopted from previous studies that have assessed identical resources (i.e., adopting from existing emergy calculations, where there are existing studies), or equally can be calculated, if such calculations do not yet exist, by using equivalent or similar UEVs while making rational assumptions.

4.2 Managing data

Microsoft Excel is a simple, user-friendly tool for processing statistical data, so that it can be input into the EM-DEA approach. Data needs to be quantitative in order to be useful for analysis using the EM-DEA approach. If raw data is qualitative by default, this data can be converted into classes, Boolean or binary data to render it quantitative and compatible. Table 2 presents a hypothetical dataset with a structure and format, to illustrate compatible input data using the EM-DEA approach.

By combining primary data as exemplified in Mwambo (2020; for a link to this data, see Section 7.2) with secondary data, like unit emergy values obtained from secondary sources (e.g., the national environmental accounting database, the Center for Environmental Policy, University of Florida; for the link to this data, see Section 7.1), the user can produce composite data, like that seen in Mwambo (2021a).

Table 2. An illustration of resource input and output data in Excel

Note	Item	Data	Unit	Exergy (J)	UEV (sej/unit)	Emergy (sej/yr)	Ref.
	Primary sources						
1	Sun	A	*J*	A_{exe}	A_{UEV}	$A_{exe}A_{UEV}$	[a]
2	Deep heat	B	*J*	B_{exe}	B_{UEV}	$B_{exe}B_{UEV}$	[b]
3	Gravity	C	*J*	C_{exe}	C_{UEV}	$C_{exe}C_{UEV}$	[c]
	Sum of primary sources					$A_{exe}A_{UEV}+B_{exe}B_{UEV}+C_{exe}C_{UEV}$	
	Secondary sources						
4	Water/rain/irrigation	D	*J*	D_{exe}	D_{UEV}	$D_{exe}D_{UEV}$	[d]
5	Wind	E	*J*	E_{exe}	E_{UEV}	$E_{exe}E_{UEV}$	[e]
	max. of secondary sources					$\max(D_{exe}D_{UEV}, E_{exe}E_{UEV})$	
	Max. of Renewables (R)					$\text{Max}[A_{exe}A_{UEV}+B_{exe}B_{UEV}+C_{exe}C_{UEV},\max(D_{exe}D_{UEV},E_{exe}E_{UEV})]$	
	Non-renewable sources (N)						
6	Topsoil loss	F	*J*	F_{exe}	F_{UEV}	$F_{exe}F_{UEV}$	[f]
	Imported sources (F)						
7	Agrochemicals	G	*g*	G_{exe}	G_{UEV}	$G_{exe}G_{UEV}$	[g]
8	Crop seeds/ tree seedlings	H	*g*	H_{exe}	H_{UEV}	$H_{exe}H_{UEV}$	[h]
9	Traction (animal/ mechanized)	I	*hr/yr*	I_{exe}	I_{UEV}	$I_{exe}I_{UEV}$	[i]
10	Cattle manure	J	*g*	J_{exe}	J_{UEV}	$J_{exe}J_{UEV}$	[j]
	Labour & Services (L&S)						
11	Human labour (L)	K	*yr*	K_{exe}	K_{UEV}	$K_{exe}K_{UEV}$	[k]
12	Services (S)	L	*$*	L_{exe}	L_{UEV}	$L_{exe}L_{UEV}$	[l]
	Total Emergy without L&S					(Equation 19)	
	Total Emergy with L&S					(Equation 20)	
	Yielded Outputs (Y)						
13	Edible crop biomass	M	*g*	M_{exe}	M_{UEV}	$M_{exe}M_{UEV}$	[m]
14	Timber products	N	*g*	N_{exe}	N_{UEV}	$N_{exe}N_{UEV}$	[n]

continued on next page

$$\textit{Total Emergy}_{(without\ L\&S)} = \mathrm{Max}\ (aA' + bB' + cC', \max\ (dD', eE')) + fF' + gG' + hH' + \max\ (iI',\ jJ') \tag{19}$$

$$\textit{Total Emergy}_{(with\ L\&S)} = \mathrm{Max}\ (aA' + bB' + cC', \max\ (dD', eE')) + fF' + gG' + hH' + \max\ (iI',\ jJ') + kK' + iI' \tag{20}$$

where,

A, …, Z	resources estimated in their physical unit of measurement (e.g., grams)
A_{exe}	exergy of the resource "A"
A_{UEV}	UEV of the resource "A"
[a]	reference of the UEV for resource "A"
(L)	human labour, i.e., all forms of physical labour that contribute directly towards production e.g., sowing seeds/ seedlings
(S)	services, i.e., purchased inputs that come from outside the system and contribute towards production e.g., manufacture of agrochemicals
g	grams
J	Joule
hr/yr	hours/year
$	dollar

Source: Mwambo and Fürst (2019)

Note: Table 2 has been included for illustration purposes. Mwambo (2021a) also provides an example of empirical data (see Section 7.2 on further reading).

Learning outcome check: How to curate, process, organize, use and import data

The reader has learned the following:

- ✓ How to acquire some data types that could be useful.
- ✓ Few data types that may be required for assessments in the area agroecosystems.
- ✓ An illustration of the structural format the emergy worksheet in Excel.
- ✓ How to complement raw data with other data to form a dataset.

5 Efficiency and sustainability assessment using EM-DEA approach

5.1 Step-by-step instructions with illustrations

5.1.1 Phase 1: Applying emergy accounting (EMA)

i. Sketch an emergy diagram of each system that has to be analysed

To apply the emergy-data envelopment analysis (EM-DEA) approach to account for resource use efficiency when given a set of peer production systems that you wish to analyse and compare, you need to adopt emergy accounting (EMA) methodology (Section 3.1.1). You begin by representing the given peer systems graphically, using energy systems language and symbols (for the link to this support, see Section 7.1) (Odum 1994). To do this, you may use Microsoft Visio or Edraw as a diagramming software. This graphical representation of each system, also called an emergy diagram, helps you to visualize each system in graphics. This will also help you in the process of representing material and energy flows (fluxes) in each system, as illustrated in Figure 1.

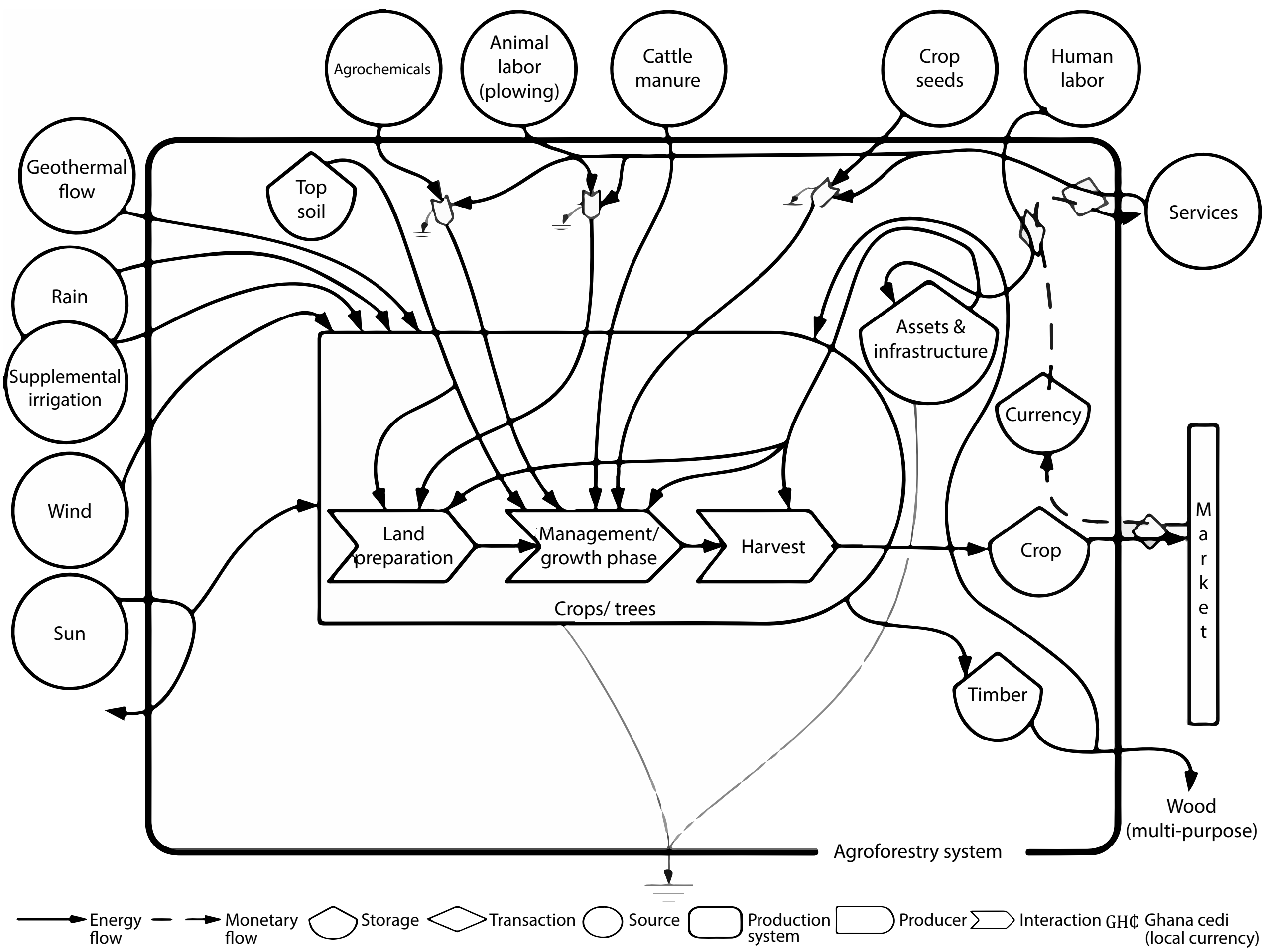

Figure 1. A simplified and generalized emergy diagram of an agroecosystem system

Source: Mwambo et al. (2020, 2021), adapted from Zucaro et al. (2013).

ii. Use Microsoft Excel to manage and process input and output resource data

Next, create a database in Microsoft Excel (Table 3–Table 8). Use this Excel file to manage and process your data. Quantify the annual input and output resources for each of your peer systems that has to be analysed and compared. Measure resources in their standard units of measurement. Organise the worksheets of your Excel workbook as follows:

- *User interface:*
  Itemise the inputs and outputs. Provide the basic data that you would need for quantifying the inputs and outputs. Present the basic data worksheet as exemplified in Table 3.

- *Calculation:*
  Do the calculation to quantify the inputs and outputs by importing basic data from the user interface worksheet of your workbook. Present the calculation worksheet as exemplified in Table 4.

- *Unit emergy value:*
  Quote the unit emergy values (UEVs) of inputs and outputs that are involved in the given systems. You may have to calculate a UEV, if there is no existing value that can be assigned to a given input or output. In this case, you may calculate it on another worksheet (e.g., UEVs based on this study) of the workbook. Present the UEV worksheet as exemplified in Table 5.

- *Emergy:*
  Calculate the emergies (see Equation 1), by importing data from the user interface, calculation, and unit emergy value worksheets of your workbook. To avoid double counting of multiple resources from the same source, retain only the resource with the greatest emergy in the final calculation of emergies. This is based on the application of the refined procedure of emergy accounting (Brown and Ulgiati 2016a). For instance, manure and draft animal labour are from the same source, farm animal. The emergy of animal labour will be retained (see Table 6). Next, you group the itemised inputs and outputs into the follows categories: renewable sources (R), non-renewable sources (N), imported sources (F), yield (Y), labour and services (L&S) (for the definition of the categories, see the glossary). Then, sum up the emergies of the primary sources (e.g., sun, deep heat, and gravitational potential), and call this: “SUM of primary sources”. Next, compare the magnitude of the emergies of the secondary sources (e.g., rain, and wind which are both from a common source, the sun). Retain the secondary source that has the greatest emergy, and call this: “maximum of secondary sources”. Next, compare the magnitude of the “SUM of primary sources” and “maximum of secondary”, and retain the one that is greater, and call this: “Maximum of renewable sources (R)”. Present the emergy worksheet as exemplified in Table 6.

- *Indicators:*
  Calculate the emergy-based indicators using Equations 4 – 7, 9 – 18, by importing the necessary data required for this calculation from the user interface, calculation, UEV, and emergy worksheets of your workbook. Present your indicators worksheet as exemplified in Table 7. You will learn more about how to interpret these indicators in Chapter 6: Interpretation of assessment results.

- *References:*
  Provide a complete list of bibliography that you used in compiling this database as exemplified in Table 8.

Table 3. User interface worksheet

	A	B	C	D	E	F
1	**Multi-method analysis**					
2	Material Flow Accounting, Embodied Energy Analysis and Emergy Analysis for maize production in Ghana, Africa (Mwambo et al. 2020, 2021)					
3						
4						
5	Total land area of Ghana	2.30E+07	ha	2.30E+11	m²	[https://knoema.com/atlas/Ghana/topics/Land-Use/Area/Surface-area]
6	Total area cropped with maize in Bolga. & Bongo Districts (2011	3.31E+03	ha	3.31E+07	m²	MoFA, 2012
7	Unit area for analysis in this study	1.00E+00	ha	1.00E+04	m²	This study
8						
9	**Item**	**Value**	**Unit**	**Variation**	**Reference**	
10	**Sun** insolation	1.20E+21	J/m²/yr		[http://www.cep.ees.ufl.edu/nead/data.php?country=74&year=247#]	
11	**Wind** velocity	2.6	m/s		[worldweatheronline.com]	
12	**Rainfall**	0.911	m/yr		MoFA, 2012	
13	Fraction evapotranspired water	0.73			Nurudeen (2011)	
14	Supplemental irrigation	0.179	m/yr		Adams et al, (2014)	
15	Cost of supplemental irrigation	8.00E+02	Gh₵/ha		[Dey & Avumegah, 2016]	
16	**Deep heat** (average heat flow per area)	4.20E+01	mW/m²		[Beck & Mustonen, 1972]	
17	**Soil erosion**	1.29E+01	g/m²/yr		[Badmos et al., 2015]	
18		6.46E+00	g/m²/yr		[This study]	
19	**Fertilizer**					

user interface | calculation | Unit Emergy Value (UEV) | emergy | Indicators | References | UEVs based on this study

Source: Mwambo (2021a). See Section 7.2 for the full reference and link to access the complete sheet.

Table 4. Calculation worksheet

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1		**CALCULAT**	**Extensive0**	units	Ref.	**Extensive12**	units	Ref.	**Intercrop20**	units	Ref.	**Intensive50**	units	Ref.	**Intensive100**	units	Ref.
2																	
3		N.B. The inventory data refers to primary input data for analysis. The collection of inventory data was done by															
4		means of farmer interviews using semi-structured questionnaires that were administred during the field survey.															
5		The survey was conducted in Bolgatanga and Bongo Districts located in Upper East Region of Ghana. The inventory															
6		data were complemented with secondary data from other sources. Referenes have been provided where necessary.															
7		The inventory data were normalised using standard statistical methods. Considered in this study were the mean															
8		values of input variables of the inventory data. Also the cropped area was normalised to 1 hectare = 10000m².															
9																	
10		Area of analysis	1.00E+04	m²	[Inventor	1.00E+04	m²	[Inve	1.00E+04			1.00E+04			1.00E+04	m²	[Inventory survey]
11	**Renewable Inputs (locally available)**																
12	1	**Sun insolation**															
13		Average insolation	1.20E+21	J/yr	[http://w	1.20E+21	J/yr	[http	1.20E+21	J/yr		1.20E+21	J/yr	[http	1.20E+21	J/yr	[http://www.cep.ees.ufl.edu/nead/data.php?country=74&year=247#]
14		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	
15		Albedo	0.15		[Arku, 20	0.15		[Arku	0.15			0.15		[Arku	0.15		[Arku, 2011]
16		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	
17																	
18	2	**Wind**															
19		Wind energy = (air density,kg/m³)(drag coeff.,)(geostrophic wind velo., m/s)³(area, m²)(sec/year)															
20		Air density =	1.15	kg/m³		1.15	kg/m³		1.15	kg/m³		1.15	kg/m³		1.15	kg/m³	[Assumption: same wind speed in the area]
21		Wind velocity (2015) =	2.6	m/s	[worldwe	2.6	m/s	[wor	2.6			2.6			2.6	m/s	[worldweatheronline.com]
22		Geostrophic wind velocity =	4.0	m/s		4.0	m/s		4.0			4.0			4.0	m/s	

user interface | calculation | Unit Emergy Value (UEV) | emergy | Indicators | References | UEVs based on this study

Source: Mwambo (2021a). See Section 7.2 for the full reference and link to access the complete sheet.

Table 5. Unit emergy value worksheet

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				

Source: Mwambo (2021a). See Section 7.2 for the full reference and link to access the complete sheet.

Table 6. Emergy worksheet

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	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 sources						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 fo	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

Source: Mwambo (2021a). See Section 7.2 for the full reference and link to access the complete sheet.

Table 7. Indicators worksheet

	A	B	C	D	E	F	G
1	**Indicators**	*Extensive0*	*Extensive12*	*Intercrop20*	*Intensive50*	*Intensive100*	Unit
3	*Assessment without labour and services (L&S)*						
4	Total Emergy (U without L&S)	2.73E+14	3.96E+14	3.85E+14	6.11E+14	9.04E+14	sej/ha
6	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
8	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
10	Emergy Yield Ratio (EYR)	6.60	2.42	2.49	1.83	1.44	ratio
12	Environmental Loading Ratio (ELR)	0.19	0.72	0.67	1.22	2.28	ratio
14	Emergy Sustainability Index (ESI)	34.97	3.35	3.70	1.50	0.63	ratio
16	Percentage Renewability (R%), then multiple by 100	0.84	0.58	0.60	0.45	0.30	percent
18	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¢

user interface | calculation | Unit Emergy Value (UEV) | emergy | **Indicators** | References | UEVs based on this study

Source: Mwambo (2021a). See Section 7.2 for the full reference and link to access the complete sheet.

Table 8. References worksheet

	A
1	**References**
3	Adams, S., Quansah1, G. W., Issaka, R. N., Asamoah, E. A., Nketia, K. A., Amfo-otu, R. (2014). Water requirements of some selected crops in Tono irrigation area. *J.Bio.& Env.Sci.*
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13	Badmos, B. K., Agodzo, S. K., Villamor, G. B., & Odai, S. N. (2015). An approach for simulating soil loss from an agro-ecosystem using multi-agent simulation: A case study for semi-arid ghana. Land, 4(3), 607-626.
15	Beck, A. E., & Mustonen, E. (1972). Preliminary heat flow data from Ghana. Nature, 235(61), 172-174.
17	Brown, M. T., & Ulgiati, S. (2004). Emergy analysis and environmental accounting. Encyclopaedia of energy vol. 2.
19	Brown, M. T., & Ulgiati, S. (2016). Emergy assessment of global renewable sources. *Ecological modelling*, *339*, 148-156.
21	Dawidson, E., & Nilsson, C. (2000). Soil organic carbon in Upper East Region, Ghana: mesaurements and modelling. *Lunds universitets Naturgeografiska institution-Seminarieuppsatser*.

user interface | calculation | Unit Emergy Value (UEV) | emergy | Indicators | **References** | UEVs based on this study

Source: Mwambo (2021a). See Section 7.2 for the full reference and link to access the complete sheet.

iii. Summarise the output and input emergies of peer systems in a spreadsheet to be imported into DEA model

Next, create another spreadsheet. Make a summary of the retained outputs and inputs emergies of the peer systems by copying the values from the emergy worksheet. Call the peer systems: decision making units (DMUs). Have this spreadsheet saved in comma-separated values (CSV) format, in order to make it compatible for importation into data envelopment analysis (DEA) model (Section 5.1.2). Present this summary as exemplified in Table 9.

Table 9. An example of an empirical output-output data table of peer DMUs, ready to be imported into an executable OSDEA model

	A	B	C	D	E	F	G	H	I	J
1	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 labour (sej/ha/yr)	Seeds (sej/ha/yr)	Human labour (sej/ha/yr)	Services (sej/ha/yr)
2	Extensive0	936	876	2.30E+14	1.96E+12	0.00E+00	3.32E+13	8.19E+12	4.41E+15	6.67E+14
3	Extensive12	960	899	2.30E+14	1.96E+12	1.22E+14	3.32E+13	8.19E+12	4.77E+15	7.03E+14
4	Intercrop20	1500	1410	2.30E+14	0.49E+12	1.17E+14	3.32E+13	4.10E+12	3.55E+15	7.11E+14
5	Intensive50	2200	2250	2.75E+14	1.96E+12	2.93E+14	3.32E+13	8.19E+12	6.14E+15	21.0E+14
6	Intensive100	2250	2110	2.75E+14	1.96E+12	5.85E+14	3.32E+13	8.19E+12	6.41E+15	22.4E+14
7										

Sammary output-input emergies

Source: Mwambo et al. (2020, 2021)

5.1.2 Phase 2: Applying data envelopment analysis (DEA)

iv. Download and install a DEA model

Next, you download and install the open-source data envelopment analysis (OSDEA) model – from https://opensourcedea.org/download-osdea-gui/. This will lead to the homepage (Figure 2).

Depending on the operating system of your computer, download and install the OSDEA model that is appropriate with your computer by clicking and selecting from the OSDEA GUI button (Figure 3).

After downloading and installing OSDEA, click on the executable Java Archive (JAR) file (Figure 4). This will enable the graphical user interface (GUI) of OSDEA to be displayed (Figure 5). This will provide you the means to navigate and manipulate the OSDEA model.

v. Import data and configure the OSDEA model

Next, you configure the OSDEA model by doing the following:

- *Import the summary of outputs-inputs emergies*
  Click on the import button (Figure 6), to import the summary of outputs-inputs emergies of the DMUs which you had earlier created in Section 5.1.1 and step (iii) above.

- *Configure the OSDEA model*
  Configure the OSDEA model by clicking and selecting the appropriate options from the dropdown button provided on your displayed GUI of OSDEA model. You may select Charnes Cooper Rhodes input-oriented model (CCR_I) or Charnes Cooper Rhodes output-oriented model (CCR_O); this step will help to configure DEA. While the input-oriented model (CCR_I) minimizes the inputs to achieve a desired level of output, alternatively the output-oriented model (CCR_O) maximizes outputs while keeping input at a constant level, respectively. What both input- and output-oriented models have in common is that they both seek to maximize the outputs and minimize the inputs, in an effort to maximize the efficiency. Figure 7 provides an illustration of this step. By selecting "CCR_I" from the dropdown button; your OSDEA model will be configured to input-oriented model type and will calculate the technical efficiency and assume constants.

After you have imported the data and configured the OSDEA model correctly, the GUI will appear as illustrated in Figure 8. Your DEA model is now set to calculate the technical efficiency of the peer DMUs.

vi. Calculate the technical efficiencies of the peer DMUs

Next, click on the "Solve the DEA Problem" button on the GUI of OSDEA model to calculate the technical efficiency as illustrated in Figure 9. DEA will use the configuration that you entered and apply Pareto efficiency to select the appropriate 'weights' for the variables contained in imported data. The optimization function in DEA will assume the multiple ordinary least square regression, as stated in Equation 8. Using the imported variables, DEA will then apply Equation 2 to calculate the technical efficiency scores of the peer DMUs. Call this the relative technical efficiency (rTE).

Figure 2. The open-source data envelopment analysis model homepage

Figure 3. OSDEA GUI for download

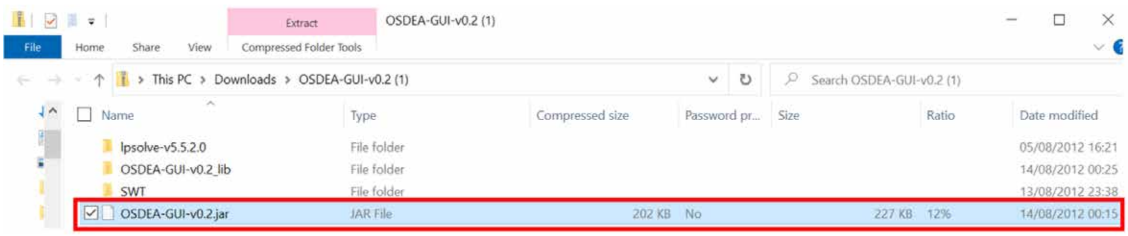

Figure 4. OSDEA-GUI executable Java archive file

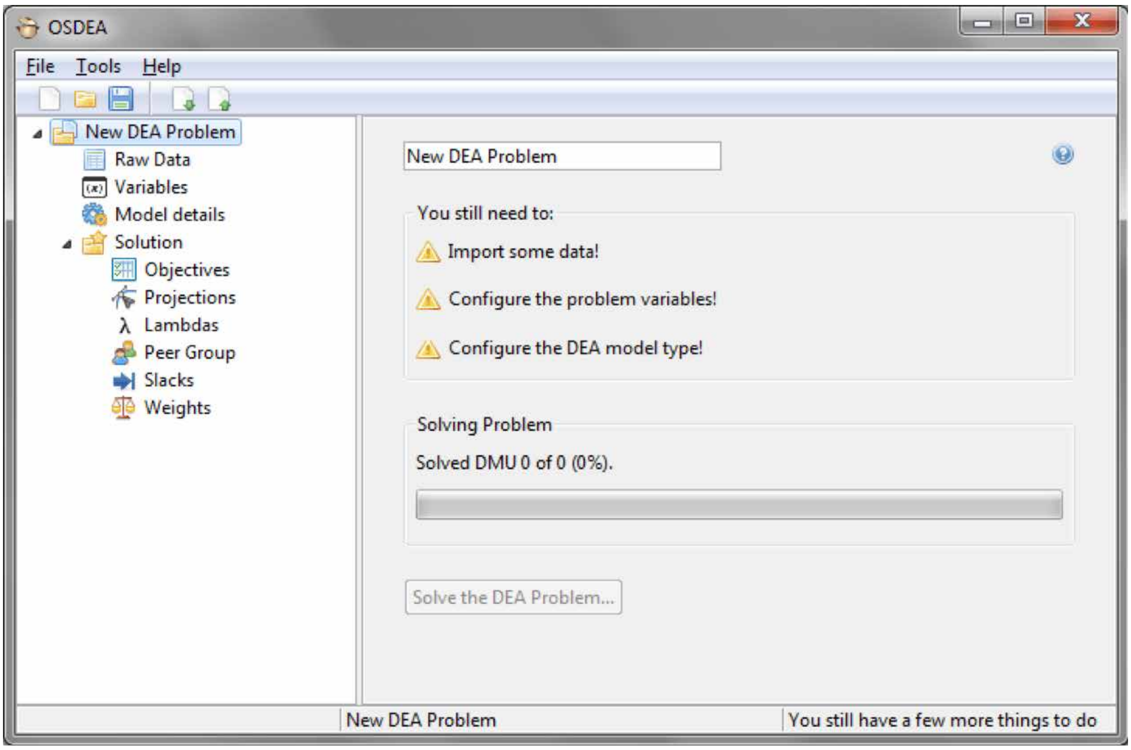

Figure 5. The graphical user interface (GUI) of an executable open-source data envelopment analysis (OSDEA) model, ready for importing output-inputs data of peer DMUs

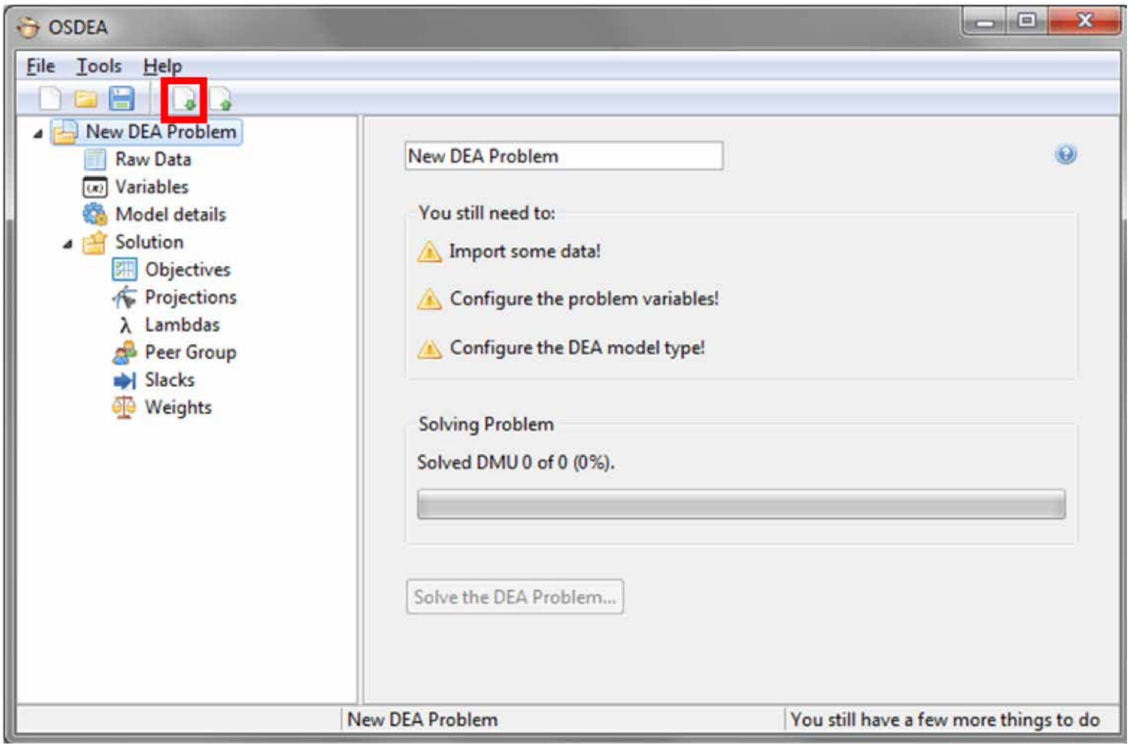

Figure 6. Import data into OSDEA

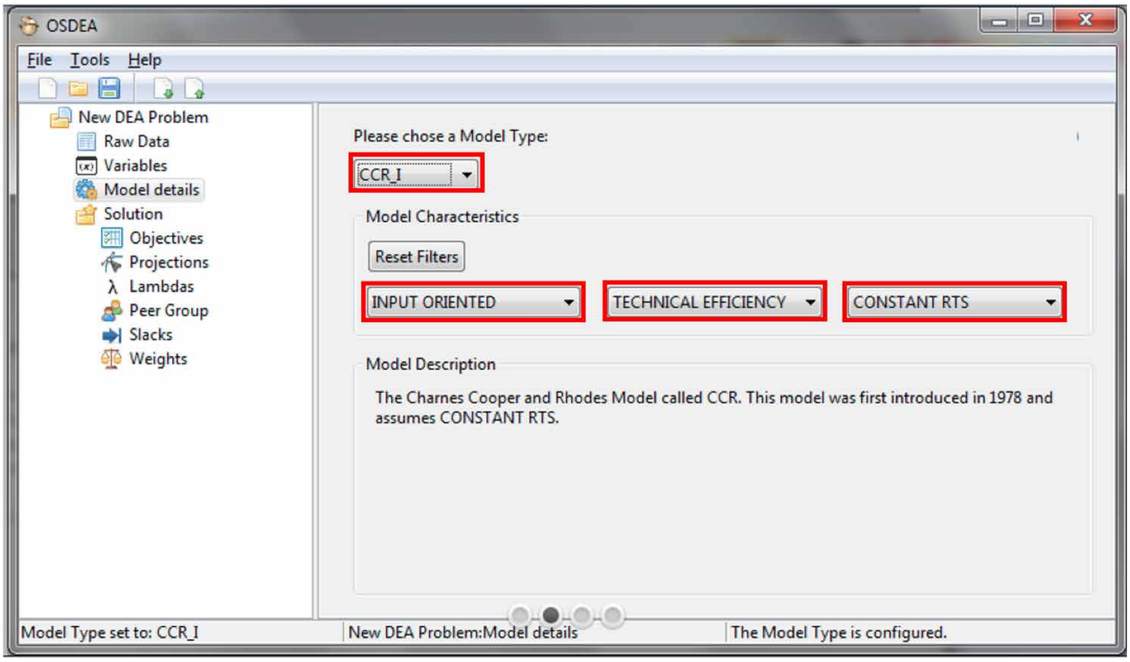

Figure 7. Configure OSDEA model

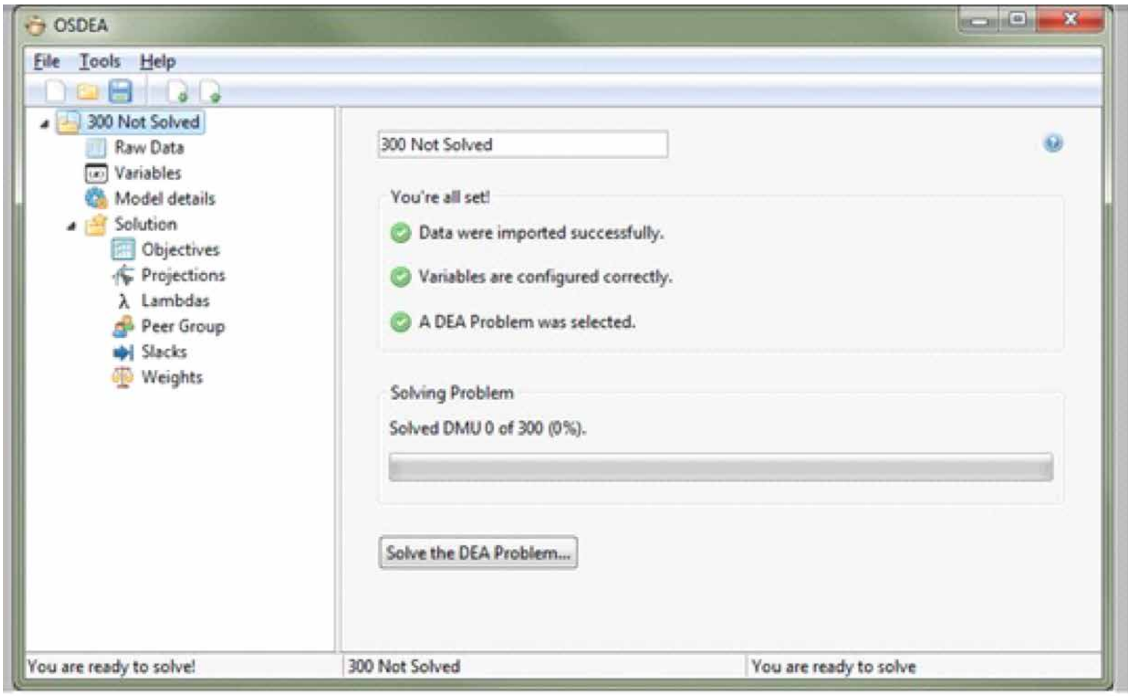

Figure 8. The graphical user interface of an executable OSDEA model, after importing data and configured DEA correctly

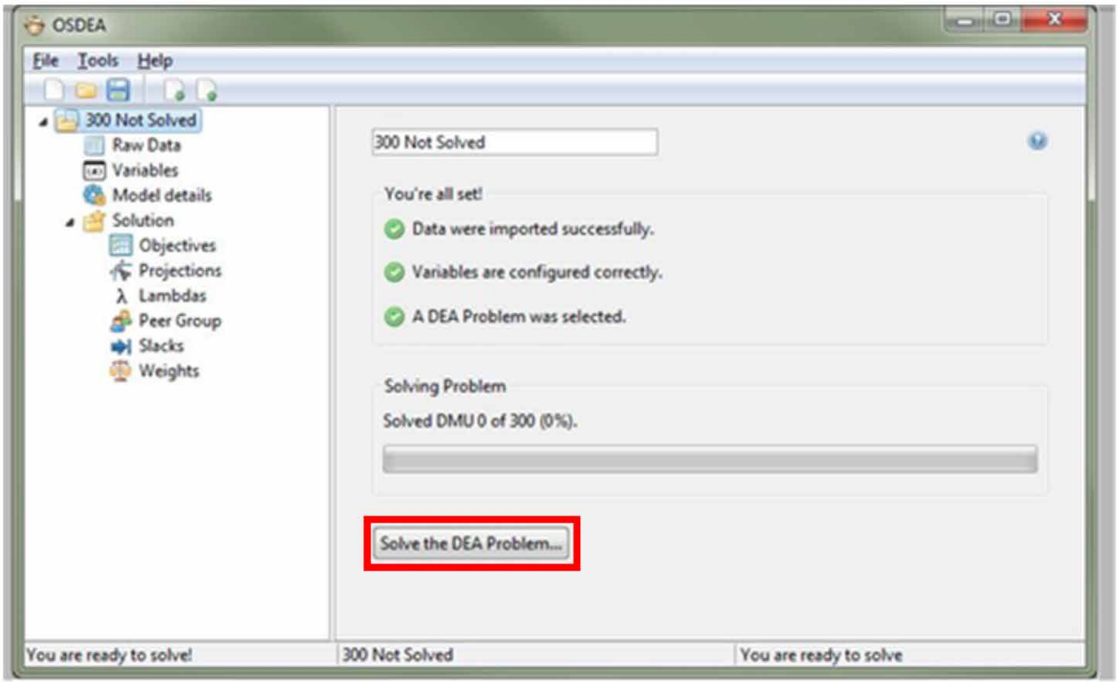

Figure 9. Calculate the relative technical efficiency in DEA

vii. Visualise and export the results

After DEA has calculated the technical efficiency, you may call this the relative technical efficiency (rTE), the GUI of OSDEA will appear as illustrated in Figure 10. The results are saved in the folder "Solution". Click on "Objectives" to visualise the calculated rTE as exemplified in Figure 11. To explore the results further, you may click on the other parameters under the "Solution" folder.

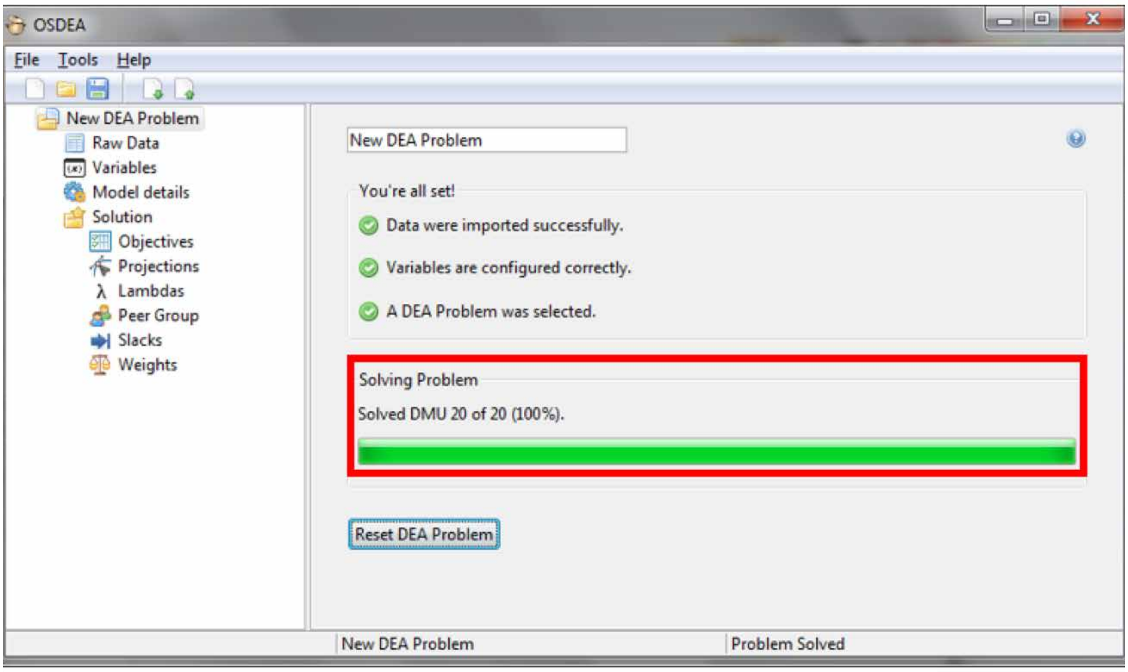

Figure 10. DEA has finished to calculate the relative technical efficiency

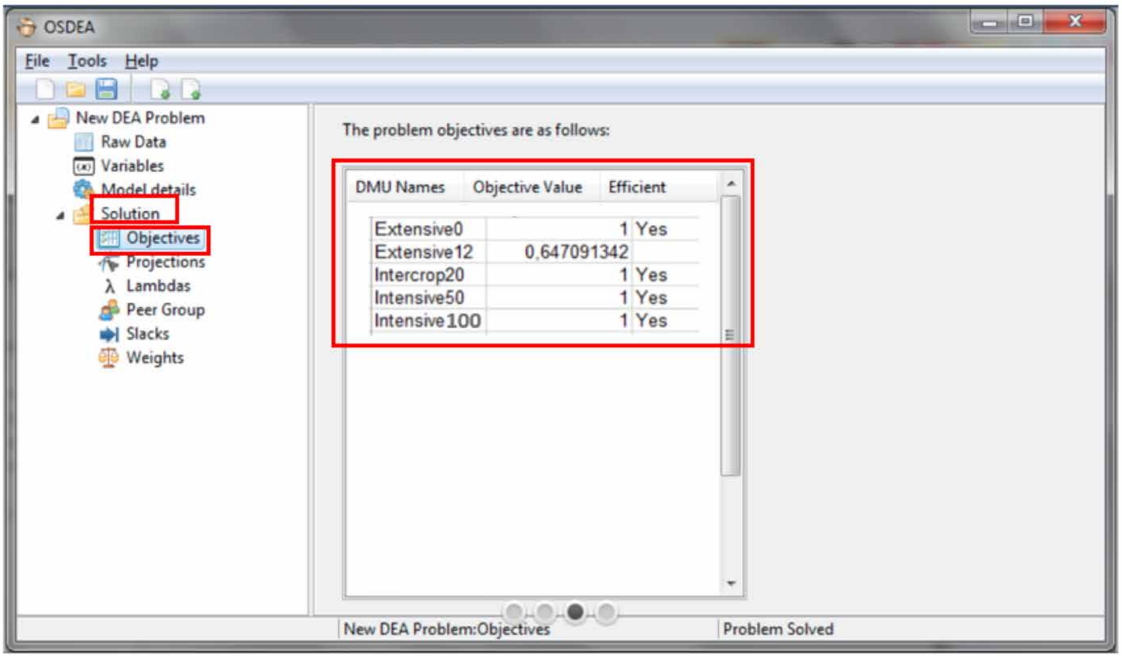

Figure 11. Empirical results of the technical efficiency (objective) displayed in OSDEA

Learning outcome check: How to implement the EM-DEA approach step-by-step

The reader has learned the following:

- ✓ To build database to assess efficiency and sustainability using EM-DEA approach.How to import and use data for analysis using the EM-DEA approach.
- ✓ How to implement the EM-DEA approach step-by-step.
- ✓ What assessment parameters are applied when using the EM-DEA approach.
- ✓ The mathematical derivations of these parameters.

6 Interpretation of assessment results

6.1 Compiling assessment results

Next, you compile the results that you obtain from the emergy-based evaluations and the DEA model into a table as illustrated in Table 11. You obtain a value for the emergy-based indicators by applying the mathematical formulae (Equations 4 – 7, 9 - 18) on the data in Excel (see Section 5.1.1). You obtain a value for the rTE by following the steps in Section 5.1.2. The technical efficiency value that you obtain with DEA is illustrated in Table 10.

Table 10. Generalized relative technical efficiency scores calculated using data envelopment analysis (DEA)

DMUs	Objective value	Efficient
DMU 1	$0 \le x \le 1$	Yes/No
DMU 2	$0 \le x \le 1$	Yes/No
DMU 3	$0 \le x \le 1$	Yes/No
DMU 4	$0 \le x \le 1$	Yes/No
DMU 5	$0 \le x \le 1$	Yes/No
DMU *n*	$0 \le x \le 1$	Yes/No

where,

DMUs = the names of peer agroforestry production systems

Objective value = estimated rTE scores of peer systems, lie in the range
i.e., a system is efficient if the Objective value, $x = 1$
a system is inefficient if the Objective value, $x < 1$

Efficient = Yes, if the Objective value, $x = 1$
= No, if the Objective value, $x < 1$

6.2 Assessment matrix

The results that you get after following the steps in Chapter 5, then, you follow the steps in Section 6.1 and compile your results into an assessment matrix. Table 11 gives an idea of the compiled results that can be obtained using EM-DEA approach. For a comparison with empirical results, see Table 12 which has identical formatting but is based on real data. The original sources of Table 12 (Mwambo et al. 2020, 2021) present EM-DEA approach results obtained while analysing manually-cultivated maize systems in Ghana.

Table 11. An illustration of an assessment matrix of the assessment results using an EM-DEA approach

Indicator	DMU 1		DMU 2		DMU 3		DMU 4		DMU n	
	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±sn *sej*/ha yr)	x.xx	xx.z	xxx	xxx	xxx	xxx	xxx	x.zy	xy.x	xx.x
UEV$_R$ (E+sn *sej*/*g*)	y.xx	y.zx	z.xx	x.yy	x.zx	x.xy	z.zx	xxx	xxx	xxx
UEV$_E$ (E±sn sej/*J*)	x.zy	xyy	xzx	zx.y	xxx	xxx	yz.x	xxx	xzx	xxx
EYR	xxx	x.zx	x.yx	y.zx	z.xx	y.xx	y.zx	x.zy	x.xy	x.yz
ELR	zx.y	x.zx	x.xx	yy.xz	z.xy	yy.zz	xz.x	xx.y	xx.z	xx.x
ESI	x.zx	x.yx	x.zx	z.yx	x.zy	xxx	x.zz	y.xx	xxx	x.xx
%REN	xx	yx	xz	yx	zx	yz	xy	xz	yy	zz
rTE	xy.x		xx.x		xx.z		xz.x		zy.x	
UEV$_{currency}$ (E±sn sej/Gh₵)	x.yx		z.xy		y.zx		x.zx		x.yz	

where,

x, y, z assessment outcome in real numbers
sn assessment outcome in real numbers written in scientific notation

Table 12. An example of assessment matrix

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	
UEV$_{currency}$ (E+12 sej/Gh₵)	1.30		1.30		1.30		1.30		1.30	

Source: Mwambo et al. (2020, 2021)

6.3 Indicators and what they mean

Table 13 shows the indicators that are measured when assessing RUE and sustainability using EM-DEA approach, and their significance when interpreting the assessment results. These implications can support informed decision making.

Table 13. Indicators and what they imply

Indicator	Unit	Implications
Total emergy (U)	sej	The total environmental support that a system needs from the biosphere. The less resources a given system demands, the more efficient and sustainable a system is relative to its peer systems, because fewer resources are needed to sustain production. For example, the efficiency and sustainability with respect to total emergy of the systems from high to low, and if material resources only were considered (without L&S): *Extension0, Intercrop20, Extension12, Intensive50,* and *Intensive100*. If both material resources and contribution from the human economy were considered (with L&S): *Intercrop20, Extensive0, Extensive12, Intensive50,* and *Intensive100* (Table 7).
Unit emergy value in terms of resource use (UEV_R)	sej/g	The efficiency of a given system in terms of transforming allocated input material resources into output products. The smaller the value of UEV_R is, the more efficient that system is – fewer input resources are used to produce more output products. For example, the efficiency with respect to unit emergy value in terms of resource use of the systems from high to low, and if material resources only were considered (without L&S): *Intercrop20, Intensive50, Extension0, Intensive100* and *Extension12*. When both material resources and contribution from the human economy were considered (with L&S): *Intercrop20, Intensive50, Intensive100, Extensive0,* and *Extensive12* (Table 7).
Unit emergy value in terms of exergy use (UEV_E)	sej/J	The UEV_E is the ratio of environmental impact to economic value added in terms of exergy use. It is the measure of efficiency of a given system based on the use of the allocated input resources, expressed in terms of exergy (i.e., available energy) in the output products. The smaller the value of UEV_E is, the more efficient that system is – fewer exergy is used up to produce the given output products. For example, the efficiency with respect to unit emergy value in terms of exergy use of the systems from high to low, and if material resources only were considered (without L&S): *Intercrop20, Intensive50, Extension0, Intensive100,* and *Extension12,* and. If both material resources and contribution from the human economy were considered (with L&S): *Intercrop20, Intensive50, Intensive100, Extensive0,* and *Extensive12* (Table 7).
Emergy yield ratio (EYR)	unit less, i.e., ratio	The EYR is the reliance on local resources. It is the ratio of the total emergy (local and imported) driving a production process or system compared to the emergy imported. This ratio is a measure of the potential contribution of the process to the main economy, due to the exploitation of local resources. A greater EYR value implies that a given system is reliant on local resources. A system which is reliant on local resources will be more resilient compared to a system reliant on resources imported from outside a system. For example, the sustainability with respect to EYR of the systems from high to low, and if material resources only were considered (without L&S): *Extension0, Intercrop20, Extension12, Intensive50,* and *Intensive100*. If both material resources and contribution from the human economy are considered (with L&S): *Intercrop20, Extensive0, Extensive12, Intensive50,* and *Intensive100*.

continued on next page

Table 13. Continued

Indicator	Unit	Implications
Environmental loading ratio (ELR)	unit less, i.e., ratio	The ELR is the ratio of non-renewable and imported emergy use to renewable emergy use. This indicator measures the pressure of a transformation process on the environment, and can be considered a measure of ecosystem stress due to a production or transformation activity. The ELR signifies the distance from equilibrium, i.e., excess pressure from outside the system. For example, the sustainability with respect to ELR of the systems from high to low, and if material resources only were considered (without L&S): *Extension0, Intercrop20, Extension12, Intensive50*, and *Intensive100*. If both material resources and contribution from the human economy are considered (with L&S): *Intercrop20, Extensive0, Extensive12, Intensive50*, and *Intensive100*.
Emergy sustainability index (ESI)	unit less, i.e., ratio	The ESI is the ratio of the EYR to the ELR. It measures the potential contribution of a resource or process to the economy, per unit of environmental loading. The ESI highlights environmental sustainability i.e., higher yield per unit of environmental loading. The greater the ESI, the better the sustainability of a given system. For example, the sustainability with respect to ESI of the systems from high to low, and if material resources only were considered (without L&S): *Extension0, Intercrop20, Extension12, Intensive50*, and *Intensive100*. If both material resources and contribution from the human economy are considered (with L&S): *Intercrop20, Extensive0, Extensive12, Intensive50*, and *Intensive100*.
Percentage renewability (%REN)	percent	The % REN is the ratio of renewable emergy to total emergy use, in other words, the fraction of the product which originated from renewable input resources. Greater %REN signifies that a product was produced using more renewable resources, and thus points to more sustainable systems. In the long term, only processes with high %REN will be sustainable. For example, the sustainability with respect to %REN of the systems from high to low, and if material resources only were considered (without L&S): *Extension0, Intercrop20, Extension12, Intensive50*, and *Intensive100*. If both material resources and contribution from the human economy are considered (with L&S): *Intercrop20, Extensive0, Extensive12, Intensive50*, and *Intensive100*.
Relative technical efficiency (rTE)	scalar, i.e., ratio	The rTE is the scalar indicator that expresses the performance of a system relative to its peers. It is therefore the proxy indicator for expressing the relative sustainability. For example, *Extension0, Intercrop20, Intensive50*, and *Intensive100* were equally efficient and more efficient at converting input resources into outputs compared with *Extension12* which was only 64.7 as good as the other systems.
Unit emergy value to currency, i.e., emergy to money (UEV_c)	sej/ currency	This is the emergy to money ratio. It is the amount of economic activity that can be supported by a given emergy flow or storage in a given country and given year. The UEV_c indicates the buying power of money in the given economy. The UEV_c is also a used as an estimator of the average value of human service.

Overall, if all the indicators are considered under the two situations of resource use accounting i.e., input material resources only as well as material resources and contribution from the human economy, *Intercrop20* emerges as the most efficient and sustainable system comparatively. It provides the most benefits such as outputs (grain yield) including other benefits (e.g., reduced soil erosion) at the least environmental costs i.e., inputs resources. In this light, *Intensive50* was the runner-up system. More so, *Extensive12* was less competitive in converting inputs into outputs, while *Intensive100* was the most demanding in terms of input material resources when compared with the other systems.

In general, the peer systems are called the decision making units (DMUs) in data envelopment analysis (DEA). The process of resource accounting was on the basis of emergy accounting. The combination of both emergy accounting and DEA methodologies to form the emergy-data envelopment (EM-DEA) approach is innovative for the assessment of efficiency and sustainability of peer systems, which you may want to analyse and compare. This provides a decision maker the means to quantify diverse inputs and outputs of peer production systems, as well as the opportunity to compare multiple systems in terms of their productivity and impact on the environment. With such information, a decision maker can make smart decisions. For example, considering optimal efficiency and long-term sustainability as the goal of a decision maker, *Intercrop20* and *Intensive50* would be considered the benchmark systems for low-input (e.g. *Extensive0*, *Extensive12*) and high-input (e.g. *Intensive100*) categories of maize production systems, respectively.

Learning outcome check: Interpreting and presenting assessment outcomes.

The reader has learned the following:

- ✓ How to logically present results obtained using the EM-DEA approach.
- ✓ How to interpret the assessment outcomes obtained using the EM-DEA approach.
- ✓ How to derive information from obtained results.
- ✓ How to use this information to guide decision making towards a specific goal.

7 User support

7.1 Toolbox

The following links provide access to helpful online resources for users applying emergy for environmental and economic accounting. These include an accessible repository at the Center for Environmental Policy, University of Florida: https://cep.ees.ufl.edu/emergy/index.shtml, from where a user can access various online resources, as illustrated in Figure 12.

Figure 12. Illustration of how to access online resources via the Center for Environmental Policy repository

From here, users have access to various resources, including:

i. Symbols and energy systems language: https://cep.ees.ufl.edu/emergy/resources/symbols_diagrams.shtml. https://www.emergysociety.com/esl-symbols/, (for symbols accessible at the emergy society).
ii. The national environmental accounting database (NEAD): https://cep.ees.ufl.edu/emergy/nead.shtml.

To access the NEAD, select the country and year of interest from the drop-down arrows, as illustrated in Figure 13.

i. Unit Emergy Values (UEVs) https://cep.ees.ufl.edu/nead/data.php#
ii. To access UEV resources, select the country and year of interest using the drop-down arrows, as illustrated in Figure 14.
iii. Open-source data envelopment analysis (OSDEA) model, which is downloadable using the following link: https://opensourcedea.org/dea/.

Figure 13. Illustration of how to access the national environmental accounting database (NEAD)

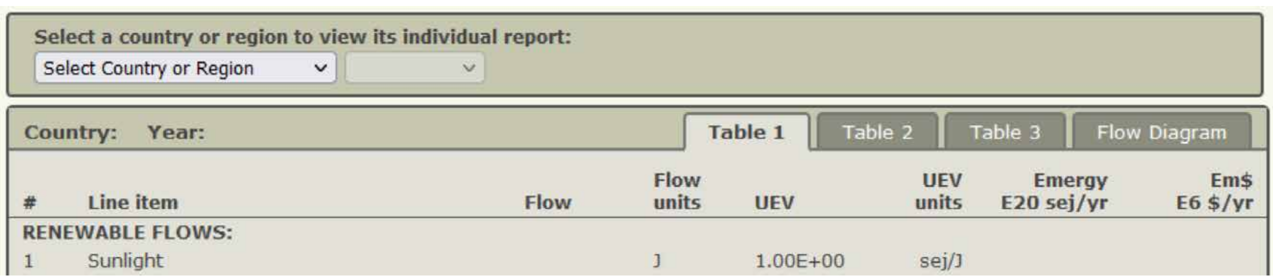

Figure 14. Illustration of how to access unit emergy value (UEV) resources

7.2 Further reading

Empirical studies demonstrate practical applications of the EM-DEA approach. The materials for recommended reading are not part of this handbook, however they can be a helpful source of extra support in familiarizing users with the EM-DEA approach. Users can develop hands-on experience by using empirical data of their choice, while using the supplementary material as an exemplary guide during the learning process. Here is a list of online resources that can support users to deepen their understanding of the approach and possible applications.

i. Mwambo and Fürst (2019) provides a background of the EM-DEA approach: https://doi.org/10.5890/JEAM.2019.03.003,
ii. Mwambo (2020) provides an example primary data on resource use in a small scale maize production system in which farm operations are manual: https://daten.zef.de/#/metadata/9831985d-1e57-44ba-8e5a-b48af5fc3bb5,
iii. Mwambo (2021a) which provides an example of emergy analysis for maize production in Ghana: https://daten.zef.de/#/metadata/0b40d479-d6dd-41e0-abd9-cc7e8e2a4240,
iv. Using empirical studies to demonstrate practical applications of the EM-DEA approach: https://www.cifor.org/knowledge/author/mwambo-f-m/.

7.3 How the EM-DEA approach can contribute to CIFOR-ICRAF's work?

Application of the EM-DEA approach can support CIFOR-ICRAF to address five global challenges as outlined in the CIFOR-ICRAF Strategy for 2020–2030[5]:

i. Deforestation and biodiversity loss
ii. A climate in crisis
iii. Transforming food systems
iv. Unsustainable supply and value chains
v. Extreme inequality

While these challenges interact to produce complex and aggravated impacts, it is evident that agriculture and logging are the principal drivers of deforestation, biodiversity loss and climate change[6]. Unsustainable agricultural land use and inefficient use of bioresources that are produced in agriculture add to food insecurity through land degradation and food waste. Meanwhile unrealistic valuing of ecosystems goods adds to unsustainable supply, and inefficiencies in the value chain is manifested as waste and pollution in systems. Looking at the agricultural and forestry sectors – where most of the world's poor are employed – low productivity and unrealistic valuing of agricultural and forestry commodities could add to unfair income earning potential by the poor employed in these sectors[4].

Applications of the EM-DEA approach in agricultural, forestry or agroforestry could produce information which may contribute to CIFOR-ICRAF's work. In particular, to make informed decisions concerning land use in certain communities. Detailed environmental accounting of land use systems could be a basis for land use planning. Detailed resource accounting i.e., appraising the work of nature to produce ecosystem services when measured using emergy accounting could be a proxy to a more realistic valorisation of some ecosystem services such as timber and non-timber forest products (NTFPs) which at times could be difficult to monetize. This could contribute to the CIFOR-ICRAF 2020-2030 strategy.

Learning outcome check: Further support for those using the EM-DEA approach

The reader has learned about the following:

- ✓ Where to access online support material for symbols and energy systems language.
- ✓ Where to access online support material on the national environmental accounting database.
- ✓ Where to find further reading material on the EM-DEA approach.
- ✓ How the EM-DEA approach could contribute to the work of CIFOR-ICRAF.

5 https://www.cifor.org/our-work/cifor-icraf-strategy/

6 https://www.cifor-icraf.org/event/cifor-icraf-at-cop-26/

8 Conclusions

8.1 Main takeaways

This handbook provides the background concepts and theories used to develop the emergy-data envelopment analysis (EM-DEA) approach, as well as step-by-step instructions on how to use the approach to assess resource-use efficiency (RUE), energy-use efficiency (EUE) and the overall sustainability of peer ecosystems. The approach was developed by linking the emergy accounting (EMA) and data envelopment analysis (DEA) methods to form an assessment framework, before integrating the concept of eco-efficiency. While EMA's flexibility allows us to account for various input and output fluxes, DEA offers a means to compare the performance of different production systems that use similar inputs to produce similar outputs. The linking of these two methods and the integrating of eco-efficiency makes for a synergistic, detailed and holistic assessment of RUE, EUE and overall ecosystem sustainability, especially suited to agricultural, forestry and agroforestry systems. This far, the EM-DEA approach has been empirically tested and applied in agricultural systems; specifically to evaluate the environmental impacts of manually-cultivated maize systems in Africa (Mwambo et al. 2020, 2021) a study which provided detailed, quantitative assessment outcomes. In future, the EM-DEA approach could be useful to CIFOR-ICRAF in addressing global environmental challenges that involve forests, agroforest systems and people whose livelihoods depend on these systems. This handbook provides the basics to support the learning of users who may want to apply the EM-DEA approach to analyse forestry and agroforestry systems.

8.2 Closing remarks

Given that improved reporting is frequently called for, it is essential to explore alternative methods and approaches to obtaining detailed accounting of material and energy flows. The EM-DEA approach offers a flexible, complete and holistic approach for assessing RUE, EUE and sustainability of forestry and agroforestry systems. Organizations and sectors that take stock and make key improvements now will gain a competitive advantage in the future. As well as improving environmental outcomes, exploring the EM-DEA approach in the forestry and agroforestry sectors could offer an opportunity to build back better.

Learning outcome check: The EM-DEA approach as an innovative tool for assessing

- ✓ RUE, EUE and the sustainability of ecosystems.
- ✓ What are the basic concepts and theories that have been used to frame the EM-DEA approach.
- ✓ How to curate data for analysis using the EM-DEA approach.
- ✓ How to implement the EM-DEA approach step-by-step.
- ✓ How to compile evaluation outcomes to present results logically.
- ✓ How to interpret results in non-technical language to support decision-making processes.
- ✓ Where to find recommended supplementary reading materials as additional support.
- ✓ How to use this handbook and supplementary materials to get a hands-on-experience of the EM-DEA approach.
- ✓ A highlight of how EM-DEA approach could be applied to do environmental accounting, and how this could contribute to the work of CIFOR-ICRAF.

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DOI: 10.17528/cifor-icraf/008793

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Emergy-Data Envelopment Analysis (EM-DEA) is a methodological approach for achieving complete environmental-economic accounting of different production systems. In an age when resources are scarcer than ever before, and the environmental impact of humanly designed systems of production is a major concern when deciding which system could better contribute to human and economic development without compromising the future of the global environment, using a reliable method for the comparative assessment of the efficiency and sustainability of different production systems is critical when making smart decisions. This handbook provides a step-by-step instruction to help users apply the EM-DEA approach to simultaneously assess the resource and energy use efficiencies, and sustainability of agricultural and forestry ecosystems as a whole. This approach was developed to address the lack of a singular method to assess complete environmental accounting and compare the sustainability performance of agro-ecosystems. The EM-DEA approach does so by combining emergy analysis (EMA) and data envelopment analysis (DEA) methods. By offering flexibility to account for various natural, human and economic resources such as land or input contributions from farm animals, it provides a means to do a comprehensive environmental accounting throughout the lifetime of agricultural and forestry systems. This approach was empirically tested with a comparative analysis of five maize production systems in Ghana, Africa. The results demonstrated that the application of the EM-DEA approach leads to complete environmental-economic accounting. Thus, EM-DEA is an innovative approach that could be used to support decision making when comparing different production systems as a whole.

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CIFOR-ICRAF is the world's leader on harnessing the power of trees, forests and agroforestry landscapes to address the most pressing global challenges of our time – biodiversity loss, climate change, food security, livelihoods and inequity. The Center for International Forestry Research (CIFOR) and World Agroforestry (ICRAF) merged in 2019. CIFOR and ICRAF are CGIAR Research Centers.

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