Energy demand in agricultural biomass production in Parana state, Brazil

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Abstract: Energy flow analysis is an interesting approach to assess and to improve sustainability of agricultural production systems, represented by the economy of energy resources and other inputs translated into energy terms. This type of analysis can complement the economic view contributing to more efficient production systems. Moreover, assessing crops with traditional food use may play an important role in energy provision. Energy efficiency tools were applied in order to determine the energy demand as well as the efficiency of the biomass production of several forage crops in mechanized systems conducted at Paraná state, Brazil. Material flow, input and output energy, energy balance, energy return over investment and embodied energy were used and identified that maize and sorghum were the crops that uses energy in the most efficient way, represented by the best results at net energy availability, profitability and embodied energy at the final product. Oat and ryegrass were the crops that presented the least efficient energy uses in the biomass production systems.

Keywords: bioenergy, energy indicators, sustainability, embodied energy

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1 Introduction

Increasing agricultural yield has intensified the use of industrial inputs such as fertilizers, pesticides, fuel and machinery. So, the demand for energy resources became more intense, especially those from fossil fuels, such as oil (Campos and Campos, 2004; Romanelli and Milan, 2010a). Analyses of energy flows allow the determination of energy consumption related to the inputs used, and the efficiency of energy use in a production process. The use of this type of analysis in agriculture allows determining steps and factors considered "energy bottleneck", such as applied fertilizers and fuel used in mechanized operations (Angelini et al., 2005; Campos et al., 2005; Tsatsarelis, 1993). Energy flows analysis enables the use of a management decision making based on the economy of energy resources, which is reflected in economic and environmental results, such as saving financial resources and decreasing emission of the greenhouse gases (Cavalett and Ortega, 2010; Musango and Brent, 2011; Orecchini, 2011). Regarding energy supply and its use, Brazil is a country with a unique energy matrix. Biomass sources (sugarcane and

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eucalyptus) represent more than 40% of the total amount of energy produced all over the country (EPE, 2012). Worldwide, on the other hand, the use of biofuels and wastes accounts for only 10% of the total primary energy production (IEA, 2011). Concerning sustainable development in agriculture, Brazil, with its large territory and favorable climate for agricultural production, could play an important role in supporting it. This country has been appointed concerning the importance of having a change in the strategy of its agricultural production, which has a continued expansion in natural ecosystems for productivity growth in existing agricultural land with minimal environmental degradation possible (Martinelli et al., 2010). Paraná is a state with great emphasis when it comes to the sustainable agriculture production. It is one of the Brazilian states with one of the highest index of crop production (such as maize, barley, oats, wheat and beans). The state represents the highest maize and barley yields, and the second highest oat yields at national level (SEAB, 2012), and it is considered the second biggest state in cereal production, behind Mato Grosso state (CONAB, 2012).

The focus on rational use of energy resources complements the economic view, and allows a more complete analysis about the use of resources, allowing decrease in energy inputs, increasing energy efficiency, without compromising the economics of crop production (Fluck and Baird, 1982; Panesar and Fluck, 1993). In this type of analysis, one can determine whether a process or system is producing greater or lesser amount of energy than it consumes, and the efficiency of this production, enabling comparison between different processes and consequently aiding in decision making.

The energy assessment of biomass production systems (even for crops traditionally used for feeding) plays two important roles. One, concerns the energy use and its efficiency in the biomass production process, representing consequent subsidy in the use of energetic resources (Assenheimer et al., 2009; Campos and Campos, 2004). The other, concerns the importance in the search of energy provision, as it was made for maize and sugarcane for ethanol in both USA and Brazil.

Using energy efficiency indicators, authors studied the energy finality in agricultural crops. By using Energy Return Over Investment (EROI), and applying it to corn ethanol production around United States, Murphy et al. (2011) reported that this production is not efficient, since the results shows that it requires more energy for production than that contained in the ethanol product. Silva et al. (2010) used indicators of the energy use efficiency (Energy Balance -EB; Energy Return Over Investment - EROI, and Energy Intensity -EI) in the evaluation of biomass as a possible bioenergy source. The used tools allowed comparison between two types of cropping systems, low and medium technology, and thus identify the best options for the production system, according to the supply and demand of the product. Angelini et al. (2005) evaluated different management practices of a grass during six years, these being fertilization, harvest time and plant density to identify the most suitable management for it as an energy crop. The conclusion was that the species in question is suitable for use as an energy crop due to its high productivity in that particular region, and favorable results for the indicators used (EB, EROI). Campos et al. (2005) applied EROI at the *Cynodon dactylon* hay production, from crop establishment to haying and storage. They concluded, through EROI value, that this process was energy favorable. With other purpose than energy use efficiency in agriculture, but also using energy efficiency indicators in energy production systems, Gagnon et al. (2009) used EROI indicator for the analysis of world oil and gas production in a time series. The indicator had their values decreased over the years, which was attributed that to the increase in drilling annual levels.

For Brown and Herendeen (1996), the basic motivation for energy flows analyzes, is to quantify the human activities and the demand for energy resources' connections, since the issue of power consumption is more important than the economic analyzes may indicate. For analyzing energy use, it is important to define the system's limits. So, one can determine the energy resource's use, coming from the materials and supplies, and also quantifies its incorporation into the final product. Consequently, one can obtain consumption and efficiency of energy use in the production process.

Considering the benefits of energy analysis in production systems and the role that energy has played as an alternative for producers, this study aimed to determine the energy demand of several biomass production systems in Paraná state, Brazil, and the process efficiency, as well, by implementing various performance indicators.

2 Material and methods

2.1 Local and data used

The data collection was made on different forage crops, all of which were conducted at Paraná state, southern region of Brazil (Figure 1). The production systems evaluated are located in Campos Gerais region (Figure 1), which presents high yields of agricultural production.

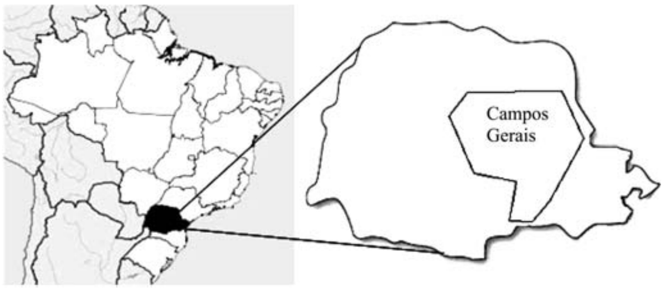

Figure 1 Campos Gerais region of Paraná state, southern region of Brazil

2.2 Evaluated crops

Data concerning applied inputs and mechanized operations characteristics for all crops were provided by Foundation ABC, which represents producers of the region who are cooperative's associated. All the crops evaluated are presented in Table 1 with their respective yields found in the region.

Table 1 Evaluated crops and related characteristics

Usual name	Scientific name	Cycle	Yield (DM) Mg ha^{-1} yr^{-1}
Maize	*Zea mays*	Annual	16.5
Black oat	*Avena strigosa*Schreb.	Annual	4.2
Ryegrass	*Lolium multiflorum*Lam.	Annual	4.5
Tifton 85	*Cynodon spp*. Cv. Tifton 85	Perennial	10.0
P. maximum (Áries, Atlas, Mombaça and Tanzânia cultivars)	*Panicum maximum*	Perennial	10.0
Millet	*Pennisetum glaucum*	Annual	6.3
Sorghum	*Sorghum bicolor*	Annual	9.0
Barley	*Hordeum vulgare*	Annual	6.0

2.3 Evaluated inputs

In all evaluated crops, since the studied region uses no-tillage system, operations from soil acidity correction (lime application) to harvest were assessed. At the following mechanized operations, limestone, manure and fertilizer distribution, spraying and harvest, the same type of implements and tractors (concerning main characteristics such as power and size) were considered. The only mechanized operation in which there is a variation in the used equipment was sowing. For maize and sorghum, it is used an eight-row planter spaced in 0.40 m. For all the other crops, it is used a 19-row planter spaced in 0.17 m. For each mechanized operation, it was determined the fuel consumption, machinery's physical depreciation and the agricultural input application. All the mechanized operations are represented by the tractor and implement used, and the applied inputs in each operation are listed in Table 2.

Table 2 Mechanized operations and inputs assessed

Operation	Tractor	Implement	Applied input
Limestone Distribution	4×2 FTA Tractor 67 kW	Limestone distributor	Limestone
Manure Distribution	4×2 FTA Tractor 82 kW	Liquid manure distributor	Manure
Sowing	[1] 4×2 FTA Tractor 67 kW [2] 4×2 FTA Tractor 82 kW	[1] Planter, 7 or 8 lines, 45 cm spaced [2] Drill, 17 to 19 lines, 17 cm spaced	Seeds
Fertilizer Distribution	4×2 FTA Tractor 67 kW	Fertilizer distributor	Fertilizers
Spraying	4×2 FTA Tractor 90 kW	Boom-type sprayer	Pesticides
Harvest	4×2 FTA Tractor 67 kW	[3] Forage harvester	-
[4] Self-propelled forage harvester			-

Note: [1] Refers to maize; [2] refers to all the other crops; [3] Refers to maize, sorghum, *P. maximum* and millet; [4] Refers to barley, oat, rye and Tifton 85.

2.4 Material flow determination

The first step is the determination of the material flow, which is a tool that proposes to quantify the materials or inputs intensity used per unit area, and which in turn undergo transformations resulting in system's output. Secondly, energy content (embodied energy) is assigned to all used inputs, and the input energy is determined. Along with the system's output energy, the energy efficiency indicators can be determined, and one can obtain a view of the energy use for biomass production more complete from the sustainable and resources use's approach.

2.4.1 Direct applied inputs

At the Material Flow determination, it is important to do an input classification concerning their use. Inputs can be directly or indirectly used. The adopted classification determines that direct inputs are those directly applied on field, being a result of agronomic prescription (Romanelli and Milan, 2010b). The inputs are measured in terms of product quantity to be used by area unit (kg ha^{-1} of fertilizer, seeds and seedlings, and l ha^{-1} of pesticides).

2.4.2 Indirectly applied inputs

The indirect input consumption can be defined as the one that helps out the phases or operations to be done, such as the use of diesel fuel, labor and machinery for the mechanized operations. These are also measured on an area basis, as determined for the directly used inputs, (l ha^{-1} of diesel, h ha^{-1} of human labor, and kg ha^{-1} of the equipment and facilities depreciation).

At the present work, it was chosen not to consider human labor, since this kind of contribution represents a very small fraction of the system's total energy demand (Boustead and Hancock, 1979; Franzese et al., 2009; Romanelli et al., 2012; Silva et al., 2010).

Machinery and facilities depreciation

The machines, equipment and facilities' use is accounted by their depreciation. In this study, only the depreciation of the used equipment in the mechanized operations (tractors, harvesters and implements) was calculated. Therefore, the depreciation can be calculated (Equation (1)).

$$MD = \frac{M}{(UL \times OFC)} \tag{1}$$

where: MD = Machinery depreciation, kg ha^{-1}; M = machinery mass, kg; UL = Machinery and implement useful lifetime, h; OFC = Operational field capacity, ha h^{-1}.

Fuel

The fuel used in the mechanized operations was determined by the model proposed by Molin and Milan (2002), due to its practicability, since it only depends on the machine power and consume factor and results to less consumption variation than the model proposed by ASAE tandard D497.4 (ASAE, 2003), as shown by Romanelli and Milan (2012) (Equation (2)).

$$FC = \frac{EP \times SC}{OFC} \tag{2}$$

where: FC = fuel consumption, l h^{-1}; EP = Gross engine power, kW; SC= Specific consumption (diesel engine factor), 0.163 kW l^{-1} h^{-1} (Molin and Milan, 2002).

2.5 Energy consumption determination

Based on inputs consumption data (machinery, fuel and inputs directly applied, all obtained by material flow) in input used per unit area, and its association with their respective energy content (embodied energy per input unit) the energy consumption or energy input system was determined (Equation (3)) (Romanelli and Milan, 2010a).

$$IE = \sum (MF \times EE \ inputs) \tag{3}$$

where: IE = Energy Input (MJ ha^{-1} yr^{-1}); MF = Material Flow (unit ha^{-1} yr^{-1}); EE = Embodied Energy in inputs (MJ unit^{-1}). The embodied energy indices of farm inputs were adopted from references (Table 3).

Table 3 Agricultural inputs energy indices

Inputs (unit)	MJ unit^{-1}	Source
N (kg)	56.3	IPT (1985)
P_2O_5 (kg)	7.5	IPT (1985)
K_2O (kg)	7.0	Lockeretz (1980)
Lime (kg)	1.7	Pimentel (1980)
Herbicide (kg)	355.6	Seabra (2008)
Insecticide (kg)	358.0	Seabra (2008)
Fungicide (kg)	115.0	Pimentel (1980)
Seeds (kg)	10.5	Pelizzi (1992)
Diesel (l)	45.7	Boustead and Hancock (1979)
Tractors (kg)	14.6	Doering III (1980)
Forage harvester (kg)	13.0	Doering III (1980)
Plow (kg)	8.6	Doering III (1980)
Disc arrow (kg)	8.3	Doering III (1980)
Planter (kg)	8.6	Doering III (1980)
Sprayer, Fertilizer distributor (kg)	7.3	Doering III (1980)
Forage and hay equipment (kg)	6.3	Doering III (1980)

2.6 Output energy determination

The energy output was calculated by two different ways: one based on the crop productivity (Equation (4)) based on the calorific value of the whole biomass, and the other one crop specific based on the crop structural composition (Equation (5)): lignin, cellulose, and hemicelluloses content of each species. Both of them demonstrate the energy availability potential.

$$OEy = Y \times CV \quad (4)$$

where: OEy = Energy output for crop yield (MJ ha^{-1} yr^{-1}); Y = Yield (Mg ha^{-1} yr^{-1}); CV = Calorific value (MJ Mg^{-1}). According to McKendry (2002a), the biomass energy content (on a dry and ash free basis) is similar to all species, in the range of 17-21 MJ kg^{-1} (for both herbaceous and woody species).

$$OEs = (LCV \times LCD) + (CCV \times CCD) + (HCV \times HCD) \quad (5)$$

where: OEs = Energy output crop specific (MJ ha^{-1} yr^{-1}); LCV = Lignin calorific value (MJ kg^{-1}); LDC = Lignin content in dry matter (kg ha^{-1} yr^{-1}); CCV = Cellulose calorific value (MJ kg^{-1}); CCD = Cellulose content in dry matter (kg ha^{-1} yr^{-1}); HCV = Hemicellulose calorific value (MJ kg^{-1}); HCD = Hemicellulose content in dry matter (kg ha^{-1} yr^{-1}). According to Santos et al. (2011), lignin, cellulose, and hemicelluloses calorific values are 20.1, 17, and 17.5 MJ kg^{-1}, respectively.

2.7 Energy use efficiency

2.7.1 Energy Balance (EB)

The energy balance is an indicator of the net energy availability per area. Romanelli and Milan (2010a) pointed it out as the available energy produced by the process or production system indicator, and it can be calculated by subtracting the used inputs by the final product (final energy output - inputs). It was also stated that this same measure also depends on the analysis limits, either related to area (MJ ha^{-1}), to time (MJ year^{-1}), or even both (MJ h^{-1} yr^{-1}). Campos and Campos (2004) stated that the energy balance aims to establish energy flows, identifying the total demand and efficiency reflected by the net gain and by the output and input relation. The EB is then calculated according to Hall, 2004 (Equation (6)).

$$EB = OE - IE \quad (6)$$

where: EB = energy balance, MJ ha^{-1}

2.7.2 Energy Return Over Investment (EROI)

EROI is an indicator of the energy production process profitability, and it is calculated by the ratio between the output energy and the input energy. Gagnon et al. (2009) pointed it out as being the ratio of energy produced required for the production process of the energy source to occur, and if the EROI is high, only a small fraction of the energy produced is needed to maintain the process. In contrast, if the EROI is low, then most of the energy produced is used to maintain the production process. The EROI is then calculated according to Hall, 2004 (Equation (7)).

$$EROI = \frac{OE}{IE} \quad (7)$$

where: $EROI$ = Energy return over on investment, profitability or energy, MJ MJ^{-1}.

2.7.3 Embodied Energy (EE)

The final product embodied or incorporated energy represents another way of determining the energy obtained by, or incorporated by, the production process. Also known as the product energy intensity, it is the relationship between the energy load obtained per unit mass of product (MJ Mg^{-1}), or an index that relates the biomass produced with the energy demanded by the production system. It represents the result of all inputs embodied energy (already reported in literature) that participated in the production process.

This indicator can then be determined according to Romanelli and Milan, (2010a) (Equation (8)).

$$EE = IE/Y \quad (8)$$

where: EE = Embodied or Incorporated Energy of the final product (dry matter), MJ Mg^{-1}.

3 Results and discussion

After calculating the Material Flow, one can associate it with their evaluated inputs respective embodied energy indices (EE) and calculate the total energy demand (IE), and determine the share of each considered input in all of the crops production system's energy demand. Table 4 shows the shares of inputs (% of total demand of each production system).

Table 4 Input participation in total energy demand in the production systems

Crop	Fertilizer /%	Pesticide /%	Limestone /%	Seed /%	Machinery /%	Diesel /%
Maize	70.1	8.4	5.6	1.8	0.3	13.8
Black oat	60.3	5.5	9.1	9.2	0.4	15.2
Ryegrass	69.7	4.6	7.5	4.7	0.3	13.1
Tifton 85	58.7	0.0	19.8	0.0	0.5	21.0
P. maximum	50.6	3.9	17.0	3.2	0.5	24.8
Millet	65.8	4.0	8.6	2.7	0.3	18.5
Sorghum	71.8	9.1	0.0	1.0	0.3	17.4
Barley	62.4	5.8	7.6	9.6	0.3	14.3

Regarding fertilizers, one can observe that in all crops, fertilizers accounts for the largest share in total system's energy consumption (more than 58% of total demand). This is due to the fertilizer's high energy content, especially nitrogen sources.

As for the pesticides applied, one can notice varied shares of energy demand between crops. For Tifton 85 grass, it was not considered the crop establishment. In sorghum crop, the involvement of pesticides in total energy consumption was the highest, due to the fact that on this crop there is high insect incidence, from sowing to harvest (Coelho et al., 2002).

As for the lime applied, in grasses (*P. maximum* cultivars and Tifton 85) it was applied 1,000 kg ha^{-1}. In all other crops (except sorghum, which was not made any lime application), it was applied 500 kg ha^{-1} of this material. The different shares in total energy demand are a result of different values of total consumption in each crop.

Regarding seeds, since it was used the same energy content to all crops (embodied energy for forage and cereal seeds), so the difference in shares of energy demand is due to the different quantities of material used, and compared with the total consumption of each culture. In Tifton 85, since it is accounted only the maintenance, no seeds were accounted.

Regarding the equipment used (tractors, implements, and harvesters) through its depreciation, energy demand represented 0.5% or less, of total energy consumption in all crops and is therefore the lowest energy demand evaluated in all the production systems.

Diesel, meanwhile, appears as the second largest share in energy demand, with contribution between 13% and 25% of total energy demand in all crops. This is due to the high system's mechanization, and it is accentuated by the fuel high energy content, and its operational use, especially in the operations with low field capacity (such as sowing and manure distribution).

Some authors reported diesel as the greatest energy demand in agricultural and forestry mechanized production systems: Campos et al., 2005, due to the haying operation; Romanelli and Milan, 2010a, due to the very low field capacity of a forestry harvester; and fertilizers applied as the second greater demand. On the other hand, fertilizers are presented as the greater energy demand in biomass production systems by several authors (Gollmann et al., 2004; Rathke and Diepenbrock, 2006; Rathke et al., 2007; Busato and Berruto, 2011) beyond the presented work here.

It should be noted that the shares (%) are relative to the total energy demand of each particular production system, therefore the values shown in Table 3 refer to different absolute values (IE of each crop).

Swine manure, applied input of manure distribution, as a biological material, appears more complex when it comes to assign itself some energetic content, since in this work nature contribution is not being considered (sun, rain, evapotranspiration). One could consider the energetic content of the main nutrients (N, P_2O_5, K_2O) in its composition, in an approach that would imply that those nutrients were "avoided" from being applied. But, through this approach, manure energy content would be high in comparison to others, since the values assigned are regarding the fertilizer's industrial processes for its production. So, since that approach wouldn't represent accurately the energy content of manure and there is not a total suited methodology for this kind of assigning, in this study it has been chosen not to consider manure embodied energy and consider the energy demand on the mechanized operation through machinery and diesel.

With energy rates associated with all evaluated inputs, one could perform the calculation of indicators IE, OE, EB, EROI and EE (Table 5). Calculations were made for all crops already indicated.

Table 5 Energy performance of the evaluated crops

Crop	IE	OEy	OEs	EB		EROI	EE
	GJ ha^{-1} yr^{-1}			GJ ha^{-1} yr^{-1}	GJ ha^{-1} day^{-1}	-	MJ kg^{-1}
Maize	14.8	313.5	150.1	135.2	0.9	10.1	0.9
Sorghum	10.1	171.0	89.0	78.9	0.7	8.9	1.1
Black oat	9.2	79.8	34.7	25.6	0.2	3.8	2.3
Ryegrass	11.1	85.5	55.0	43.9	0.3	5.0	1.9
Barley	11.0	114.0	50.1	39.2	0.3	4.6	1.8
Millet	9.7	119.7	69.8	60.1	0.5	7.2	1.5
P. maximum	11.5	190.0	130.2	118.7	0.7	11.3	1.2
Tifton 85	8.5	190.0	115.8	107.4	0.7	13.7	0.8

When analyzing IE, one can observe that maize presented the highest value, that is, it was the system in which was used the greater amount of energy, followed by *P. maximum*, ryegrass, barley, sorghum, millet, black oat, and finally Tifton 85, the crop in which was used the smaller amount of energy.

The OEy presents higher values for maize, showing that this was the crop that has the greater energy producing potential. This one is followed by *P. maximum* and Tifton 85 (both with same values), millet, barley, ryegrass, and black oat. By considering OEy, one is assuming the whole plant standard calorific values provided by thermal conversion, so, the higher the yield, the higher the OEy.

The OEs presents higher values for maize, followed by *P. maximum*, Tifton 85, sorghum, millet, ryegrass, barley, and black oat. By considering the OEs, one is assuming the calorific value content provided by thermal conversion of each species, since lignin, cellulose, and hemicelluloses contents vary between them. One can notice here that besides *P. maximum* and Tifton 85 presented equal values in OEy, in OEs they're different. This is due to the structural component's composition varying between species. In all other species the OEs values presented the same pattern as that presented in OEy. OEs presented lower values than OEy, but they can be considered more suitable due to its specificity.

One must keep in mind that the OEy and OEs values here presented illustrate the energy availability potential provided by thermal conversion through combustion. So, through other conversion routes (such as gasification, pyrolysis, digestion, and fermentation) that uses the structural and other components in different manners, others potentials energy availability are expected.

When relating IE and OE values in order to calculate EB, one can notice that maize presented the highest indicator value. This shows that this crop was the one that provided greater amount of net energy per area, so favorable outcome in terms of energy. It is followed by P. maximum, Tifton 85, sorghum, millet, ryegrass, and oats, the last one providing the least amount of net energy per area. EB was also presented on a daily basis, in order to compare the values between crops. One must remember that there's annual and perennial crops, so it is known that the perennial crops stays on field during all year, and not just during the favorable time of the year for growing, as it happens with the annual ones, so the comparison must be carefully analyzed.

By doing another relation between IE and OE, for the EROI calculation, one can observe that the highest value is provided by Tifton 85, followed by *P. maximum*, maize, sorghum, millet, ryegrass, barley, and oat. This means that the higher values represented crops use smaller fraction of the output energy to maintain their respective production processes. In *P. maximum* and Tifton 85, this was due to the high dry matter production (10 Mg ha^{-1} yr^{-1}) only behind maize dry matter production) and intermediate values of input energy. In maize, this was due to the fact that this crop presented the higher energy demand, but at the same time, the higher energy availability. Sorghum also provided great amount of energy, with the lowest energy demand. All of these characteristics contributed to a high EROI index.

Concerning the perennial crops, one has to remember that even though they provide amounts of energy similar to the more efficient in energy use crops (maize and sorghum), those ones occupy land all year. Despite the fact of land use, several perennial grasses are being studied for several years, for the use as energy sources (switchgrass, miscanthus, giant reed), specially due to their rusticity and great biomass potential (Angelini et al., 2009; Angelini et al., 2005; McLaughlin and Kszos, 2005; Smeets et al., 2009; Varvel et al., 2008). However, in Brazil the major use for these crops is for animal feeding.

The resulted EROI values when compared to the literature (Campos, 2004; Campos et al., 2005; Oliveira et al., 2005) are high due to the system's limits considered, from soil preparing to harvest, without considering transport, pretreatment and availability in final usable energy. Reported EROI values from ethanol from sugarcane 8.3 and 9.2 in Lamonica, (2007) and Macedo, (1998), respectively, presents itself more advantageous from the energetic point of view than black oat, ryegrass, barley, and millet compared to the outcome in this work. Here, one can observe a suggestion for future studies including the steps necessary in providing final energy available (transport and industrial processes, all made after harvest) from the biomass sources that presented the highest energy efficiency levels, considering its different transformation routes (McKendry, 2002b; Romanelli and Raucci, 2011).

Regarding the embodied energy, the crop that presented the best result (here represented by lower absolute value) were Tifton 85, followed by maize, sorghum, *P. maximum*, millet, barley, ryegrass, and black oat. This means that for the crops with the lowest absolute values, it was used lower amounts of energy in dry matter production when compared to the others.

4 Conclusions

The proposed method could assess and compare the energy use between several forage crops concerning the biomass production. Maize, sorghum, *P. maximum* and Tifton 85 were the crops that presented the most efficient energy use, since they provided the greatest amounts of energy, in more profitable processes concerning the dry matter production. Oat and ryegrass on the other hand, were the crops that presented the least efficient energy uses in the production processes, meaning that these crops were the ones that provided the lowest amounts of energy concerning the bioenergy approach, and spent more energy in dry matter production.

The high energy efficiency of the perennial crops should be carefully analyzed, since these crops occupy the land during more time to present values similar to maize and sorghum (annual crops that were more efficient concerning energy use and availability).

The high profitability values are due to the absence of the post-harvest industrial steps in the energy analysis.

Efficiency indicator of the more efficient on the energy approach, maize, sorghum, *P. maximum*, and Tifton 85, are high enough (when compared to successful energy sources like sugarcane and perennial grasses) to consider further studies concerning all the processes to provide final energy use.

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