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Energy efficiency in maize crops in different regions of Brazil

Eficiência energética na cultura do milho cultivado em diferentes regiões brasileiras

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Highlights

Energy efficiency analysis helps to identify economic and environmental bottlenecks.
High N-Fertilizer Spending on Maize Crops Reduces Energy Efficiency of Crop System.
Energy efficiency should be assessed in different representative producing regions.

Abstract

Assessment of energy efficiency (EE) enables the evaluation of the sustainability of agrosystems, as well as decision-making regarding reduction in production costs and environmental pollution and even to increase production in a sustainable way. In this context, the objective of this study was to assess energy efficiency in maize in different regions of Brazil. For this purpose, 32 areas of maize crop distributed across the major producing states and regions were assessed. Energy inputs and outputs of agricultural operations and/or agricultural inputs were calculated by multiplying the amount used by their calorific value or energy coefficient at each stage of production. Energy efficiency was calculated as the ratio between the total output energy and the total input energy during the production process. For every megajoule (MJ) of energy consumed in the production of second-crop maize and first-crop maize seasons, 9.9 and 8.7 MJ respectively of renewable energy were produced in the form of grain. In both maize cropping seasons, most of the energy use was attributed to fertilizers, herbicides and fuel. To be representative the evaluation of energy efficiency of the maize crop should be performed in different Brazilian cultivation regions, as it will represent different edaphoclimatic and management conditions spread over the national territory within

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an agricultural year.
Key words: Energy consumption. Grain yield. *Zea mays.*

Resumo

A avaliação da eficiência energética (EE) pode evidenciar a sustentabilidade dos agrossistemas e a tomada de decisões relativas à redução dos custos de produção, poluição do ambiente e até mesmo aumento de produção de forma sustentável. Diante deste contexto, o objetivo deste trabalho foi avaliar a eficiência energética na cultura do milho em diferentes regiões brasileiras. Para isso, foram avaliadas 32 áreas de milho distribuídas pelos principais estados das regiões produtoras desta cultura. As entradas e saídas de energia das operações agrícolas e/ou insumos utilizados foram calculadas pela multiplicação da quantidade utilizada pelo seu poder calorífico ou coeficiente energético em cada etapa de produção. A eficiência energética foi obtida pela razão entre a quantidade de energia total de saída e o consumo total de energia durante o processo produtivo. Para cada 1,0 MJ de energia consumida na produção de milho safrinha e safra, produziu-se respectivamente 9,9 e 8,7 MJ de energia renovável, na forma de grãos desta cultura. Os principais gastos energéticos foram com fertilizantes, herbicidas e combustível. A avaliação da eficiência energética na cultura do milho para ser bem representativa deve ser realizada em diferentes regiões brasileiras de cultivo, pois assim representará diferentes condições edafoclimáticas e de manejo espalhadas pelo território nacional dentro de um ano agrícola.
Palavras-chave: Consumo energético. Produção de grãos. *Zea mays.*

Introduction

Considering the projection and/or estimation of world maize production for the 2017-2018 crop year, Brazil stands out as the second largest producer of maize (95 Mt), only behind the United States with a production of 371 Mt of maize (United States Department of Agricultures [USDA], 2018). This grain production is associated with techniques highly dependent on energy consumption primarily from fossil fuel burning resulting in significant amounts of CO2 emission to the atmosphere.

The assessment of energy efficiency (EE) in agriculture can help to identify the energy bottlenecks of the adopted cropping systems, with the intention of finding energy-saving technologies (especially for fossil-fuel energy). The use of fuel, fertilizers, pesticides, irrigation, and the manufacture of machines and implements are examples of items that consume great amounts of energy in agriculture (Cunha et al., 2015; Chen et al., 2018). Therefore, studies on EE in agriculture contribute to the assessment of the sustainability of agricultural and livestock systems.

There are several ways to estimate the EE of a crop, such as the amount of energy used per unit mass of harvested product (Alluvione, Moretti, Sacco, & Grignani, 2011) or the energy content (Joules, J) of the crop per unit of energy used to produce it, in J J-1 (Cunha et al., 2015). The literature presents a wide variation in the values of EE for maize crops cultivated in Brazil. For example, in the cultivation of maize, most of the total energy input for maize production was in the form of fertilizers, especially nitrogen fertilizers, with

EE results ranging between 4.9 J J-1 (Melo et al., 2007) and 22.0 J J-1 (Campos et al., 2004).

These wide variations in the EE values of maize crops in Brazil may be attributed to differences in crop productivity and crop management adopted in each locality. It is necessary to determine the EE of various representative localities to decrease these discrepancies and increase the representativeness of the EE results of maize crops.

The detailed description of the practices and inputs that have an effect on EE in agriculture contributes to the establishment of the best practices for a lower environmental impact and economically more efficient agricultural production. Thus, the objective of the present study was to assess EE in maize crops in different regions of Brazil in the 2014-2015 crop year.

Materials and Methods

This was an exploratory study that followed the methodological approach used in multiple-case studies, with bibliographical research and interviews with producers. In multiple-case studies, the selected production units are distinguished by the adopted production systems, which precludes generalization of their results and provides a basis and a tool for other studies because they are not considered "sampling units" (Ferreira, Neumann, & Hoffmann, 2014).

Data collection for the calculations was performed for 32 maize crops planted as first and/or second-crops in the 2014-2015 crop year. The survey was performed using structured interviews with farmers and/or data obtained from research institutions such as the National Food Supply Company (CONAB), the Federation of Agriculture and Livestock of Goiás (FAEG), the Agriculture Research and Rural Extension Company of Santa Catarina (EPAGRI), and the Center of Social Economy and Agricultural Planning of the School of Agriculture "Luiz de Queiroz" (CEPA-ESALQ).

The data collected were categorized as follow: a) amount of human labor, fuel, synthetic and organic fertilizers, seeds, seedlings, herbicides, insecticides, fungicides, and other inputs involved from sowing to harvest; b) agricultural operations used in crop management, and tractors, machinery, and/or implements used for these services; c) crop grain yield; and d) technical parameters such as duration of each agricultural operation and fuel consumption (L h^{-1}). The detailed data of the maize areas assessed in this study are described in Table 1.

Table 1
Location, size of the area, and average yield of maize fields in different regions of Brazil

Area	City/State	Size of the area (ha)	Average yield (Mg ha^{-1})	Area	City/State	Size of the area (ha)	Average yield (Mg ha^{-1})
Second-crop maize season				First crop maize season			
1	FAEG GO[2,6]		6.60	22	FAEG GO[2,6]		10.50
2	Rio Verde GO[1,6]	280	5.10	23	FAEG GO[2]		9.60
3	Montividiu GO[5,6]	1800	8.94	24	EPAGRI/CEPA SC[3]		10.80
4	Montividiu GO[5,6]	1298	10.68	25	Santo Ângelo RS[1,6]	100	7.50
5	Rio Verde GO[5,6]	390	8.88	26	Santo Ângelo RS[1,6]	100	4.80
6	Montividiu GO[5,6]	300	7.50	27	Passo Fundo RS[1,6]	60	7.50
7	Montividiu GO[5,6]	515	7.44	28	Chapadão do Sul MS[1,6]	200	9.60
8	Montividiu GO[5,6]	300	6.00	29	Unaí MG[1]	100	9.00
9	Rio Verde GO[5,6]	155	9.00	30	Campo Mourão PR[1,6]	40	8.50
10	Montividiu GO[5,6]	100	10.20	31	Londrina PR[1,6]	50	8.00
11	Montividiu GO[5,6]	215	9.00	32	Barreiras BA[1,6]	360	8.60
12	Sorriso MT[1,6]	900	5.40				
13	Campo N. Parecis MT[1,6]	1300	6.00				
14	Campo Verde MT[1,6]	800	6.00				
15	Primavera do Leste MT[1,6]	1050	6.00				
16	Passo Fundo RS[1,6]	20	4.80				
17	Ubiratã PR[1,6]	45	5.70				
18	Campo Mourão PR[1,6]	40	4.50				
19	Londrina PR[1,6]	50	5.20				
20	Unaí MG[1]	100	5.70				
21	Chapadão do Sul MS[1,6]	350	6.60				

[1] Data provided by the National Food Supply Company (CONAB). [2] Data provided by the Federation of Agriculture and Livestock of Goiás (FAEG). [3] Data provided by the Agriculture Research and Rural Extension Company of Santa Catarina (EPAGRI). [4] Center of Social Economy and Agricultural Planning (CEPA). [5] Data provided by several farmers in the region. [6] Sowing performed using transgenic seeds.

The data regarding the amount of inputs and the agricultural practices were converted into units of energy by multiplying the physical product by the respective conversion factors, known as energy coefficients, expressed as MJ (Assenheimer, Campos, & Gonçalves, 2009; Capellesso & Cazella, 2013). The energy coefficients used in the present study were based on data from the literature, both for inputs (factors required for production) and outputs (grain production) (Table 2).

Table 2
Main energy coefficients that were used to determine the energy consumption by the analyzed crops

1. Direct energy			
Specifications	Unity	Energy coefficient (EC)	Bibliographic reference
Human labor	MJ h^{-1} men	7.84	Boddey, Soares, Alves and Urquiaga (2008)
Synthetic Nitrogen Fertilizer (N)	MJ kg^{-1}	63.79	Macedônio and Picchioni (1985)
Phosphate Synthetic Fertilizer (P_2O_5)	MJ kg^{-1}	13.97	Macedônio and Picchioni (1985)
Potash Synthetic Fertilizer (K_2O)	MJ kg^{-1}	9.79	Macedônio and Picchioni (1985)
Limestone	MJ kg^{-1}	0.167	Comitre (1993)
Plaster	MJ kg^{-1}	0.167	Vieira (2007)
Micronutrient Zinc	MJ kg^{-1}	8.37	Pimentel (1980)
Cobalt + Molybdenum (CoMo)	MJ L^{-1}	0.042	Gomes (2012)
Micronutrients in general	MJ kg^{-1}	6.32	Souza, Casali, Santos and Cecon (2008)
Chicken litter	MJ kg^{-1}	0.126	Souza et al. (2008)
Natural phosphate	MJ kg^{-1}	0.63	Quadros and Kokuszka (2007)
[1]Energy converter	MJ R$	2.23	Empresa de Pesquisa Energética [EPE] (2015)
Calorific value of diesel oil	MJ L^{-1}	43.93	Comitre (1993)
[2]Calorific value of lubricating oil	MJ L^{-1}	35.94	Comitre (1993)
[2]Calorific value of grease	MJ L^{-1}	49.22	Comitre (1993)
Maize Seeds	MJ kg^{-1}	32.45	Beber (1989)
4 Herbicides, insecticides, fungicides, etc ...	kg ou L /a.i	(Table 3)	Pimentel (1980)
2. Indirect energies			
[5,6]Tractor or machines (Self Propelled)	MJ kg^{-1}	69.83	Macedônio and Picchioni (1985)
Self-Propelled Harvesters	MJ kg^{-1}	69.87	Macedônio and Picchioni (1985)
Attachments (not self-propelled)	MJ kg^{-1}	57.2	Macedônio and Picchioni (1985)

[1]For very specific inputs with little significant contribution, the energy value was estimated based on the cost of one monetary unit for the Gross Domestic Product related to the National Energy Balance, both of 2014. [2] The consumption of lubricating oil was considered 1.5% of diesel consumption and for grease, 33% of lubricant consumption. [4] Varies according to the active ingredient (a.i) and formulation used (Table 3). [5] An energy value for repairing tractors, machines and agricultural implements was also established, which corresponds to 5% of the total energy used in their manufacture. [6] A value of 2.24% (Boddey et al., 2008) was also considered in relation to total energy expenditure in agricultural production as an estimate of energy expenditure on the transportation of machinery, implements and inputs to the crop.

Energy depreciation (ED) and indirect energy associated with tractors, machinery, and/or agricultural implements was calculated using the equation (Beber, 1989):

$$ED = \frac{0.9 \times M}{Sl} \times du \times EC$$

Where M is the mass of the tractor or agricultural implement in kg, *Sl* is the service life of the tractor or agricultural implement in hours, *du* is the duration of use in hours, and *EC* is the energy coefficient of the tractor, machinery or agricultural implement. The masses of the tractors, machinery, and implements were obtained from manufacturers catalogues. The values of service life were obtained from Companhia Nacional de Abastecimento [CONAB] (2010).

The energy coefficients used for the conversion quantities of herbicide, insecticide and fungicide into energy values were estimated based on the literature (Pimentel, 1980); the amount of energy used with these inputs was thus attributed according to their formulations (Table 3).

Table 3
Energy coefficients used to calculate energy expenditures with herbicides and pesticides for the control of pests and diseases in the crops assessed in this study (Pimentel, 1980)

Formulation	Energy coefficient of a.i. (MJ kg^{-1} or L^{-1})
Herbicides	
Dispersible concentrate	418.3
Soluble powder	262.8
Pellets	362.6
**Mean value*	347.9
Plant protection products for pest control	
Dispersible concentrate	363.9
Soluble powder	311.1
Granulate	311.1
Wettable powder	257.4
*Mean value	310.8
Plant protection products for disease control	
Dispersible concentrate	271.8
Soluble powder	116.3
Granulate	216.0
Wettable powder	216.0
*Mean value**	205.0

a.i. - active ingredient. * Mean value attributed by the authors to other types of formulations.

The calculations of energy consumption in the agricultural operations, including the application of additives and fertilizers, sowing, internal transportation, application of herbicides, insecticides and fungicides, and harvesting were obtained using the fuel used (L h^{-1}) by the tractor-implement system or machine combined with the performance of this system or machine (ha h^{-1}). Based on these data, the fuel expenditure in L h^{-1} was divided by the operational yield in ha h^{-1} to obtain the fuel expenditure in L ha^{-1}. Energy input (in MJ ha^{-1}) was obtained considering the calorific value of diesel oil (47.73 MJ L^{-1}).

Some correction factors were used in the calculations of the fuel (diesel) used in operations such as grain transportation and transshipping, transport of water, and tillage. The expenditure of fuel during grain and water transportation operations was divided by the cargo-carrying capacity per hectare. For example, if a tractor water tanker uses 10 L of diesel to carry 2000 L of water, and the volume of the solution used is 200 L ha^{-1}, 10 L of diesel is consumed in this operation for each 10 ha, i.e., 1 L ha^{-1} of diesel was used for the transportation of water. Diesel consumption in tillage operations was divided by the number of years of residual effect on the soil from the used management system. In plowing and harrowing operations, for example, a conservative timeframe of 10 years was used for the mean residual effect of these operations because all the areas were under the system of direct seeding.

The list of tractors, machines, and agricultural implements, as well as their operational yields (h ha^{-1}) and diesel consumptions (L ha^{-1} $year^{-1}$) in the abovementioned maize crop areas, are shown in Table 4. The agricultural operations performed in each property are described in Table 5.

The number of hours worked and total diesel consumption for all these operations, as well as the quantities of seeds, herbicides and pesticides used are listed below in Table 6.

The amounts of nitrogen, phosphorous, potassium, limestone, and gypsum that were applied are listed in Table 7, respectively.

To standardize the calculations of energy output, it was assumed that the mass of grain contained 13% moisture and that the yield of energy (output) from grain was 15.11 MJ kg^{-1} for maize (Sá et al., 2013). Thus, to calculate the total energy outputs from agrosystems, grain yield was multiplied by the energy coefficient. The harvest residues were not considered outputs because they are reincorporated into the system (Capellesso & Cazella, 2013).

Lastly, EE was calculated by dividing the output energy (MJ ha^{-1}) by the energy input (MJ ha^{-1}) in each production unit (H. P. Santos, Fontaneli, Spera, & Dreon, 2013).

The descriptive statistical analysis to obtain the means, minimum and maximum values, and standard deviation was based on the estimation of EE obtained from each data collection in the 32 maize crop areas.

Table 4
Identification of tractor sets, machines and implements used in the areas (Id), as well as their Potency in cv (Pt), and Operational indicator in h ha^{-1} (Op) and Fuel Consumption in L diesel ha^{-1} year^{-1} (CC)

*Id	*ST	*Pt	* Ip	*Op	* CC	*Id	*ST	*Pt	* Ip	*Op	* CC
1	[1]Tra	110	[6]Ss	0.16	1.62	112	[2]Sps	128		0.13	1.52
2	[2]Sps	125		0.04	0.48	113	[1]Tra	180	[41]Se	0.5	9.81
4	[3]Spc	152		0.16	2.31	114	[1]Tra	88	[42]Ss	0.13	1.12
6	[4]Har	270		0.33	8.48	117	[2]Sps	245		0.05	1.16
10	[1]Tra	110	[9]Ss	0.08	0.47	118	[1]Tra	110	[6]Ss	0.13	0.32
11	[2]Sps	128		0.05	0.6	119	[1]Tra	86	[14]Sp	0.33	3.09
12	[1]Tra	110	[10]Tt	0.01	0.003	120	[1]Tra	127	[16]Se	0.46	4.55
13	[1]Tra	110	[11]Ss	0.1	1.18	121	[1]Tra	127	[16]Se	1	15.16
14	[3]Spc	152		0.1	1.57	122	[4]Har	270		0.5	7.36
16	[4]Har	378		0.25	8.99	123	[1]Tra	86	[20]Tp	0.6	6.17
17	[1]Tra	110	[11]Ss	0.16	1.9	124	Truck	110		0.46	4.17
18	[2]Sps	245		0.03	0.77	125	[1]Tra	145	[27]Se	0.37	7.05
19	[1]Tra	110	[11]Ss	0.08	0.95	126	[1]Tra	125	[11]Ss	0.25	2.97
20	[3]Spc	152		0.12	1.88	127	Truck	110		0.46	1.89
21	[1]Tra	225	[7]Se	0.12	2.76	128	[1]Tra	217	[11]Ss	0.09	1.04
25	[1]Tra	68	[14]Sp	0.2	1.62	129	[1]Tra	217	[11]Ss	0.03	0.35
26	[1]Tra	68	[15]Tt	0.5	0.27	130	[1]Tra	210	[27]Se	0.1	2.03
27	[1]Tra	105	[16]Se	0.7	8.73	131	[1]Tra	165	[13]Tt	0.46	3.14
28	[4]Har	196		0.5	11.68	132	Truck	360		0.8	7.67
36	[1]Tra	120	[19]Se	0.4	3.93	133	Truck	280		0.76	0.21
37	[1]Tra	75	[15]Tt	0.33	0.14	134	[1]Tra	217	[13]Tt	0.46	3.14
38	[4]Har	175		0.33	5.49	135	Truck	480		0.56	5.03
43	[1]Tra	127	[17]Ss	0.2	3.03	136	[1]Tra	127	[18]Ss	0.33	2.46
44	[1]Tra	86	[14]Sp	0.4	4.12	137	[1]Tra	127	[16]Se	0.17	2.24
48	[1]Tra	110	[11]Ss	0.03	0.39	138	[1]Tra	127	[9]Ss	0.11	0.66
49	[1]Tra	110	[21]Hs	0.25	2.38	139	[1]Tra	127	[34]Tt	0.46	5.78
51	[4]Har	270		0.37	9.51	140	Truck	360		0.8	7.67
55	[1]Tra	140	[24]Se	0.6	9.19	141	[1]Tra	127	[36]Tt	0.33	1.99
59	[2]Sps	128		0.03	0.31	142	[1]Tra	86	[39]Sp	0.12	1.44
66	[1]Tra	175	[11]Ss	0.14	1.65	143	[4]Har	375		0.4	14.3
67	[2]Sps	245		0.02	0.4	144	[1]Tra	127	[32]Tt	0.28	1.66
68	[1]Tra	217	[11]Ss	0.07	0.79	145	Truck	345		0.8	3.94
69	[1]Tra	335	[30]Se	0.1	3.17	146	[4]Har	270		0.22	5.58
70	[4]Har	375		0.1	3.61	147	[1]Tra	95	[32]Tt	0.04	0.54
73	[1]Tra	127	[31]Ss	0.11	1.45	148	Truck	440		0.41	3.49
74	[1]Tra	127	[31]Ss	0.04	0.54	149	[4]Har	330		0.19	5.98

continue...

contuation...

75	[1]Tra	127	[27]Se	0.33	5.15	150	[1]Tra	165	[32]Tt	0.25	3.57
80	[1]Tra	86	[14]Sp	0.14	1.14	151	Truck	360		0.66	6.89
81	[1]Tra	68	[15]Tt	3.33	1.45	152	[1]Tra	127	[13]Tt	0.27	2.96
83	[4]Har	270		0.48	12.23	153	Truck	110		0.14	0.86
85	truck	110		0.26	0.046	154	[1]Tra	225	[7]Se	0.12	3.71
86	[1]Tra	127	[35]Se	0.22	2.98	155	[1]Tra	225	[28]Tt	0.15	0.59
90	[1]Tra	127	[38]Ss	0.17	2.18	156	Truck	110		0.46	2.01
91	[1]Tra	86	[39]Sp	0.12	0.98	157	[1]Tra	225	[7]Se	0.26	8.14
92	[1]Tra	127	[38]Ss	0.08	1.09	158	Truck	110		0.46	2.23
95	[1]Tra	127	[23]Ss	0.11	1.32	170	[1]Tra	68	[20]Tp	0.4	2.68
96	[1]Tra	75	[14]Sp	0.06	0.41	171	Truck	250	[28]Tt	1	10
97	[4]Har	270		0.24	6.2	172	[1]Tra	73	[15]Tt	0.13	0.05
100	[2]Sps	165		0.04	0.62	173	[1]Tra	112	[19]Se	0.83	8.2
101	[4]Har	284		0.25	6.75	174	Truck	110		0.46	3.18
102	[2]Sps	128		0.08	0.97	175	[1]Tra	110	[17]Ss	0.5	6.27
106	[4]Har	270		0.4	10.28	176	Truck	110		0.46	2.98
107	[1]Tra	68	[17]Ss	0.6	4.9	177	[1]Tra	217	[41]Se	0.3	7.86
108	[1]Tra	68	[14]Sp	0.6	4.9	178	Truck	110		0.46	2.68

*ST (Source of traction), Ip (Implements). **PR (required power). [1]Tra (Tractor), [2]Sps (Self-propelled sprayer), [3]Spc (Self-propelled crawler excavator), [4]Har (Harvester), [5]Ssp (Solids Spreader, self-propelled), [6]Ss (Solids spreader (2-3 m^{-3}), [7]Se (Seeder PR 193cv), [8]Pd (Plow 26 discs), [9]Ss (Solids spreader up to 1 m^{-3}), [10]Tt (Tank trailer 4000 a 5000 L), [11]Ss (Spreader Stara Hércules 10000), [12]Se (Seeder John Deere 2117), [13]Tt (Trailer Stara Reboke Ninja 25000), [14]Sp (Sprayer 2000 L), [15]Tt (Tank trailer 3000 L), [16]Se (Seeder PR 99 cv), [17]Ss (Solids spreader 4 to 6 m^{-3}), [18]Ss (Solids spreader 1 to 2 m^{-3}), [19]Se (Seeder PR 82 cv), [20]Sp (Sprayer 600 L), [20]Tp (Transshipping trailer 2m^{-3}), [21]Hs (Hydraulic shovel Stara), [22]Se (Seeder JM7080 PD Guerra), [23]Ss (Spreader Stara Bruttus 6000), [24]Se (Seeder PR 128 cv), [25]Sp (Subsoiler plow 9 shanks), [26]Pl (Plow 18 discs), [27]Se (Seeder Jumil JM3090), [28]Tt (Transshipping trailer JAN Tanker 25000), [29]Lh (Levelling harrow 48 discs), [30]Se (Seeder John Deere DB50), [31]Ss (Spreader Jan Lancer 12000 TM), [32]Tt (Transshipping trailer 8 to 10 m^{-3}), [33]Se (Seeder Tatu Marchesan PST DUO), [34]Tt (Trailer JAN Tanker 10.000), [35]Se (Seeder Tatu Marchesan Ultra Flex Suprema), [36]Tt (Transshipping trailer JAN Tanker Polietileno 17000), [37]Lh (Levelling harrow 42 discs), [38]Ss (Spreader Jumil Precisa), [39]Sp (Sprayer 3000 L), [40]Ss (Spreader Stara Hércules 15000), [41]Se (Seeder PR 143 cv), [42]Ss (Spreader Stara Twister 1500 APS).

Table 5
Description of the agricultural operations performed in the maize fields surveyed in the present study

Areas evaluated	Agricultural operations*																					
	a**	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v
Second-crop maize season																						
1	-	-	-	-	-	-	1	-	119	-	-	-	120	119	$119^{(\times2)}$	-	$121^{(\times2)}$	-	β	122	123	124
2	-	-	-	-	-	-	48	-	11	-	-	49	125	-	$11^{(\times2)}$	-	126	-	-	106	-	127
3	-	-	-	-	-	-	128	-	-	129	-	-	130	59	-	60	129	-	$\beta^{(\times2)}$	101	131	132
4	-	-	-	-	-	-	66	-	-	129	-	-	69	67	-	133	129	-	$\beta^{(\times2)}$	70	134	135
5	-	-	-	-	-	-	66	-	-	129	-	-	69	67	-	133	129	-	$\beta^{(\times2)}$	70	134	135
6	-	-	-	-	-	-	136	-	-	-	-	-	137	80	-	81	138	-	$\beta^{(\times2)}$)	83	139	140
7	-	-	-	-	-	-	128	-	-	-	-	-	137	59	$59^{(\times3)}$	85	74	-	$\beta^{(\times2)}$	97	141	140
8	-	-	-	-	-	-	90	90	-	-	-	-	86	142	-	85	92	-	β	143	144	145
9	-	-	-	-	-	-	73	-	-	-	-	-	75	59	59	$37^{(\times2)}$	74	-	β	146	147	148
10	-	-	-	-	-	-	126	-	-	129	-	-	21	59	$59^{(\times2)}$	$85^{(\times3)}$	10	-	-	149	150	151
11	-	-	-	-	-	-	13	-	96	-	-	-	75	$96^{(\times2)}$	96	-	10	-	β	101	152	153
12	-	-	-	-	-	-	17	-	18	19	-	20	154	18	$18^{(\times3)}$	$12^{(\times4)}$	19	-	-	38	155	156
13	-	-	-	-	-	-	17	-	2	-	-	4	157	2	$2^{(\times2)}$	$12^{(\times4)}$	19	-	-	83	-	158
14	-	-	-	-	-	-	19	19	18	-	-	14	75	18	$18^{(\times2)}$	$12^{(\times4)}$	68	-	-	28	-	158
15	-	-	8	-	-	-	13	13	11	13	-	14	159	11	$11^{(\times3)}$	$12^{(\times5)}$	13	-	-	16	-	158
16	-	-	-	-	-	-	13	-	142	-	-	-	113	142	-	-	-	-	-	83	-	160
17	-	-	-	-	-	-	13	-	-	-	-	-	36	2	$2^{(\times3)}$	-	13	-	-	146	-	158
18	-	-	-	-	-	-	1	-	161	-	-	-	27	161	$161^{(\times4)}$	$12^{(\times6)}$	17	-	-	122	-	162
19	-	-	-	-	-	-	1	-	44	-	-	-	163	44	$44^{(\times2)}$	$12^{(\times4)}$	95	-	-	51	-	156
20	-	-	-	-	-	-	126	126	91	-	-	14	55	91	$91^{(\times2)}$	-	19	-	-	106	131	158
21	-	-	-	-	-	-	48	-	117	-	-	164	159	117	$117^{(\times2)}$	-	68	-	β	97	144	148
First-crop maize season																						
22	-	-	-	-	-	-	43	43	119	-	-	-	120	119	$119^{(\times3)}$	-	-	-	β	83	123	124
23	-	-	-	-	-	-	43	43	119	-	-	-	120	119	$119^{(\times3)}$	-	-	-	β	83	123	124
24	-	-	-	-	-	-	107	-	108	-	-	-	157	108	108	-	$107^{(\times2)}$	-	-	83	-	167

continue...

contuation...

25	-	-	-	-	-	-	165	-	142	-	-	20	163	142	142	-	166	-	-	83	-	167
26	-	-	-	-	-	-	107	-	25	-	-	20	113	25	25	-	166	-	-	83	-	167
27	-	-	-	-	-	-	13	-	102	-	-	-	163	102	-	$26^{(\times 2)}$	$141^{(\times 2)}$	-	-	83	-	160
28	-	-	-	-	-	-	48	-	117	-	-	164	159	117	$117^{(\times 2)}$	-	68	-	β	97	66	168
29	-	-	-	-	-	-	169	169	91	-	-	14	55	91	$91^{(\times 4)}$	-	114	-	-	106	170	156
30	-	-	-	-	-	-	171	-	161	-	-	-	173	161	$161^{(\times 4)}$	$172^{(\times 6)}$	141	-	-	83	-	174
31	-	-	-	-	-	-	175	-	44	-	-	-	163	44	$44^{(\times 2)}$	$172^{(\times 4)}$	166	-	-	143	-	176
32	-	-	-	-	-	-	13	-	100	-	-	-	177	100	100	$12^{(\times 3)}$	13	-	-	6	-	174

* Equipment and operational yields were identified according to the identification numbers from Table 4. The multiplication sign followed by a number indicates the number of repeated operations. **Agricultural operations: a, subsoiling; b, other types of plowing; c, heavy plowing; d, intermediate harrowing; e, leveling, harrowing; f, phosphate application; g, liming; h, gypsum application; i, desiccation; j, early application of fertilizers; k, application of green fertilizer or top dressing; l, limestone loading; m-seeding; n, application of herbicides; o, application of pesticides, p, water transportation; q, top dressing; r, desiccation for harvesting; s, aerial application of pesticides; t, harvesting; u, transshipping; v, transportation to the warehouse.

Table 6
Quantities of seeds, herbicides, insecticides, fungicides, fuel and human labor used in the study areas

City / State	Seeds	Herbicides	Insecticides	Fungicides	Fuel	Human labor
		-------- kg ha^{-1} $year^{-1}$ -------			L ha^{-1} $year^{-1}$	h ha^{-1} $year^{-1}$
1	20	2.25	0.08	0.14	63.9	5.7
2	20	3.12	0.22	0.21	26.3	2.0
3	20	2.69	0.00	0.32	13.2	1.5
4	20	2.69	0.00	0.32	10.1	1.2
5	20	2.69	0.00	0.32	10.1	1.2
6	20	2.46	0.23	0.32	23.2	2.5
7	20	2.46	0.00	0.08	14.0	1.8
8	20	1.20	0.00	0.30	21.8	1.6
9	20	1.33	0.23	0.34	14.7	1.6
10	20	2.53	0.25	1.11	16.4	1.7
11	17	2.99	0.16	0.14	17.8	1.7
12	20	2.99	0.16	0.14	19.6	1.5
13	20	0.87	0.16	0.95	30.2	2.0
14	21	2.28	0.20	0.08	22.6	1.6
15	20	2.82	0.48	0.08	32.0	2.2
16	20	2.77	0.61	1.73	33.5	5.1
17	20	2.75	1.35	0.26	13.6	1.7
18	20	2.65	0.11	0.27	26.9	3.6
19	20	1.36	0.03	0.27	39.4	4.6
20	20	1.29	0.08	0.00	26.7	3.1
21	20	2.01	0.48	0.00	21.8	1.7
22	20	3.55	0.18	0.00	73.1	6.8
23	20	3.55	0.18	0.00	45.2	5.1
24	20	4.53	0.19	0.00	31.6	3.9
25	20	3.48	1.51	0.26	31.1	4.7
26	20	3.71	1.84	1.82	31.1	4.3
27	22	3.05	0.19	0.00	21.8	1.7
28	20	4.74	0.49	0.08	28.5	3.4
29	23	3.42	0.48	0.13	34.1	4.7
30	19	4.74	0.49	0.08	46.8	4.6
31	20	3.42	0.48	0.13	21.4	1.3
32	20	3.24	0.02	0.11	32.4	3.0

Table 7
Amounts of limestone, gypsum, macro and micronutrients applied in the maize fields surveyed in the present study

City/State	Rates (kg ha^{-1} yr^{-1})								
	N	P*	K*	Limestone	Gypsum	B	Zn	Mn	Co+Mo
Second-crop maize season									
FAEG - GO	106	56	36	250	-	-	6.0	-	-
Rio Verde-GO	95	70	70	250	-	-	-	-	-
Montividiu-GO	121	40	40	650	-	-	-	-	-
Montividiu-GO	142	40	40	361	-	-	-	-	-
Rio Verde-GO	142	40	40	361	-	-	-	-	-
Montividiu-GO	121	40	40	650	-	-	-	-	-
Montividiu-GO	92	50	62	250	-	-	-	-	-
Montividiu-GO	85	62	56	333	125	-	-	-	-
Rio Verde-GO	63	82	82	225	-	-	-	-	-
Montividiu-GO	100	50	50	250	-	-	-	-	-
Montividiu-GO	93	62	56	333	-	-	-	-	-
Sorriso-MT	110	50	50	250	-	-	-	-	-
Campo Novo do Parecis-MT	77	34	63	375	-	-	-	-	-
Campo Verde-MT	88	50	50	250	63	-	1.0	0.28	-
Primavera do Leste-MT	88	40	40	400	-	-	-	-	-
Passo Fundo-RS	110	50	50	250	-	-	-	-	-
Ubiratã-PR	75	38	38	250	-	-	-	-	-
Campo Mourão-PR	61	40	40	250	-	-	-	-	-
Londrina-PR	59	30	30	250	-	-	-	-	-
Unaí-MG	45	69	60	250	63	-	-	0.30	-
Chapadão do Sul-MS	84	40	20	313	-	-	0.1	0.40	-
Mean	93	49	48	322	83	-	2.4	0.33	-
First-crop maize season									
FAEG - GO	144	120	100	300	150	-	12.0	-	-
FAEG - GO	144	120	100	300	150	-	12.0	-	-
EPAGRI-CEPA - SC	194	132	48	333	-	-	-	-	-
Santo Ângelo-RS	132	105	70	375	-	-	-	-	-
Santo Ângelo-RS	81	50	50	376	-	-	-	-	-
Passo Fundo-RS	146	70	65	500	-	-	-	-	-
Chapadão do Sul-MS	88	70	95	313	-	-	0.1	0.40	-
Unaí-MG	113	69	90	250	63	-	-	0.30	-
Campo Mourão-PR	114	90	60	250	-	-	-	-	-
Londrina-PR	125	33	33	250	-	-	-	-	-
Barreiras-BA	112	96	128	250	-	-	-	-	-
Balsas-MA	118	130	120	250	-	-	-	-	-
Mean	126	90	80	312	121	-	8.0	0.35	-

*The amounts of P and K were obtained by multiplying P_2O_5 by 0.436 and K_2O by 0.830 for conversion.

Results and Discussion

The mean EE of the assessed second crop season maize areas was 9.9, and the mean of first crop season maize areas was 8.7 (Figure 1). The higher mean EE of the second maize crop relative to the first maize crop seasons was the usually due to the lower use of fertilizers and agricultural operations in second maize crop seasons taking advantage of the residual effect of fertilizers applied in the previous crop (usually soybean) and also some atypical high yields in the state of Goiás (Tables 5, 6 and Figure 1). These high yields for the second maize crop season in the areas assessed in the state of Goiás resulted from the influence of the good rainfall that is unusual for the that crop season, being higher than the normal regional values. This greater input of water during the second crop period led to increase in maize yield by 34.1% in the areas assessed in the state of Goiás, relative to the national average maize yield for the 2014-2015 cropping year (CONAB, 2015).

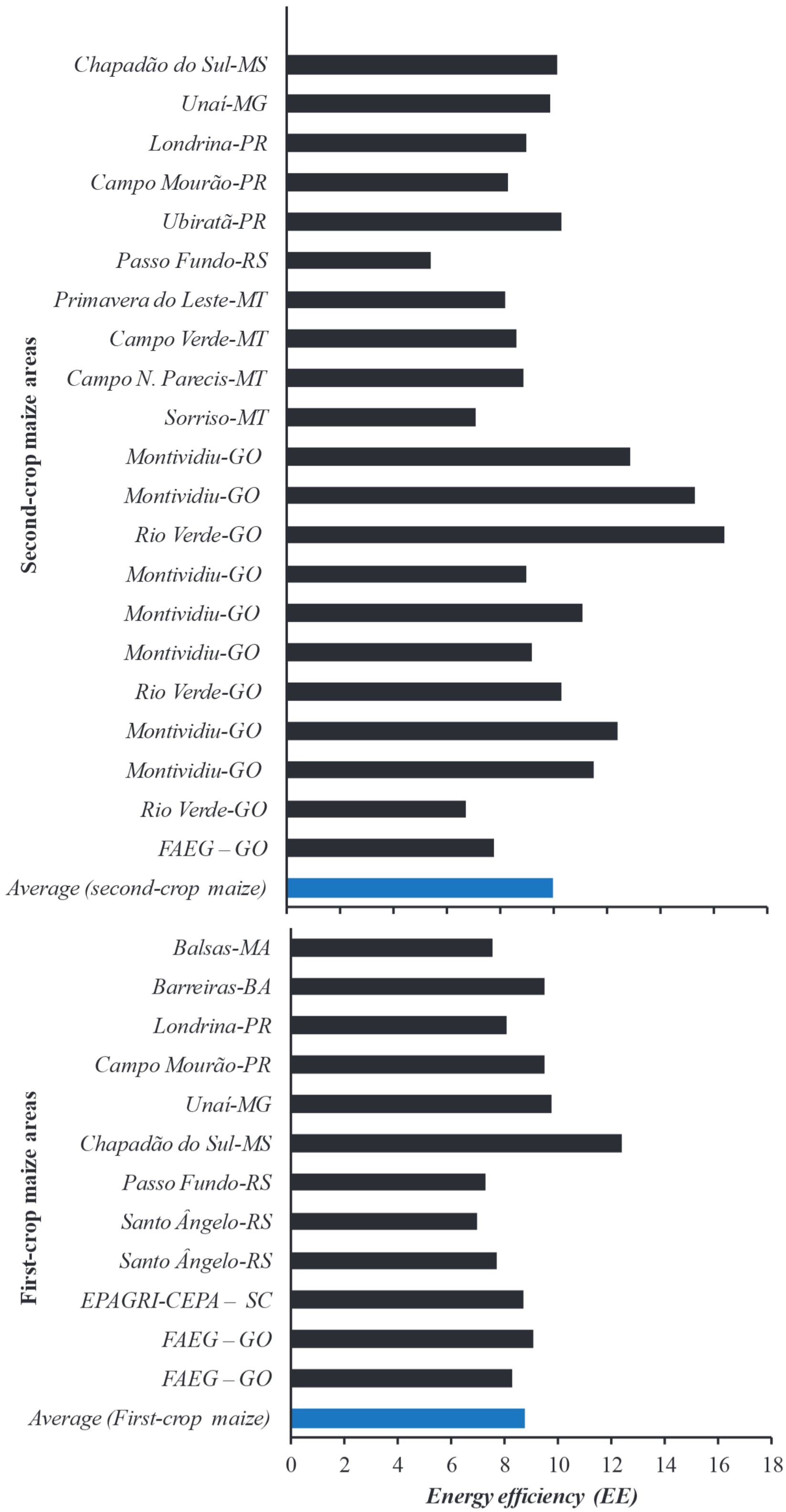

Figure 1. Energy efficiency (EE) of maize areas in different regions of Brazil. The EE is calculated as ratio of total energy produced as grains (GJ ha^{-1}) to total energy consumed in its production (GJ ha^{-1}).

The mean results of EE obtained for the maize crop in the present study (9.9 and 8.7) were lower than many reports found in the Brazilian and international literature: 21.95 (Campos et al., 2004), 20.14 (H. P. Santos et al., 2013), 12.86 (R. R. Santos & Simon, 2010; Riquetti, Benez, & Silva, 2012), 13.11 (Cunha et al., 2015) and 10.0 (Ruiz-Vega, Mena-Mesa, Diego-Nava, & Herrera-Suárez, 2015). The higher EEs found in those studies were a result of differences in crop management and grain yield among the assessed areas and between the crop years, and of the fact that those studies included a small number of areas in specific regions. Therefore, the various areas assessed in the regions included in the present study were under different edaphoclimatic conditions and technological packages that together interfered with the energy inputs and outputs within the crop production system. The results obtained in the present study attest to this observation, namely minimum EE values of 5.4 and 7.0, and maximum EE values of 16.4 and 12.4 in the first and second maize crop seasons, respectively (Figure 1).

Another important fact is the lack of rain in the first cropping period led to a decrease in soybean yield and favored that of second maize crop in the 2014-2015 crop year (CONAB, 2015). Considering that the second crop takes advantage of first crop fertilization residuals, it would be interesting to consider in future EE assessment studies that in crop years with warm autumns during the first crop, this variable might be accounted for as a mean of the production system, i.e., a mean EE of the soybean/second-crop maize sequence.

On average, the greatest energy expenditures in the second maize crop areas were associated with fertilizers (66.8%), herbicides (10.3%), fuel (9.8%), and seeds (6.1%) (Figure 2), whereas in the first maize crop areas, they were associated with fertilizers (68.9%), fuel (11.7), herbicides (9.1%), and seeds (4.5%) (Figure 3). Other studies (Cunha et al., 2015; Melo et al., 2007; R. R. Santos & Simon, 2010) also show these inputs as the major energy users in maize cultivation. The greatest difference between the first and the second crops of maize was fuel consumption, with more fuel being used in the summer (first crop) because of a higher number of crop management operations (Table 5).

As demonstrated in other studies (Cunha et al., 2015; R. R. Santos & Simon, 2010), fertilizers, in particular nitrogen fertilizer, continue to account for the main energy input in maize cultivation, both in the first and second crop seasons (Figure 2 and 3). Energy consumption for nitrogen fertilizers is usually extremely high due to the large amount of energy required (63.79 MJ kg-1) for its production (Häber-Bosch), a process which requires high temperatures and pressures and uses natural gas (Soares, Alves, Boddey, & Urquiaga, 2009; Macedônio & Picchioni, 1985). Likewise, an increase in efficiency in the use of nitrogen fertilizers may reduce the doses applied to the miaze crop and thus increase the energy efficiency of the crop. Therefore, several strategies are proposed in the literature aiming to increase efficiency and efficiency in the use of N-fertilizer, such as: 1) use of N stabilizers such as NBPT (N-(n-butyl) thiophosphoric triamide) and dicyanodiamide (DCD), which reduce N losses (Rajkovich et al., 2017). 2) use of plant growth-promoting bacteria (Spolaor et al., 2016). 3) use of grain legumes and green manure in rotation or in combination (thus supplying N derived from biological nitrogen fixation - BNF) (Portugal, Arf, Peres, Gitti, & Garcia, 2017). 4) the application of organic waste from the farm itself.

Energy expenditures as herbicides and fuels could be mitigated through the adoption of a direct seeding (no-till) system, improvements in herbicide production and application efficiency, and improvements in the operational yields of engines and agricultural machinery. The second-crop maize areas had lower energy use associated with herbicides and fuels than did the first crop maize areas (Figure 2 and 3), mainly for two reasons: 1) in all the assessed second maize crop areas, some management operations (physical or chemical treatment) had already been performed in the first soybean crop (Tables 4 and 5). For example, in the soybean areas where pre-harvest desiccation was performed, the need for desiccation of the area to control weeds before maize sowing was eliminated in some areas for the second maize crop (Table 5).

Given the above, it can be seen that the variation in productivity between years/crops and the different producing regions of Brazil influence the result of the average values of EE. It can be verified in the following estimative and/or example: 1) Considering the average energy consumption of all areas evaluated in this study, we have an energy expenditure of 10666 and 14689 MJ ha^{-1} respectively for second and first maize crop seasons. 2) Considering the current average yield in Brazil in the 2018/2019 in second e first maize crop seasons, which was 5854 and 5355 kg ha^{-1} respectively (CONAB, 2019) for the calculation of the energy produced, we have values of 88454 and 80914 MJ ha^{-1} respectively. 3) Given this reasoning in the 2018/2019 crop season would have an EE of 8.29 and 5.50 respectively in second e first maize crop seasons, very close to the average found in the evaluated areas of second maize crop of this study.

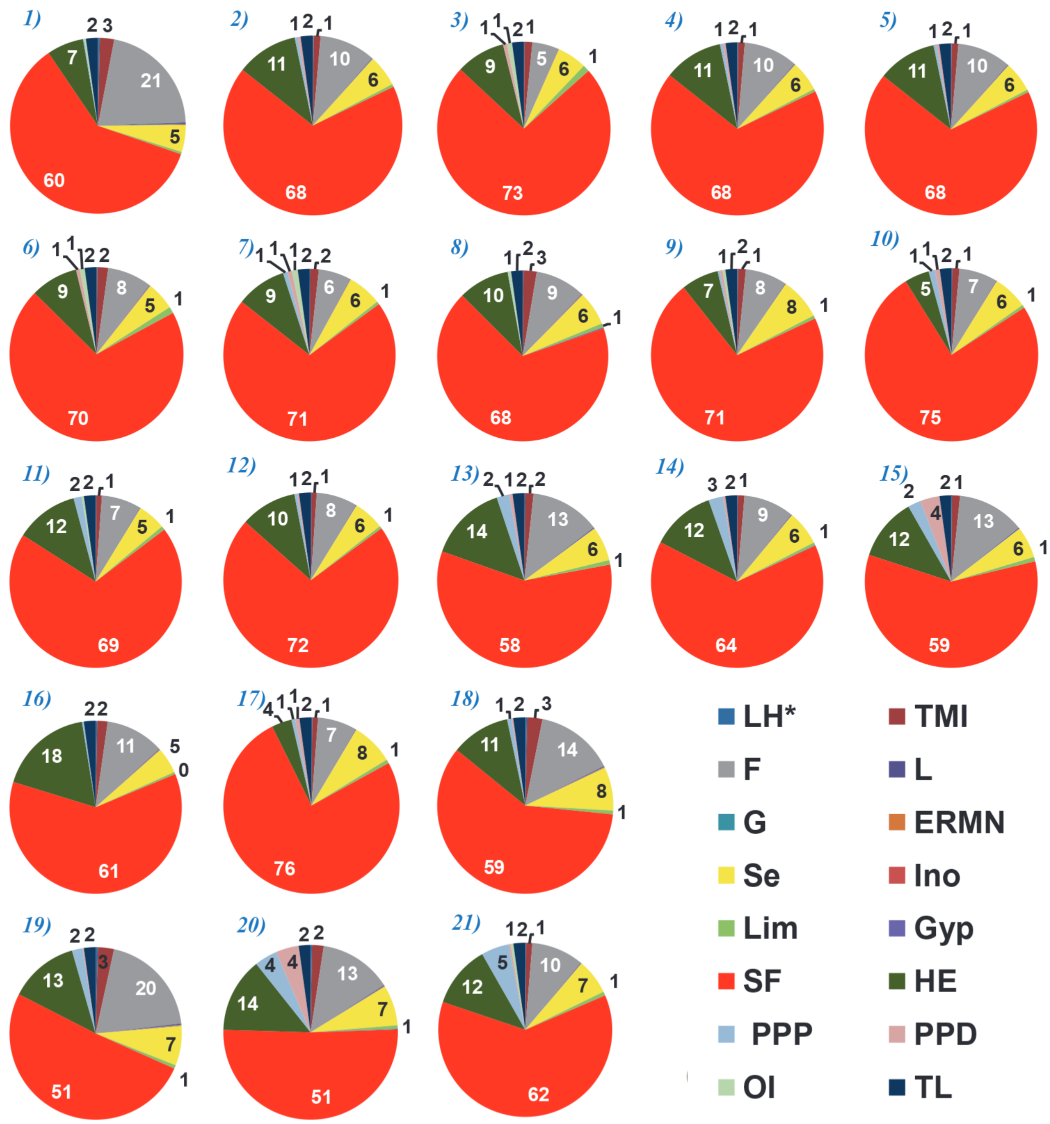

Figure 2. Main energy expenditure (%) on the charts and total energy consumed (GJ ha^{-1}) (a), total energy produced (GJ ha^{-1}) (b) in the agricultural stage of second crop maize in the following caption. 1) FAEG-GO, a=12.8 and b=99.7; 2) Rio Verde-GO, a=11.4 and b=77.1; 3) Montividiu-GO, a=11.8 and b=135.1; 4) Montividiu-GO, a=13.0 and b=161.4; 5) Rio Verde-GO, a=13.0 and b=134.2; 6) Montividiu-GO, a=12.3 and b=113.3; 7) Montividiu-GO, a=10.1 and b=112.4; 8) Montividiu-GO, a=10.1 and b=90.7; 9) Rio Verde-GO, a=8.3 and b=136.0; 10) Montividiu-GO, a=10.1 and b=154.1; 11) Montividiu-GO, a=10.6 and b=136.0 12) Sorriso-MT, a=11.4 and b=81.6; 13) Campo Novo do Parecis-MT, a=10.2 and b= 90.7; 14) Campo Verde-MT, a=10.5 and b=90.7; 15) Primavera do Leste-MT, a=11.1 and b=90.7; 16) Passo Fundo-RS, a=13.4 and b=72.5; 17) Ubiratã-PR, a=8.3 and b=86.1; 18) Campo Mourão-PR, a= 8.2 and b=68.0; 19) Londrina-PR, a=8.8 and b=78.6; 20) Unaí-MG, a=8.7 and b=86.1; 21) Chapadão do Sul-MS, a=9.9 and b=99.7. * Human labor (HL), Tractors, machinery and agricultural implements (TMI), Fuels (F), Lubricants (L), Grease (G), Energy used in the repair of tractors, machinery, and agricultural implements (ERMN), Seeds (Se), Inoculants (Ino), Limestone (Lim), Gypsum (Gyp), Industrial fertilizers (SF), Herbicides (HE), Plant protection products for the control of pests (PPP), Plant protection products for the control of diseases (PPD), Other inputs (OI), Transportation of machinery, implements, and inputs to the field (TL). Labels of slices <1% were not shown in the pie charts.

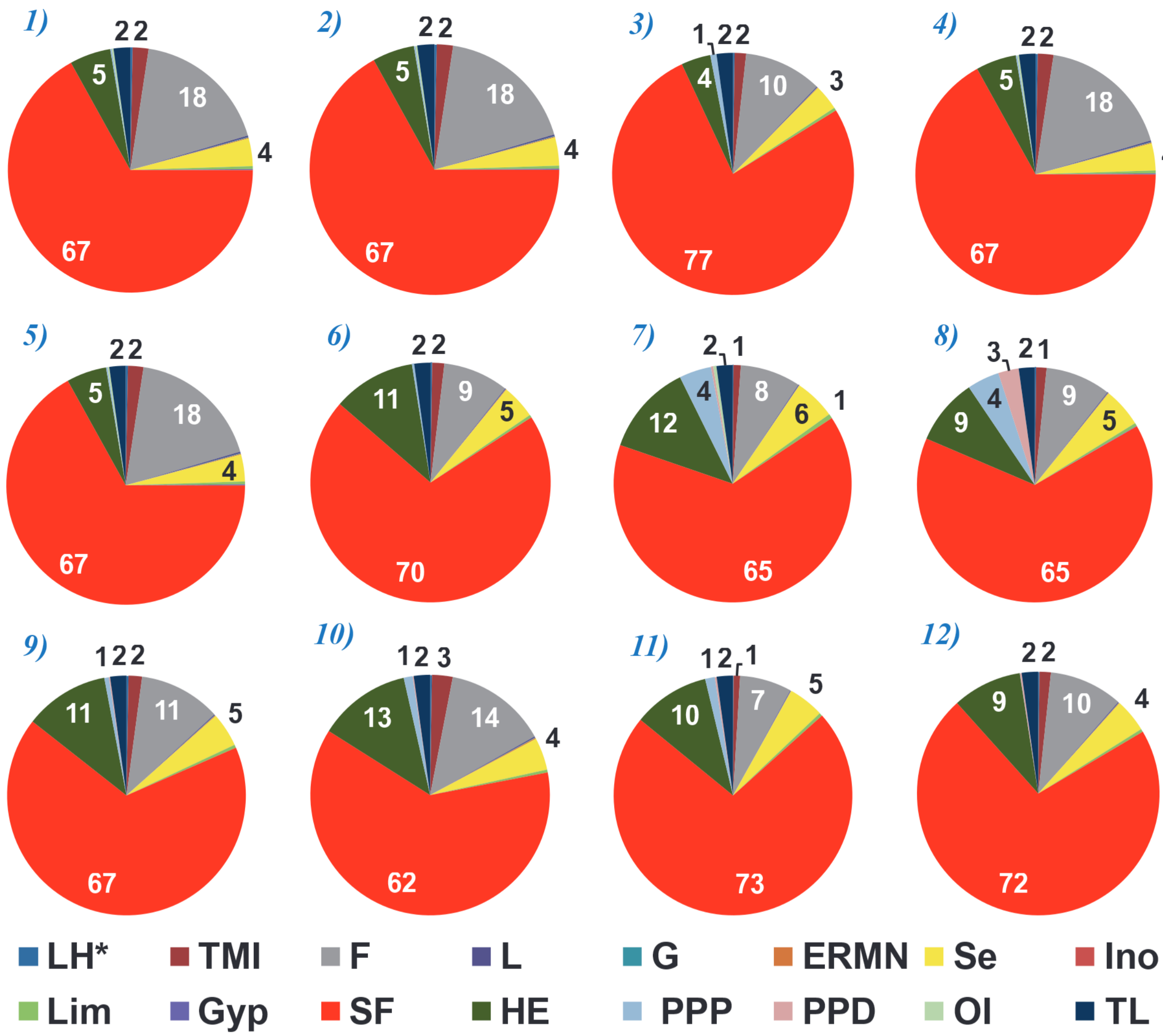

Figure 3. Main energy expenditure (%) on the charts and total energy consumed (GJ ha^{-1}) (a), total energy produced (GJ ha^{-1}) (b) in the agricultural stage of first crop maize in the following caption. Areas: 1) FAEG-GO, a=17.5 and b=145.1; 2) FAEG-GO, a=17.5 and b=158.7; 3) EPAGRI-CEPA-SC, a=18.7 and b=163.2; 4) Santo Ângelo-RS, a=14.7 and b=113.3; 5) Santo Ângelo-RS, a=10.4 and b=72.5; 6) Passo Fundo-RS, a=15.0 and b=113.3; 7) Chapadão do Sul-MS, a=11.7 and b=145.1; 8) Unaí-MG, a=13.9 and b=136.0; 9) Campo Mourão-PR, a=13.6 and b=128.4; 10) Londrina-PR, a=14.9 and b=120.9; 11) Barreiras-BA, a=13.4 and b= 126.9; 12) Balsas-MA, a=14.6 and b=108.8. * Human labor (HL), Tractors, machinery and agricultural implements (TMI), Fuels (F), Lubricants (L), Grease (G), Energy used in the repair of tractors, machinery, and agricultural implements (ERMN), Seeds (Se), Inoculants (Ino), Limestone (Lim), Gypsum (Gyp), Industrial fertilizers (SF), Herbicides (HE), Plant protection products for the control of pests (PPP), Plant protection products for the control of diseases (PPD), Other inputs (OI), Transportation of machinery, implements, and inputs to the field (TL). Labels of slices <1% were not shown in the pie charts.

Conclusions

For every MJ of energy consumed in the production of second and first-crop maize seasons, 9.9, and 8.7 MJ of renewable energy were produced in the form of grain, respectively. In each maize crop seasons the main input of energy was associated with the use of fertilizers, herbicides and fuel.

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