Food and Biogas Production in a Ghanaian Village – Results and New Perspectives on Labor UEVs

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ABSTRACT

Integrated food and energy production based on small-scale, semi-mechanized farming in rural Ghana was studied in a context of reducing dependence on purchased materials, particularly inorganic fertilizer, petrochemicals, diesel and wood fuel. The aim of the study was to evaluate two food and energy-for-cooking production systems, the current and a modeled, suggested future system. The current system is comprised of a maize-bean farming system with wood fuel used for cooking. The modeled system is also based on a maize-bean farming system but utilizes residue-based, local biogas production to partially substitute for wood fuel and inorganic fertilizer. Both systems produce the same amount of food products and energy carriers able to satisfy the same cooking demand (a food and cooking energy ‘basket’). Emergy accounting was used to compare resource use efficiency and composition of production inventories of the two systems.

Results indicate that there is no significant improvement in terms of resource use efficiency by changing the present provision methods (Unit Emergy Value of 4.8E05 seJ/J of food and cooking energy ‘basket’) to an integrated food and biogas practice (UEV of 5.1E05 seJ/J). A marginal but not insignificant increase in labor is associated with marginal reductions in soil carbon loss and inorganic fertilizer dependence. Large losses of harvested residue biomass are identified as being a primary cause of the minor effect of the nutrient recycling scheme.

It is suggested to use differentiated direct labor UEVs and location-specific indirect labor UEVs as alternatives to the usually used national average labor UEVs. More specific labor UEVs highlight the dependence on the resource use that is actually required to sustain labor inputs. It is shown that this change in calculation of labor UEV changes the system UEVs significantly.

INTRODUCTION

The prosperous way down (PWD) suggested by Odum and Odum (2001) presupposes a coming, radical decrease in the availability of energy and materials that we have taken for granted over the last decades. In line with arguments of a limits to growth outlook (Meadows et al. 1972, Randers 2012) and peak oil perspectives (Hirsch et al. 2005; Murphy and Hall 2011; Raina 2011; Markussen 2013)) for the functioning of the economic system, the PWD envisions a not too distant future where the supply of food and energy carriers take place under significant constraints. Adapting to such conditions implies not only international cooperation, awareness campaigns, re-shaping national energy systems, re-distribution of resources among regions of the World, national self-sufficiency measures, etc. which can be categorized top-down approaches and that are usually recommended in texts that apply a global scope as the ones just mentioned. Adapting to conditions of scarcity implies also the implementation of small-
scale solutions, local in scope, central for survival and social stability, and that may function when supply lines of critical inputs weaken or disappear entirely. The study of systems that can be expected to function when e.g. inorganic fertilizer, diesel, pesticides, wood, and embodied labor become too costly to base food and energy production on is a prelude to the development of practices that take over as the present practices are abandoned.

We study the integration of food and bioenergy production in a stockless, small-scale, semi-mechanized farming area in rural Ghana. The study compares two food and energy-for-cooking systems: The present system is designated ‘food and wood fuel’, and characterized by maize-bean farming and wood fuel for cooking. The suggested system is designated ‘food and biogas’, and characterized by maize-bean farming and biogas for cooking. The study assesses whether the use of an available residue can increase resource use efficiency. The scope of the study is food production and energy consumption of approximately seven households on approximately 45 hectares over the course of one year. The study provides Unit Emergy Values (UEVs) for each system. Furthermore, the study highlights the role labor inputs play in a low-tech, farming-based production system and suggests using differentiated, consumption-based UEVs for direct labor and location-specific UEVs for indirect labor. The effect on system UEVs of using alternative labor UEVs is calculated.

**MATERIALS**

The present system comprises a maize-bean farming system, characterized by heavy dependence on external inputs of inorganic fertilizer, pesticides and diesel and by resulting soil degradation, and is complemented by wood fuel in the shapes of firewood and charcoal from the surrounding area (Figure 1). At present, the deforestation rate in Ghana is approximately 2 percent per year (Owusu et al. 2012). The suggested system comprises integrated food and energy-for-cooking production using biogas to substitute for wood fuel and, partially, for nutrient and soil inputs in the maize-bean farming (Figure 2).

![Image of diagram showing the present means of providing food and wood fuel.](image-url)
The assessment of resource use is based on an emergy baseline of 15.8E24 seJ/year (Odum 2000). The UEVs of the outputs are calculated as joint transformities (Bastianoni and Marchettini 2000) applying a ‘full system’ perspective (Kamp and Østergård 2013) where the output is a ‘basket’ of different food products and cooking energy, constituting the two significant co-production outputs of the systems. The basket of outputs is the same for each system allowing for direct comparison. Cooking energy is calculated as the ‘useful fuel’, i.e. the energy content of the fuel multiplied with the thermal energy yield of the particular fuel in a particular fireplace. The applied thermal energy yield for firewood in a three-stone stove is 8% (Keita 1987), charcoal in a coal pot stove 28% (ibid.), and biogas in a biogas cook stove 55% (Bhattacharya and Salam 2002). Other significant assumptions used in the assessment include soil loss of 1 t SOM/year of which 570 kg is considered SOC (based on Wilhelm et al. 2007 and Lefroy and Rydberg 2003), an estimated 44% of residues are recovered, of this, 21% are lost during pre-digestion storage and a further 50% of the effluent lost during pre-application storage. Biogas potentials and recoverability fractions for specific crop residues are from Thomsen et al. (2014), Kemausuor et al. (2014) and Francis Kemausuor (personal communication), while storage loss fractions are from Emery and Mosier (2012) and Stefan Heiske and Morten Jensen (personal communication). The biogas production method is an experimental, household-scale, high-solids anaerobic digestion with an assumed conversion efficiency of 50% of biogas potential (Chanakya et al. 1995, Sune Thomsen and Stefan Heiske, personal communication).

**METHODS FOR LABOR CALCULATIONS**

The assessment is carried out using two alternative approaches to calculating the emergy of labor, one for direct labor and one for indirect labor (often referred to as ‘services’ (Ulgiati and Brown 2014). A short introduction to labor in emergy accounting is given: Resource use related to direct labor is in the foreground of the assessment, supporting labor taking place within the system boundary (in this example 45 ha, 1 year) and usually counted in time units, e.g. seJ/man-hour or seJ/year. If a UEV per time unit is not available, the practice is to use the wages paid for direct labor and a money-emergy ratio. Resource
use supporting indirect labor is imported into the system and represents labor inputs that have taken place in the labor chain upstream of the foreground or, colloquially, ‘in the background’ to provide the products and services that are purchased into the system. Indirect labor is counted in a currency, e.g. seJ/USD. Both direct and indirect labor attempt to approximate the emergy required to sustain the people doing work, providing information and controlling inputs (Ulgiati and Brown 2014). Usually a national or a global emergy-to-labor ratio is applied, e.g. for Ghana: 1.1E13 seJ/man-hour, calculated as

\[
\text{emergy-to-labor ratio (man-hours)} = \frac{\text{national emergy budget}}{\text{sum of labor hours worked per year}} \quad \text{(eq.1)}
\]

(emergy budget from NEAD (2012, data from 2000) and labor hours from own calculation (see Table A-1 note 10) or 3.1E13 seJ/USD, calculated as

\[
\text{emergy-to-labor ratio (currency)} = \frac{\text{national emergy budget}}{\text{nation's GDP}} \quad \text{(eq.2)}
\]

(NEAD 2012, data from 2000).

Occasionally there is reason to believe that the approximations of average resource use per labor input are unreasonable to apply, e.g. if the worker is poor or lives an anti-materialistic life of ‘voluntary simplicity’. Whether the poverty is by choice or not, the actual resource use per laborer can be expected to be below average. Additionally, long labor input chains obscure the location of work done and thereby the actual resource base of laborers; if much of the work happens abroad, applying the national labor UEV may over- or underestimate the actual emergy of labor. Ignoring such biases may lead to substantial deviations from the actual resource use supporting labor and, if labor is a major input, significantly influence the emergy profile. We suggest two refinements to the use of average, national labor UEVs, one for direct labor and one for indirect labor.

The first suggestion, primarily applicable for direct labor inputs accounted in time units, is to consider in more detail the actual consumption pattern of the people providing the direct labor inputs. This can be done with different degrees of detail: At the one extreme, with maximum detail, is an account of the specific consumables, including food, housing, energy carriers, and transport plus training- and leisure-related requirements for sustaining say, a family, and then dividing with either hours lived or hours formally worked to calculate emergy/hour (lived) or emergy per hour worked (referred to as man-hours). This approach is time-consuming but not undoable; efforts are undertaken in this direction using input-output tables (Rugani et al. 2012). Near the other extreme, with close to minimum detail, is the approach of 1) segregating people into e.g. three consumption groups, 2) assuming that emergy is distributed approximately as income (for which distribution data exist (UNDP 2008)), 3) estimating the amount of hours lived or worked and 4) calculating the emergy per hour (lived or worked) for each income group (Table 1). This approach has the benefit of being simple to apply and continually update. We exemplify the use of this approach in this work. An additional approach to differentiation, somewhere between the two extremes in level of detail, is to calculate based on the national emergy budget and the number of individuals on different educational levels (Odum 1988).

The second suggestion, primarily applicable for indirect labor inputs accounted in monetary units, is to consider in more detail the actual location of the indirect labor inputs. It is our experience that inputs in societal systems are rarely of entirely domestic origin. Applying a national emergy-money ratio for indirect labor inputs that can be expected to have taken place partially in another country constitutes a bias that may have significant influence on the final result. To avoid this bias we suggest to, ideally, map the labor input chain and specify how much of the final price can be associated with indirect labor in each of the countries on that chain. Such a mapping can theoretically be made with life-cycle methodology similar to the input-output modeling demonstrated by Rugani et al. (2012). Each indirect

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labor input ought then to be multiplied with its respective emergy-to-money ratio\(^1\). Or, as a second-best alternative, we suggest to apply the global emergy-to-money ratio to the sum of indirect labor inputs, assuming that a global average is applicable. The global emergy-to-money ratio is 1.7E12 seJ/USD (year 2008), calculated as (global emergy budget) / (global GDP) (Brown and Ulgiati 2011).

**RESULTS**

**Emergy of Labor**

Table 1 lists labor UEVs for Ghana computed in this study using the alternative method that allocates national emergy by income group.

**The Food Energy Systems**

A summary of the emergy evaluations of the two food-energy systems is given in Table 2 (The emergy evaluation tables for the alternatives with and without labor adjustments are given in the Appendix). Our calculations do not reveal any significant efficiency gains by integrating food and biogas production under the given circumstances (Table 2). The nutrient cycling supported by residue usage, anaerobic digestion and subsequent effluent return to fields is not able to substitute for more than approximately ten percent of soil loss and fertilizer use. Labor, when calculated with national averages for direct and indirect labor comprises more than half of total emergy.

The same comparison was carried out applying alternative UEVs for labor. Instead of 1.1E13 seJ/man-hour and 3.1E13 seJ/USD which are Ghanaian averages, we have used 3.2E12 seJ/man-hour (primarily) and 1.7E12 seJ/USD. The latter represent, respectively, a low UEV for direct labor and a global UEV for indirect labor, both of which we find are more applicable under the given circumstances. Shown in Figure 3, the alternative UEVs significantly alter the emergy profile of both studied systems. Emergy of labor is lower whereby other inputs obtain a higher relative share of the profile, e.g. local, renewable flows (R) which changes from around 20% to around 43% (Figure 3).

**Table 1.** Example of suggested approach to differentiate direct labor UEVs for three income groups. See text for explanation. Data are for Ghana (see Table A-3 notes 10 and 16).

<table>
<thead>
<tr>
<th>People</th>
<th>Income Group(^a) (share of Ghana’s emergy)</th>
<th>Labor hours (man-hours)</th>
<th>Labor UEV (^b) (seJ/man-hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poorest 20%</td>
<td>5.6%</td>
<td>2.80E09</td>
<td>3.20E12</td>
</tr>
<tr>
<td>Middle 60%</td>
<td>47.8%</td>
<td>8.40E09</td>
<td>9.10E12</td>
</tr>
<tr>
<td>Richest 20%</td>
<td>46.6%</td>
<td>2.80E09</td>
<td>2.66E13</td>
</tr>
</tbody>
</table>

\(^a\) Ghana total emergy (1.6 E23 sej/y)

\(^b\) Computed as (per cent income group x 1.6 E23 sej/y) / labor hours

\(^1\) Care must be taken to avoid double counting of indirect labor of intermediate goods. The sum of indirect labor cannot exceed the final purchasing price.

<table>
<thead>
<tr>
<th>Item (unit)</th>
<th>Food &amp; wood fuel</th>
<th>Food &amp; biogas</th>
<th>UEV (seJ/unit)</th>
<th>Ref. for UEV</th>
<th>Food &amp; wood fuel Empower (seJ/year)</th>
<th>Food &amp; biogas Empower (seJ/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local, renewable flow of rain (J)</td>
<td>3.6E+12</td>
<td>3.6E+12</td>
<td>3.1E+04</td>
<td>a</td>
<td>1.1E+17</td>
<td>1.1E+17</td>
</tr>
<tr>
<td>Soil loss (kg Corg)</td>
<td>2.5E+04</td>
<td>2.2E+04</td>
<td>1.6E+12</td>
<td>b</td>
<td>4.0E+16</td>
<td>3.5E+16</td>
</tr>
<tr>
<td>Mineral fertilizer (kg)</td>
<td>3.2E+03</td>
<td>2.9E+03</td>
<td>3.3E+12</td>
<td>c</td>
<td>1.1E+16</td>
<td>9.8E+15</td>
</tr>
<tr>
<td>Other (mix)</td>
<td>mix</td>
<td>mix</td>
<td>mix</td>
<td>various</td>
<td>3.0E+16</td>
<td>1.6E+16</td>
</tr>
<tr>
<td>Direct labor (man-hours)</td>
<td>1.8E+04</td>
<td>2.1E+04</td>
<td>1.1E+13</td>
<td>d</td>
<td>2.1E+17</td>
<td>2.4E+17</td>
</tr>
<tr>
<td>Indirect labor (USD)</td>
<td>4.8E+03</td>
<td>5.5E+03</td>
<td>3.1E+13</td>
<td>e</td>
<td>1.5E+17</td>
<td>1.7E+17</td>
</tr>
<tr>
<td>Total energy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.5E+17</td>
<td>5.8E+17</td>
</tr>
</tbody>
</table>

**Figure 3.** Emergy summaries of two comparisons between food and energy production systems. On the left, the assessments are based on national, average UEVs for labor. On the right, the assessments are based on differentiated, direct labor UEVs and a global, indirect labor UEV.

With alternative UEVs for labor, UEVs for the basket of food and cooking energy become 2.3E05 seJ/J and 2.2E05 seJ/J for the respective systems. The slight difference in outcome of the comparison between the two systems is due to that direct labor plays a smaller role since the actual resource use to sustain poor laborers is considered to be lower than the average. Also, indirect labor plays a smaller role since the global economy is less resource intensive than the Ghanaian, i.e. it takes less emergy to sustain, train, transport, etc. an average global laborer than to sustain etc. an average Ghanaian laborer.

**DISCUSSION**

Under the perceived conditions and with the used assumptions, there appears to be no significant efficiency gains (5.1E05 seJ compared to 4.8E05 seJ or 2.2E05 seJ compared to 2.3E05 seJ) nor any increase in %R (19% compared to 20% or 44% compared to 43%) from replacing wood fuel use with biogas based on agricultural residues. A qualitative change, however, is associated with basing cooking
energy on a resource under own control. The findings lead to three suggestions on improvement: 1) Due to the significant labor inputs related to recovering agricultural residues, it may be possible to increase efficiency by including livestock in the system. Partially corralled livestock may play an important role in fertilizing the soil and in concentrating biomass for use as feedstock in biogas plants. 2) Utilize selected biomasses only (e.g. the processing residues and not the field-based residues) to reduce time for residue harvesting/recovery, 3) Planting trees locally, specifically for firewood in an agro-forestry approach and thus continue using wood fuel.

Labor input often constitutes a substantial part of total emergy and it is essential to estimate it in the best way. If there is reason to believe that a significant part of direct labor inputs is poorly represented by the national, average emergy-to-labor UEV, differentiating UEVs according to income level is an option. The calculation of consumption-based UEVs for different income groups appears more straightforward than calculating UEVs for different levels of training (as in Odum 1988) and can therefore be considered as a simple alternative. If there is reason to believe that a significant part of indirect labor is located in countries or regions with a more or less resource intensive economy than the country in which a study takes place, adjusting for this is recommendable. This can be done by allocating indirect labor inputs according to origin and multiplying each allocation with the country-(or region-) specific labor UEV. Additionally, indirect labor inputs can also be allocated according to income level in the respective countries. If a breakdown of indirect labor inputs by countries is considered impractical, a second-best alternative is to use a global emergy-to-money ratio. Developments in labor accounting in Emergy Assessment along these lines were studied recently by Kamp et al. (2016).

Improved statistical sources may support the development of a more detailed database of imports to be used in emergy assessments. A global mass flow analysis has recently been established in the CREEA.EU project, based on multi-regional, environmentally extended input-output tables (Tukker et al. 2014). Access to data that reveals the origin of imported goods would render possible the ability to maintain the emergy profile of imports, e.g. with respect to %R (Wright and Østergård 2014). Since money flows are included in the data sets it enables assigning the emergy of labor for specific, traded goods as they move from one country to another in global supply chains. This would facilitate an important improvement from the current view of all imports being based on non-renewable energy and having the same indirect labor UEV. The data material may also be of importance in developing further the work by Rugani et al. (2012) to specify the resource use related to consumption. An important part of this work, for emergy accounting and sustainability assessments in general, is to distinguish between direct consumption (consumables, housing, food, etc. under direct control of citizens) and indirect consumption (government administration incl. pollution control, military expenses, administration ‘overhead’, etc. not in the hands of citizens to directly affect through bottom-up approaches). Such a distinction will in theory make it possible to identify consumption patterns or life-styles that individuals may want to pursue.

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APPENDIX: EMERGY TABLES AND CALCULATION NOTES


Note | Inputs and outputs (unit) per 45 ha per year | Quantity (seJ/unit) | UEV (seJ/year) | Ref. for UEV | Empower (seJ/year) |
--- | --- | --- | --- | --- | --- |

**Biomass production**

1. Sun (J) | 2.4E+15 | 1.0E+00 | 2.4E+15 |
2. Wind (J) | 1.5E+11 | 2.5E+03 | a | 3.6E+14 |
3. Rain (J) | 3.6E+12 | 3.1E+04 | a | 1.1E+17 |
4. Soil loss (kg Corg) | 2.5E+04 | 1.6E+12 | b | 4.0E+16 |
5. Seed (kg) | 9.1E+02 | 3.1E+12 | This work | 1.1E+17 |
6. Pesticide chemicals (kg active ingredient) | 1.2E+02 | 2.5E+12 | c,d | 3.1E+14 |
7. Mineral fertilizer (kg) | 3.2E+03 | 3.3E+12 | e | 1.1E+16 |
8. Machinery (kg) | 6.2E+00 | 1.4E+13 | f,d | 8.6E+13 |
9. Diesel (L) | 8.2E+02 | 9.1E+12 | f | 7.5E+15 |
10. Direct labor (man-hours) | 1.7E+04 | 1.1E+13 | This work | 2.0E+17 |
11. Indirect labor (USD) | 4.8E+03 | 3.1E+13 | g | 1.5E+17 |

**Bioenergy production**

12. Firewood (kgdm) | 3.5E+04 | 3.1E+11 | This work | 1.1E+16 |
13. Charcoal (kg) | 2.8E+03 | 2.1E+12 | This work | 5.9E+15 |
14. Direct labor, firewood (man-hours) | 8.9E+02 | 1.1E+13 | This work | 1.0E+16 |
15. Direct labor, charcoal (man-hours) | 5.2E+01 | 1.1E+13 | This work | 6.0E+14 |
16. Indirect labor, charcoal (USD) | 1.3E+01 | 3.1E+13 | g | 4.0E+14 |

**Output**

17. Food output (kgdm) | 5.5E+04 | 3.1E+12 | 1.7E+17 |
18. Food output (kgdm), with labor | 5.5E+04 | 9.4E+12 | 5.1E+17 |
19. Food output (J NUT) | 1.0E+12 | 1.6E+05 | 1.7E+17 |
20. Food output (J NUT), with labor | 1.0E+12 | 5.0E+05 | 5.1E+17 |
21. Residue production, not recovered (kgdm) | 1.1E+05 | 1.1E+05 |
22. Useful cooking energy output (J NUT) | 9.1E+10 | 1.8E+05 | 1.6E+16 |
23. Useful cooking energy output (J NUT), with labor | 9.1E+10 | 3.0E+05 | 2.8E+16 |
24. Food and useful energy basket (J) | 1.1E+12 | 1.7E+05 | 1.9E+17 |
25. Food and useful energy basket (J), with labor | 1.1E+12 | 4.8E+05 | 5.4E+17 |

Calculation notes, Table A-1

1. **Sun (J)**
   Sunlight flow (NEAD 2012) / land area (NEAD 2012) * survey area: 1.2E21 J / 2.3E07 ha * 45 ha = 2.4E15 J.

2. **Wind (J)**
   Wind flow (NEAD 2012) / land area (NEAD 2012) * survey area: 7.5E16 J / 2.3E07 ha * 45 ha = 1.5E11 J.

3. **Rain (J)**
   Rain flow (NEAD 2009) / land area (NEAD 2012) * survey area: 1.8E18 J / 2.3E07 ha * 45 ha = 3.6E12 J.

4. **Soil loss (kg Corg)**
   Based on: SOM loss: Wilhelm et al. (2007) and Lefroy and Rydberg (2003); SOC in SOM: Cannon (2002); Energy content: Lefroy and Rydberg (2003); SOC loss: 1000 kg/ha SOM loss * 56% C/SOM = 560 kg C/ha. UEV: 1.91E05 seJ/J * 56% * 1.47E07 J/kg = 1.6E12 seJ/kg.

5. **Seed (kg)**
   Survey data. Purchased seed only. UEV estimated from survey data: 2.1E17 seJ/year / 5.5E04 kg/year = 3.9E12 seJ/kg.
6 **Pesticide chemicals (kg active ingredient)**
Survey data. 123 kg active ingredient in 288 kg product. UEV: 1.48E10 seJ/g * 1.68 = 2.49E13 seJ/kg.

7 **Mineral fertilizer (kg)**
Survey data. UEV for diammonium phosphate used for NPK (20-3-10) and ammonia.

8 **Machinery (kg)**
Survey data. UEV based on mix of materials in heavy farming machinery.

9 **Diesel (L)**
Survey data for ploughing and de-husking fuel requirements.

10 **Direct labor (man-hours)**
Survey data. Sum of stated working hours of family labor and hired farm hands. UEV: Emy budget from NEAD (2012), labor hour calculation based on 20 mio. inhabitants, 57% of working age (15-64 years), 11% unemployed, 46 working weeks/year, and 30 man-hours/week (including underemployed). UEV: 1.6E23 seJ/year / (2E07 * 57% * 89% * 30 man-hours/week * 46 weeks/year) = 1.1E13 seJ/man-hour.

11 **Indirect labor (USD)**
Survey data. Costs are divided among chemicals (27%), fertilizer (21%), seed (14%), diesel (15%), and tractor hire (23%).

12 **Firewood (kg)**
Survey estimate: 45 t/year/7 households equivalent to 35 tdm/year/7 households. UEV based on Brown & Bardi (2001, Table 13), multiplied with 1.68 for energy baseline adjustment: 9963 seJ/J * 1.68 * 18.3 MJ/kgdm = 3.1E11 seJ/kgdm.

13 **Charcoal (kg)**
Survey estimate: 2.9 t/year/7 households. UEV based on an estimated wood use of 10 tons for 40 bags of 37.5 kg charcoal/bag: (1E05 kg wood * 3.1E11 seJ/kg + 7.6L fuel * 9.1E12 seJ/L) / 40*37.5 kg = 2.1E12 seJ/kg.

14 **Direct labor, firewood (man-hours)**
Survey data. Estimated avg. of 1.2 minutes/kg firewood (to walk, cut, collect, carry).

15 **Direct labor, charcoal (man-hours)**
Survey data. Estimated avg. of 1.1 minute/kg charcoal, hereof 1/8 semi-skilled labor (chainsaw operator) and 7/8 local labor (to supervise, make and tend mound, carry).

16 **Indirect labor, charcoal (USD)**
Survey data. Cost of fuel for chainsaw.

17 **Food output (kgdm)**
Survey data. UEV based on sum of lines 3-9.

18 **Food output (kgdm), with labor**
Survey data. UEV based on sum of lines 3-11.

19 **Food output (JNUT)**
Energy content of food output based on maize energy content (18.8 MJ/kgdm from INRA et al. 2012). UEV based on sum of lines 3-9.

20 **Food output (JNUT), with labor**
See note 19. UEV based on sum of lines 3-11.

21 **Residue production, not recovered (kgdm)**
Survey data, based on production figures. Residue-to-product ratios from Kemausuor et al. (2014).

22 **Useful cooking energy output (JTH)**
44 tons of firewood and 2.8 tons of charcoal (see notes 12-13). Energy content assumptions are 18.3 MJ/kg wood and 33 MJ/kg charcoal (FAO 1983). Thermal energy yield assumption is 8% and 28% for wood and charcoal, respectively (Keita 1987): 44 tons * 18.3 GJ/ton * 8% + 2.8 tons * 33 GJ/ton * 28% = 9.1E10 JTH. UEV based on sum of lines 12-13.

23 **Useful cooking energy output (JTH), with labor**
See note 22. UEV based on sum of lines 12-16.

24 **Food and useful energy basket (J)**
Basket contains 1.0E12 JNUT and 9.1E10 JTH. UEV based on sum of lines 19 and 22.

25 **Food and useful energy basket (J), with labor**
See note 24. UEV based on sum of lines 20 and 23.

<table>
<thead>
<tr>
<th>Note</th>
<th>Inputs and outputs (unit) per 45 ha per year</th>
<th>Quantity</th>
<th>UEV (seJ/unit)</th>
<th>Ref. for UEV</th>
<th>Empower (seJ/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Biomass production</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1</td>
<td>Sun (J)</td>
<td>2.4E+15</td>
<td>1.0E+00</td>
<td></td>
<td>2.4E+15</td>
</tr>
<tr>
<td>2</td>
<td>Wind (J)</td>
<td>1.5E+11</td>
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<td>3.5E+16</td>
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<tr>
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<td>Seed (kg)</td>
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<td>2.8E+15</td>
</tr>
<tr>
<td>6</td>
<td>Pesticide chemicals (kg active ingredient)</td>
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<td>2.5E+12</td>
<td>c,d</td>
<td>3.1E+14</td>
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<td>7</td>
<td>Mineral fertilizer (kg)</td>
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<td>f,d</td>
<td>8.6E+13</td>
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<td>7.5E+15</td>
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<tr>
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<td>Direct labor (man-hours)</td>
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<td>1.1E+13</td>
<td>This work</td>
<td>2.0E+17</td>
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<tr>
<td>11</td>
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<td>4.9E+14</td>
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<td>Food output (kgdm)</td>
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<tr>
<td>21</td>
<td>Food output (J NUT)</td>
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<tr>
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<tr>
<td>23</td>
<td>Biogas output (m³ CH₄)</td>
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<tr>
<td>24</td>
<td>De-gassed material recycled (kg)</td>
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<tr>
<td>25</td>
<td>Useful cooking energy output (Jm)</td>
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<tr>
<td>26</td>
<td>Food and useful energy basket (J)</td>
<td>1.1E+12</td>
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<td>1.7E+17</td>
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<tr>
<td>27</td>
<td>Food and useful energy basket (J), with labor</td>
<td>1.1E+12</td>
<td>5.1E+05</td>
<td>5.7E+17</td>
<td></td>
</tr>
</tbody>
</table>

**Calculation notes, Table A-2**
For omitted lines, see corresponding notes for Table A-1.

4 **Soil loss (kg Corg)**
Reduced carbon loss calculated as difference between two residue management practices:
'burn all' and 'burn only unrecovered residues'. Losses when burning (Heard et al. 2006): 95% (C), 100% (N), 24% (P), 35% (K). Biomass composition assumptions are from various sources, for maize C (Latshaw 1924), N, P, and K (Sawyer and Mallarino (2007). Other residues are similar to maize.

7 **Mineral fertilizer (kg)**
Reduced fertilizer requirement estimated as for reduced soil loss, see note 4. Returned nutrients equal approx. 260 kg NPK fertilizer with N being the limiting nutrient.

11 **Indirect labor (USD)**
Reduced cost is from reduced fertilizer requirement, see note 7.
12 PVC (kg)
Digestion barrels and storage tanks, 10-year life expectancy: 
((8 barrels/household * 7 households * 10 kg/barrel) + (2 tanks/household * 7 households * 35 kg))/10 years = 105 kg/year.

13 Timber (kg)
Assumed 100 kg/household for structures, 10-year life expectancy and 7 households equals 70 kg/year.

14 Water (L)
Every week, one barrel per household is emptied and refilled with 40 L slurry water and 40 L fresh water, allowing for 6 weeks retention time. 40 L/household/week * 52 weeks/year * 7 households = 14600 L/year.

15 Manure (kgdm)
An assumed 5 kg starter/booster manure is required per digestion barrel per year. Dry matter content assumed to be 10%: 5 kg/barrel * 10% kgdm/kg * 6 barrels/household * 7 households = 21 kgdm/year.

16 Diesel (L)
46 tons of biomass transported from fields and 9 tons de-gassed slurry returned to fields, 1 L diesel/ton assumed: (46+9) tons * 1 L/ton = 55 L.

17 Machinery (kg)
Estimated wear and tear of tractor is 0.05 kg/ton transported.

18 Direct labor (man-hours)
Estimated, based on survey data. UEV: see Table A-1, note 10.

19 Indirect labor (USD)
Cost of barrels, tanks, fittings, pipes, timber, carpentry, tractor hire and diesel.

22 Residue recovered (kgdm)
Recoverability fractions from Thomsen et al. (2014), Kemausuor et al. (2014) and Francis Kemausuor (personal communication). Approximately 44% of residues are assumed recovered.

23 Biogas output (m$^3$ CH$_4$)
Pre-digestion biomass loss is assumed to be 21% (Emery and Mosier 2012, Stefan Heiske and Morten Jensen, personal communication). Biogas potentials, see Thomsen et al. (2014) and Kemausuor et al. (2014). Assumed conversion efficiency is 50% of biogas potential. Assumed leakage is 10%.

24 De-gassed material recycled (kg)
De-gassed material amounts to 18 tons of which 50% is assumed lost during pre-application storage.

25 Useful cooking energy output (J$_{TH}$)
Produced gas is 5100 m$^3$ CH$_4$ of which 10% is assumed to leak. Energy content is 36 MJ/m$^3$ (Kemausuor et al. 2014) and thermal energy yield in biogas cook stove is assumed to be 55% (Bhattacharya and Salam 2002): 5100 m$^3$ CH$_4$ * 90% * 36 MJ/m$^3$ CH$_4$ * 55% = 9.1E10 J$_{TH}$.

26 Food and useful energy basket (J)
Basket contains 1.0E12 J$_{NUT}$ and 9.1E10 J$_{TH}$. UEV based on sum of lines 3-9 and 12-17.

27 Food and useful energy basket (J), with labor
See note 26. UEV based on sum of lines 3-19.

<table>
<thead>
<tr>
<th>Note</th>
<th>Inputs and outputs (unit) per 45 ha per year</th>
<th>Quantity</th>
<th>UEV (seJ/unit)</th>
<th>Ref. for UEV</th>
<th>Empower (seJ/year)</th>
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<td>Rain (J)</td>
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<td>3.1E+04</td>
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<tr>
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<td>Soil loss (kg Corg)</td>
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<td>1.6E+12</td>
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<td>4.0E+16</td>
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<td>Seed (kg)</td>
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<td>6</td>
<td>Pesticide chemicals (kg active ingredient)</td>
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<td>This work</td>
<td>8.4E+15</td>
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<tr>
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<td>Indirect labor, global UEV (USD)</td>
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<td>1.1E+16</td>
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<td>2.5E+17</td>
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</tbody>
</table>

Calculation notes, Table A-3
For omitted lines, see corresponding notes for Table A-1.

10 Direct labor, low UEV (man-hours)
Farmland laborers considered to be part of Ghana's 20% poorest. UEV based on 5.6% of emergy appropriated by poorest 20% (UNDP 2008), 20% of nation's worked hours are worked by poorest 20% (see also Table A-1, note 10 for nation's worked hours calculation). UEV: 1.6E23 seJ/year * 5.6% / (20% * (2E07 persons * 57% * 30 man-hours/week/person * 46 weeks * 89%)) = 3.2E12 seJ/man-hour.

11 Indirect labor, global UEV (USD)
UEV: Global emergy budget and global world product from Brown and Ulgiati (2011): 1.05E26 seJ/J / 6.06E13 USD/year = 1.74E12 seJ/USD.

14 Direct labor, low UEV, firewood (man-hours)
Quantity: See Table A-1, note 14. UEV: See this Table, note 10.
15 **Direct labor, low UEV, charcoal (man-hours)**
Farmhand labor is assumed 7/8 of quantity in Table A-1, line 15. UEV: See this Table, note 10.

16 **Direct labor, middle UEV, charcoal (man-hours)**
Chainsaw operator is assumed 1/8 of quantity in Table A-1, line 15 and considered to be part of Ghana's middle income fraction. UEV based on 48% of emergy appropriated by middle 60% (UNDP 2008). 60% of nation's worked hours are assumed to be worked by middle 60% (see also Table A-1, note 10 for nation's worked hours calculation). UEV: 1.6E23 seJ/year * 48% / (60% * (2E07 persons * 57% * 30 man-hours/week/person * 46 weeks * 89%)) = 9.1E12 seJ/man-hour.

17 **Indirect labor, global UEV, charcoal (USD)**
Quantity: See Table A-1, note 16. UEV: See this Table, note 11.

Calculation notes, Table A-4
For omitted lines, see corresponding notes for Table A-2, if not there, see corresponding notes for Table A-1.

10 Direct labor, low UEV (man-hours)
   Quantity: See Table A-2, line 10. UEV: See Table A-3, note 10.

11 Indirect labor, global UEV (USD)
   Quantity: See Table A-2, line 11. UEV: See Table A-3, note 11.

18 Direct labor, low UEV (man-hours)
   Quantity: See Table A-2, line 18. UEV: See Table A-3, note 10.

19 Indirect labor, global UEV (USD)
   Quantity: See Table A-2, line 19. UEV: See Table A-3, note 11.