In Ortega, E. & Ulgiati, S. (editors): Proceedings of IV Biennial International Workshop "Advances in Energy Studies". Unicamp, Campinas, SP, Brazil. June 16-19, 2004. Pages 315-321

ENERGY BALANCE METHODOLOGY AND MODELING OF SUPPLEMENTARY FORAGE PRODUCTION

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ABSTRACT

Energy balance is a vital tool to evaluate the efficiency on how production systems use energy as it relates input and output energies. There is not a standard methodology established for this determination. It is also difficult to analyze different management options because of the production systems complexity and the interactions among their variables. Therefore the purpose of this study is to supply a methodology that supports the development of a model, using a spreadsheet, and to use it to analyze the energy balance of the production systems. The model was applied in a traditional production system of maize (*Zea mays* L.) silage and a Bermuda grass (*Cynodon* spp.) haylage. The gross energy balance presented was 14.08 for the maize silage and .98 for the haylage. For the digestible energy balance, the values were of 9.12 and –0.99, respectively. The total energy demanded was 74.3% in maize silage fertilizations and 99.7% in haylage irrigation. Yield and dry matter contents were indicated in the sensitivity analysis as being the main critical variables for maize whereas in haylage it was not possible to indicate any. The best alternative scenarios for maize silage and haylage were the reductions on fertilizer concentration and irrigation use, respectively.

1. INTRODUCTION

Brazil is considered the second largest country in cattle meat producing and due to cattle raising economical importance there is a great concern about the supplementary forage supplying to the heard during dry seasons, when pasture availability and quality are reduced. To assure feed production, innovations have appeared to produce higher yields but demanding higher levels of energy inputs (Ulbanere & Ferreira [1]). As a result of this increase the costs raised as well as energy consumption (Ferraro Jr. [2]). Therefore it can be considered that a long term sustainability of production system is threatened (Stanhill [3]).

The energy balance is vital to determine the efficiency in the use of agricultural systems, quantifying input and output flows (Hetz [4]). Although authors have determined the energy balance for maize silage, there are no established methodologies for this analysis. For instance, Pimentel [5] presented the quantity for each input applied per hectare and its relative energy content per hectare in production systems in the USA. Campos et al. [6] calculated the energy contents of inputs and their total consumption per hectare of maize silage considering the average data of 14 crops growth in Brazil during 7 years.

Phipps et al [7] presented the data about human labor and fuel required per hectare of each mechanized operation to establish and harvest the maize silage. For a conventional crop, fertilizers are responsible for 59% and fuel for 16% of the total energy demand respectively. There is a 10% reduction of the total energy demand when direct drilling is adopted. The most efficient method for reducing energy is using slurry as fertilizer. No energy enclosed in the slurry was considered but some authors suggest that it can be determined through chemical elements contained in organic fertilizers.

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Hetz [4] determined a range of maize silage energy balances, considering all the inputs applied in the production systems, such as: human labor, machinery, seed, fertilizers, fuels, lubricants, irrigation, biocides and others. It was concluded that larger farmers (> 10 ha group) tend to use more energy and fuels, N and P fertilizers are responsible for most of the energy demand representing 80% of the total. According to the author, the natural fertility, the use of natural nitrate as being the N source, the high rate of photosynthesis, the use of gravitational irrigation, more human labor and animal traction are the main factors for the higher values obtained.

Phipps et al. [7], Pimentel [8], Hetz [4] and Campos et al. [6] showed the average data of the production systems surveyed by them but they did not explained the methodology to compute these data. Although fertilizers and fuel are indicated as being the main energy demanding inputs, critical variables were not indicated to measure how they influence in the energy balance.

It is difficult to analyze different scenarios of any agricultural production systems taking into consideration the amount of variables involved and the complexity of their interactions, what makes modeling use worthwhile. In order to evaluate different production systems regarding their sustainability risks, the purpose of this work was to present a method and apply it to build a model to evaluate the energy demand of forage production systems.

2. MATERIAL AND METHODS

This work was first conducted by the methodology proposal of energy balance determination. This step gave support for the development of an algorithm in order to determine the energy balance of supplementary forage production systems. The methodology proposed that gives support to the model is presented in Equations 1 to 16. The gross energy balance (EB_G) and the digestible energy balance (EB_D) both are calculated using the net energy provided by the production system, but the latter considers the TDN (Total Digestible Nutrient) level, indicating the effective energy provided for the cattle according to Eq. 1. In order to compare different production systems, the daily gross energy balance (EB_{GD}) and the daily digestible energy balance (EB_{DD}), which considers soil occupation on the energetic efficiency of the systems, were determined as shown in Eq. 2.

$$EB_{G/D} = (OE_{G/D} - IE) \div IE \qquad (1)$$

Where: EB_G = gross energy balance (Dimensionless); OE_G = gross output energy (MJ ha^{-1}); OE_D = digestible output energy (MJ ha^{-1}); IE = input energy (MJ ha^{-1}).

$$EB_{GD/DD} = EB_{G/D} \div SO \qquad (2)$$

Where: SO = days the crop occupies the soil.

2.1. Input energy calculation

The input energy was determined according to Eq. 3.

$$IE = E_I + E_{ED} + E_F + E_L + E_{IR} \qquad (3)$$

Where: E_I = energy to produce the applied inputs (MJ ha^{-1}); E_{ED} = energy expended in machinery manufacture (MJ ha^{-1}); E_F = energy consumed by machinery (MJ ha^{-1}); E_L = energy consumed by human labor (MJ ha^{-1}); E_{IR} .= energy used in irrigation (MJ ha^{-1}).

2.1.1. Energy of applied inputs (E_I)

The applied inputs were divided in two categories: solid and liquid. The energy of applied input is determined according to Eq. 4.

$E_I = E_{si} + E_{li}$ (4)
Where: E_{si} = enclosed energy in solid inputs applied in the production systems (MJ ha^{-1}); E_{li} = enclosed energy on applied pesticides (MJ ha^{-1}).

The determination of the demanded energy of solid inputs depends on the application rate and on its embodied energy. It was obtained as shown by Eq. 5. Liquid inputs, mostly herbicides and insecticides are considered and their energy content is determined as shown in Eq. 6. Energy indexes can be found Pimentel [5], Pellizi [9], Ferraro Jr [2], Hetz [4] e Fluck & Baird [10].

E_{si} = Qt x Eci (5)
Where: Qt = input applied per hectare (kg ha^{-1}); Eci = energy content (MJ kg^{-1}).

E_{li} = (Eli x i.a. x Vp x Q) ÷ Va (6)
Where: Eli = enclosed energy (MJ L^{-1}); i.a. = concentration of the active ingredient (%); Vp = used volume (L); Va = volume to be applied (L); Q = application flow (L ha^{-1}).

2.1.2. Energetic depreciation (E_{ED})

Total energy consumed through energetic depreciation, i.e., the energy demanded in the machinery manufactoring shared by the area it will work during its lifetime, is calculated according to Eq. 7.

$E_{ED} = D_{MM} + D_{PM} + D_{IR}$ (7)
Where: D_{MM} = energy depreciated in tractors and self-propelled machinery (MJ ha^{-1}); D_{PM} = energy depreciated in pulled machines and implements (MJ ha^{-1}); D_{IR} = energy depreciated in irrigation systems (MJ ha^{-1}).

2.1.2.1. Machinery

The motorized machinery presents a specific energy demand, named here as SDE*m*, and SDE*p* for pulled machinery. The D_{MM} and D_{PM} are calculated according to Eq. 8.

$D_{MM / PM}$ = (M x SDE*m*/*p*) ÷ (Oc x UL) (8)
Where: M = mass (kg); SDE*m*/*p* = specific demand of energy for motorized (*m*) or for pulled machinery (*p*) (MJ kg^{-1}); Oc = operational work capacity (ha h^{-1}); UL = lifetime (h).

2.1.2.2. Irrigation systems

The energetic depreciation of irrigation systems (D_{IR}) is calculated according to Eq. 9.

D_{IR} = (M x SDE x Ud x ND) ÷ (UL x Ai) (9)
Where: SDE = specific demand of energy (MJ kg^{-1}); Ud = daily average use (h); ND = period of irrigation (days); (h); Ai = total irrigated area by the system (ha).

2.1.3. Fuel energy (E_F)

The applied energy through fuel consumption (E_F) is determined in Eq. 10.

E_F = (Fc x fc) ÷ Oc (10)
Where: Fc = fuel consumption (L h^{-1}); fc = heating value (MJ L^{-1}).

2.1.4. Human labor (E_L)

The energy consumed by the applied human labor (E_L) is calculated as in Eq. 11

E_L = (WH x f_L) ÷ Aw (11)
Where: WH = total worked hours (h man); f_L = consumed energy by human labor (MJ h^{-1} man^{-1}); Aw = worked area (ha).

2.1.5. Irrigation (E_{IR})

The energy consumption for the irrigation system is calculated according to Eq.12.

E_{IR} = (fee x Pe x Ud x ND) ÷ Ai (12)
Where: f_{ee} = enclosed energy in electrical energy, i.e., the energy consumed to generate electrical energy; Pe = power of the motor driving the pumping system (kW); Ud = average daily use (h).

2.2. Output energy calculation

Equation 15 was utilized to determine the gross output energy (OE_G).

OE_G = {(Y x DM) x [(CP x f_{CP}) + (EE x f_{EE}) + (CF x f_{CF}) + (NFE x f_{NFE})]} ÷ 100 (13)
Where: Y = yield (kg.ha^{-1}); DM = dry matter (%); CP = crude protein content (%); f_{CP} = crude protein enclosed energy; EE = ether extract content (%); f_{EX} = ether extract enclosed energy; FB = crude fiber content (%); f_{CF} = crude fiber enclosed energy; NFE = nitrogen free extract content (%); f_{NFE} = nitrogen free extract enclosed energy. All the enclosed energies presented at Eq. 15 were referred in Crampton & Harris [11].

Equation 16 was used to determine digestible output energy (OE_D). The efficiency of providing energy to cattle through supplementary forage is implicit.

OE_D = (OE_B x TDN) ÷ 100 (16)
Where: TDN = total digestible nutrients (%).

The algorithm was used on the developed model in an electronic sheet, which was verified and validated through comparison of data obtained from references. Field determinations were conducted to fill up the data on the model considering the mechanized systems. The crops to be ensiled were submitted to bromatological analysis, for some compounds to be quantified, these are needed to determine the output energy. The flow chart of the general algorithm, based on the production systems, is shown on Figure 1.

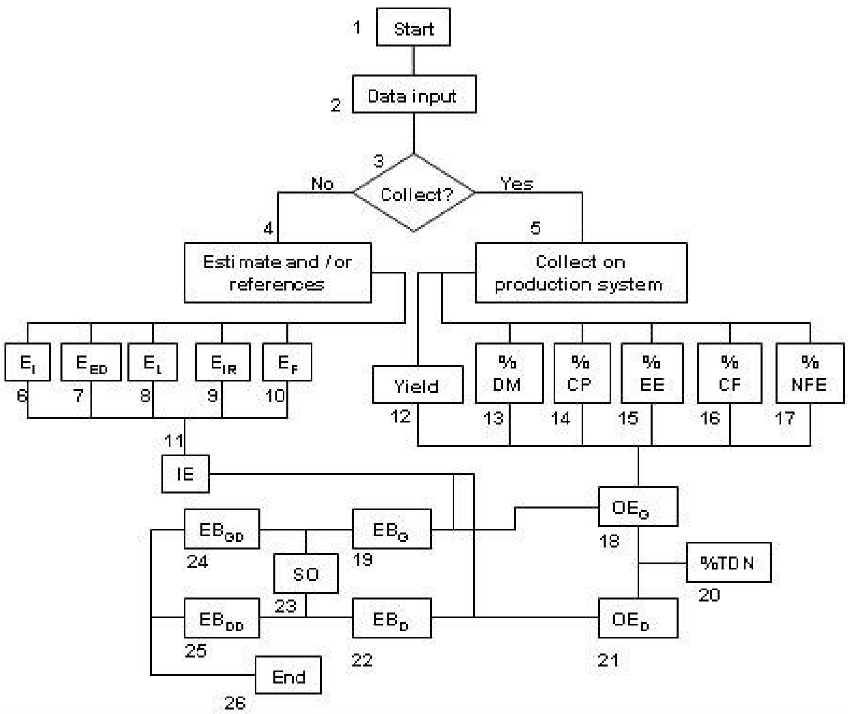

Figure 1. General flow chart of the algorithm

To run the model (1) the user provides the data regarding the production system (2) for the IE and OE to be calculated and, consequently, the energy balance (EB). The way of collecting the needed data (3) can vary, because they can either be estimated (4) or obtained by field measurements (5).

The input energy – IE (11) is calculated by summing the results of E_I (6), E_{ED} (7), E_L (8), E_{IR} (9) and E_F (10). The data concerning yield (12), dry matter content (13), crude protein (14), ether extract (15), crude fiber (16) and nitrogen free extract contents (17), allow the determination of the total available energy – OE_G (18).

The gross energy balance (19) is determined by the IE and OE_G data. To calculate the OE_D (21), the TDN (20) is used as a factor of efficiency in offering energy to cattle, since it represents the effective availability of energy. Similar to the gross energy balance (19), the digestible energy balance is determined through a relation of OE_D to IE (11). The gross and digestible energy balances are divided by the soil occupation period (23) in order to determine the daily gross (24) and daily digestible (25) energy balances. The model supplies these four energy balances indexes, the demanded energy by each mechanical operation and the total demand of the production system. Through these data distinct production systems can be compared.

The present model was used to evaluate two distinct production systems: maize silage, and Bermuda grass haylage. A sensitivity analysis was performed enabling the determination of the critical variables. The original value of each analyzed variable was increased 10%, and the new energy balance obtained was compared to the original. Afterwards, the analyses of new scenarios were proposed to each production system.

3. RESULTS AND DISCUSSION

For the maize silage production system the IE was 18732 MJ ha^{-1}, the OE_G 282503 MJ ha^{-1}, and OE_D 189644 MJ ha^{-1} (TDN = 67%), so the EB_G was 14.1 and the EB_D 9.1. For the EB_{GD} and EB_{DD} were 0.087 and 0.057, respectively. Fertilizers were responsible for 73.4% of the total demand, due to the high level of their enclosed energy.

The production of Bermuda grass haylage had a EB_G of – 0.98, consuming 198% of the OE_G supplied by this system to the growth of the crop. The IE of this system was 951997 MJ ha^{-1}, the OE_G was 16132 MJ ha^{-1} and the OE_D was 9870 MJ ha^{-1} (TDN = 61%), resulting in an EB_D of – 0.99. The EB_{GD} and EB_{DD} were both –0.022, because of the discrepancy between input and output energies. Irrigation demanded 99.7% of the IE. The highest energy demanded in maize silage production was the fertilizer application and for the Bermuda grass haylage was the use of the irrigation system use.

The maize silage production system presented a positive energy balance (sustainable), unlike the Bermuda grass haylage. Although these results do not show evidence of sustainability when considering the energy availability, it must be emphasized that only one of the annual cycles of Bermuda grass was analyzed during winter time, when yield decreases and the need of irrigation increases. Data were collected in this way because it did not seem fair to present mean energy balance, since summer and winter cycles have distinct duration. To determine the energy balance of other cycles it is only necessary to adjust the data that really differ, like the use of irrigation. Fertilizer spreading, pesticide spraying, fuel consumption and machinery efficiency of the evaluated system are the same along the cycles.

Despite the worse performance in making energy available of the Bermuda grass haylage comparing to maize silage, it is realized that energy is not the only role of supplementary forage, since there are other nutritional components, such as protein. Bermuda grass haylage contained 15.1% of crude protein while maize silage contained just 5.1%.

The results provided by the model are located among data from references, as shown in Figure 2. The validation of the Bermuda grass haylage data supplied by the model could not be done because there were no references about input and output energies for this sort of supplementary forage.

Phipps et al. (1976) presented data for the conventional method (a), direct drilling (b) and the use of slurry (c) as fertilizer. Pimentel (1984) presented data in the USA, while Campos et al. (1998) presented for 14 crops grown in Brazil along 7 years. Hetz (1992) determined the range of maize silage energy balances, from 11.6 (a) to 16.5 (b) analyzing 15 replications to areas smaller than 10 ha, and 9 to areas bigger than 10 ha in Chile. All the original energy balance data were reduced to 1 unit of the original value since the way of determining the energy balance (output/input) is different of the adopted one in the present work as shown in Eq. 1.

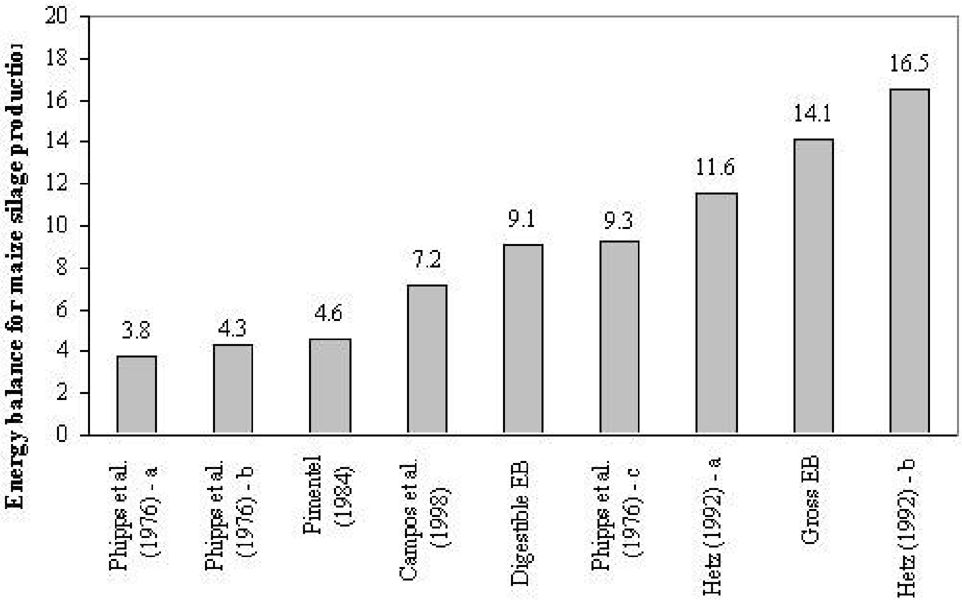

Figure 2. Comparison of energy balances of maize silage production from different sources

Since soil occupation is the denominator of the daily rates, it is the most negative influence, -8.05% for EB_{GD} and -8.77% for EB_{DD}. Due to the high enclosed energy, fertilization appears to be the main constraint for the decreasing of EB_G (-4.90%) and EB_D (-5.04). The energy balances increased when considering the 10-% decrease of fertilizer use, considering the same level of production stabilized, which could occur through use of less concentrated types, organic fertilizers or even more effective application. It was not found any alteration in Bermuda grass haylage production system, because of the magnitude of the irrigation demand. In maize silage production system the factors that have more positive influence in the EB_G and EB_D are yield (10.72% and 11.18%), dry matter (10.72% and 11.18%) and nitrogen free extract content (6.82% and 9.77%), respectively.

Regarding the crop management alternative scenarios were proposed, providing the simulation of the energy balance in the production systems.

The scenarios proposed for the maize silage were: 1: original assumptions; 2: 10% decrease in the application of 20-00-20 formula; 3: use of a 2-row harvester-chopper, with the same operational efficiency and a 25% higher fuel consumption; 4: use of a less concentrated formula in nitrogen (15-05-10 instead of 20-00-20); 5: cycle of 120 days. On simulations, yield, dry matter and TDN contents were considered the same as the original scenario.

The scenarios proposed for Bermuda grass haylage were: 1: original assumptions; 2: 30% decrease in yield, without irrigation use; 3: crop cycle reduced from 45 to 41 days.

For the maize silage crop, the scenario that presented the highest improvement (13.3%) the use of fertilizer with less concentration in nitrogen applied on coverage. Followed by the 2-row harvester-chopper (8.9%). Scenario 3 presented the highest improvement (34.5%) for the EB_{GD} for Bermuda grass haylage production and scenario 2 provided the highest improvement (445.9%). This significant improvement allowed the production system to become sustainable (positive). The worse data of the EB_{GD} in Scenario 3 occurred because the same energy deficit was produced in a shorter period. EB_D and EB_{DD} were not evaluated by sensitivity analysis because they follow the trends of EB_G and EB_{GD}, respectively.

ACKNOWLEDGEMENT

The authors would like to thank FAPESP for the financial support of this work.

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