

Energy performance of soil management systems and crop rotation

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ABSTRACT: The objective of this study was to evaluate soil management and crop rotation systems. The treatments consisted of four types of soil management: 1) no-tillage, 2) minimum tillage, 3) conventional tillage with disc plows, and 4) conventional tillage with moldboard plows, and three crop rotation systems: system I - wheat/soybean; system II - wheat/soybean and vetch/sorghum; and system III - wheat/soybean, vetch/sorghum and white oat/soybeans. An experimental design of randomized blocks with split-plots and three replicates was used. The main plot consisted of soil management systems, while the split-plots consisted of crop rotation systems. Maize and sorghum were the crops that showed the highest energy return in relation to the other studied species. No-tillage showed higher energy conversion and balance (12.31 and 45,011 Mcal ha⁻¹) than minimum tillage (11.33 and 41,100 Mcal ha⁻¹), conventional tillage using disk plow (9.94 and 34,142 Mcal ha⁻¹) and conventional tillage using moldboard plow (10.21 and 35,170 Mcal ha⁻¹), respectively. Wheat in crop rotation had higher energy efficiency than the monoculture of this cereal.

Key words: energy balance; energy conversion; no-tillage system

Desempenho energético de sistemas de manejo do solo e de rotação culturas

RESUMO: O objetivo deste trabalho foi avaliar energeticamente sistemas de manejo de solo e de rotação de culturas. Os tratamentos consistiram em quatro tipos de manejo de solo: 1) plantio direto, 2) cultivo mínimo, 3) preparo convencional de solo com arado de discos e 4) preparo convencional de solo com arado de aivecas, e três sistemas de rotação de culturas: sistema I - trigo/soja; sistema II - trigo/soja e ervilhaca/sorgo; e sistema III - trigo/soja, ervilhaca/sorgo e aveia branca/soja. O delineamento experimental foi em blocos ao acaso, com parcelas subdivididas e três repetições. A parcela principal foi constituída pelos tipos de manejo de solo, e as sub-parcelas, pelos sistemas de rotação de culturas. O milho e o sorgo foram as culturas que mostraram maior retorno energético, em relação as demais espécies estudadas. O sistema plantio direto mostrou maior conversão energética e balanço energético (12,31 e 45.011 Mcal ha⁻¹) do que o cultivo mínimo (11,33 e 41.100 Mcal ha⁻¹) e aos dos preparos convencionais de solo com arados de discos (9,94 e 34.1428 Mcal ha⁻¹) e com arado de aivecas (10,21 e 35.170 Mcal ha⁻¹), respectivamente. O trigo em rotação de cultura foi mais eficiente energeticamente do que a monocultura desse cereal.

Palavras-chave: balanço energético; conversão energética; plantio direto

Introduction

The need in producing food for meeting the growing demand of the population has been presenting itself as a major problem. Arising in order to alleviate these problems, agricultural technological innovations aim at increasing yield, which in most cases demand a greater amount of energy, such as in systems of soil management, crop rotation, production of grain or with crop-livestock integration (Sá et al., 2013; Müller et al., 2017). This increase in the required energy is supplied by using fossil energy, considering a greater use of inputs such as fertilizers, pesticides, machinery and equipment (Santos et al., 2013). The main concern with exhausting this energy is due to the scarcity of energy resources, which is threatening the sustainability of grain production systems.

The conventional monoculture production system, based on agrochemistry, brings about a reduction in energy efficiency due to the small soil coverage (which induces losses by evaporation and erosion), associated with the great dependence on external inputs (mineral fertilizers and pesticides, both of a higher energy cost) (Teixeira et al., 2007; Souza et al., 2008; Andrea et al., 2014). In this sense, employing practices that reduce said problems can be the alternative in increasing the efficiency of the grain production systems, especially by employing crop rotations and management of species suitable for green manure, soil cover and fixation of carbon and nitrogen (Santos et al., 2011b; Ferreira et al., 2014; Costa et al., 2015).

In this process, for evaluating the energy balance, all used and produced inputs, which are later transformed into energy units, are identified and quantified. Thus, the energy flow analysis requires the unification of the product from different sources and energy converters, such as machines, human labor and fuel, in the same caloric unit (Soares et al., 2007; Santos et al., 2011a; Müller et al., 2017).

In the study by Santos et al. (2011b) about production systems with crop + livestock integration, the highest energy balance indexes occurred in the systems: wheat/soybean and vetch/maize; and wheat/soybean and pea/maize, in relation to the wheat/soybean and black oat/maize pasture systems; wheat/soybean and black oat/soybean pasture; wheat/soybean, vetch/soybean and dual-purpose triticale; and wheat/soybeans, dual-purpose white oats/soybeans and dual-purpose wheat/soybeans. Maize had the highest energy return, when compared to other grain-producing crops and winter pastures.

In another study, conducted by Santos et al. (2013), the wheat/soybean, white oat/soybean and vetch/maize systems, only for grain production; wheat/soybean, white oats/soybean and vetch/maize after perennial winter pastures; wheat/soybean, white oats/soybean and vetch/maize after perennial summer pastures; and wheat/soybean, white oats/soybean and vetch/maize after lucerne were more efficient in energy conversion than the wheat/soybean, white oats/soybean and black oat + vetch pasture system. In this case, maize was the species that showed the highest energy return in relation to other grain-producing crops and winter pastures.

There are few studies available on conversion and energy balance that compare species and crops under different systems of soil management and crop rotation. According to Hetz & Barrios (1997), the energy costs of systems with minimum cultivation and no-tillage were lower than the ones who employed conventional disc plowing. Santos et al. (2011a), when studying types of soil management and crop rotation, involving winter and summer crops, also found greater efficiency in energy consumption in the no-tillage. Among the studies with crop rotation systems, involving wheat under no-tillage, Santos et al. (2015b) stands out, with their results being superior for crop rotation when in comparison to the monoculture of this grass.

The present study aimed to evaluate the effect of soil management and crop rotation systems on the energy conversion and balance.

Materials and Methods

Data that served as basis in conducting this study came from grain yield, dry matter yield and its N amount, and the remaining straw amount from the plots species in the experiment of soil management systems and crop rotation involving wheat. This experiment was set up at Embrapa Trigo, in the municipality of Passo Fundo, RS, from 2010/2011 to 2017/2018, in soil classified as a typical Dystrophic Red Latosol (Ultisol) (Weiler et al., 2017).

Treatments consisted of four soil management types: 1) no-tillage; 2) minimum tillage in winter, and no-tillage in summer; 3) conventional tillage with disc plow in winter, and no-tillage in summer; and 4) conventional tillage with moldboard plows in winter, and no-tillage (direct sowing) in summer. The three crop rotation systems were the following: system I - wheat/soybean in monoculture; system II - wheat/soybean and vetch/sorghum or maize, in 2017; and system III - wheat/soybean, vetch/sorghum or maize, in 2017 and white oat/soybean.

The experimental design was in randomized blocks, with split-plots and three replicates. The main plot (4 m wide by 90 m long) was constituted by soil management systems, sub-plots (4 m wide by 10 m long) and by the crops that are part of the rotations.

The maintenance fertilization was performed according to the recommended for each crop (Soil Fertility and Chemistry Commission - RS/SC, 2016), also based on the soil analysis results. Soil samples were collected annually, after harvesting the summer crops.

Sowing time, weed control and phytosanitary treatments were all performed following the recommended for each crop. Harvesting was carried out with a special harvester for experimental plots, except in maize and sorghum crops, which were manually harvested. The yields of white oat, maize, soy, sorghum and wheat grains was corrected for 13% humidity.

Production matrices were used when quantifying the crop data, from which transformations were made to account for the energy available and consumed in these processes (Santos et al., 2013). For calculating the several indexes from the

systems of soil management and crop rotation, grain and dry matter yield, remaining straw amount, N amount in dry matter and field operations, data and guidelines generated by Santos et al. (2013) were used. In the vetch case, yield was considered as the contribution based on the percentage of nitrogen and dry matter straw (Table 1). The data were transformed into Mcal (kcal x 1,000) (Santos et al., 2015a).

Available energy or energy revenue (Mcal ha⁻¹) was considered as the transformation into energy of the grain yield,

the amount of N in the dry matter and the remaining straw amount from the species. For consumed energy or cultural energy (Mcal ha⁻¹), it was considered the estimated sum of the energy coefficients corresponding to the correctives, fertilizers, seeds, fungicides, herbicides and insecticides used in all types of soil management or crop rotation, as well as the energy consumed in operations (sowing, fertilization, pesticides application and harvestings). The energy conversion is result from the division of the available energy (Mcal ha

Table 1. Energy coefficients per unit of inputs, field operations, grain yield and dry matter used in soil management systems and crop rotations for wheat.

| Specification | Unit | Kcal/unit | Reference |
|---|--------|-----------|----------------------|
| Consumed energy: | | | |
| Seed - white oat | kg | 4,108 | Santos et al. (2013) |
| - vetch | kg | 7,584 | Santos et al. (2013) |
| - maize | kg | 24,806 | Santos et al. (2013) |
| - soybean | kg | 7,584 | Santos et al. (2013) |
| - sorghum | kg | 14,220 | Santos et al. (2013) |
| - wheat | kg | 3,002 | Santos et al. (2013) |
| Fertilizer - N | kg | 18,518 | Santos et al. (2013) |
| - P | kg | 3,350 | Santos et al. (2013) |
| - K | kg | 2,315 | Santos et al. (2013) |
| Fungicide - azoxystrobin + benzovindiflupir | L | 64,910 | Santos et al. (2013) |
| - azoxystrobin + Ciproconazole | L | 64,910 | Santos et al. (2013) |
| - carboxine + tyrann | kg | 51,600 | Santos et al. (2013) |
| - pyraclostrobin + metconazole | L | 64,910 | Santos et al. (2013) |
| - pirasclostrobin + methyl thiophanate + fipronil | kg | 51,600 | Santos et al. (2013) |
| - tebuconazole | L | 64,910 | Santos et al. (2013) |
| - triadimenol | kg | 51,600 | Santos et al. (2013) |
| - triflostrobin + prothioconazole | L | 64,910 | Santos et al. (2013) |
| - trifoxystrobin + tebuconazole | L | 64,910 | Santos et al. (2013) |
| Herbicide - atrazine | L | 99,910 | Santos et al. (2013) |
| - atrazine + simazine | l | 99,910 | Santos et al. (2013) |
| - bentazon | l | 99,910 | Santos et al. (2013) |
| - cletodim | L | 99,100 | Santos et al. (2013) |
| - clodinafope-propargil | L | 99,100 | Santos et al. (2013) |
| - glyphosate | L | 99,910 | Santos et al. (2013) |
| - haloxifop-r-metallic | L | 99,100 | Santos et al. (2013) |
| - iodosulfuron-methyl | kg | 62,770 | Santos et al. (2013) |
| - metsulfuron-metil | L | 99,910 | Santos et al. (2013) |
| - paraquat | l | 62,770 | Santos et al. (2013) |
| - setoxydin | L | 99,910 | Santos et al. (2013) |
| Insecticide - chlorpyrifos | kg | 74,300 | Santos et al. (2013) |
| - diflubenzorom | L | 86,910 | Santos et al. (2013) |
| - imidacloprid | kg | 74,300 | Santos et al. (2013) |
| - lambda-cyhalothrin | L | 86,910 | Santos et al. (2013) |
| - thiametoxan + lambda-cyhalothrin | L | 86,910 | Santos et al. (2013) |
| - triflumumom | L | 86,910 | Santos et al. (2013) |
| Plowing, harrowing and minimal cultivation | h/e.t. | 5,190 | Santos et al. (2013) |
| Sowing and fertilization | h/e.t. | 6,994 | Santos et al. (2013) |
| Cover or product application | h/e.t. | 2,356 | Santos et al. (2013) |
| Mechanic harvest | h/col. | 187,131 | Santos et al. (2013) |
| Produced energy: | | | |
| - white oat | kg | 4,155 | Santos et al. (2013) |
| - vetch | kg | 2,319 | Santos et al. (2013) |
| - maize | kg | 3,950 | Santos et al. (2013) |
| - soybean | kg | 4,000 | Santos et al. (2013) |
| - sorghum | kg | 3,783 | Santos et al. (2013) |
| - wheat | kg | 3,691 | Santos et al. (2013) |

h/e.t.: working hour with equipment and tractor; h/col.: working hour with harvester.

¹) by the consumed energy (Mcal ha⁻¹), in each type of soil management or crop rotation. The energy balance results from the difference between the energy available and consumed, in each type of soil management or crop rotation.

The statistical analysis consisted of the analysis of variance from the energy conversion and the energy balance, within each year (winter + summer) and the years joint mean, from the 2010/2011 to 2017/2018 harvests. In the analysis of variance, the energy available and consumed by the crops part of the types of soil management and crop rotation were all considered. In the joint analyzes, treatments were considered as a fixed effect, while the effect of the year was as random. The parameters under study were subjected to analysis of variance by using the SAS statistical program version 9.4 (SAS, 2017). Means of the types of soil management or crop rotation were evaluated by employing the Duncan test, at the level of 5% probability of error.

Results and Discussion

Means of the conversion and the energy balance, both annual and from 2010/2011 to 2017/2018, as well as the statistical comparisons, the dry matter yield, winter and summer crops, soil management and crops rotation systems, are all found in the Tables, from 2 to 7.

The analysis of variance of the conversion and the energy balance from the grouped years resulted in a significant effect of the years, the types of soil management and the crop rotations (Tables 2 to 7). Santos et al. (2011a) found similar results. Santos et al. (2011b; 2013), studying grain production systems with plantation + livestock integration, also obtained similar results of conversion and energy balance. The results presentation on energy conversion and energy balance is as it follows.

Concerning the isolated energy conversion of winter and summer crops from the soil management systems, there was a difference among the means for each year. During this study period, from the grain-producing and ground-covering crops, both in winter and in summer, maize and sorghum were more efficient in energy conversion when compared to white oat, vetch, soybeans and wheat (Table 2). Santos et al. (2011a, b; 2013), while studying production systems with plantation

and livestock integration, emphasized the energy conversion of maize and sorghum as summer crops. White oat, vetch and soybeans crops had an intermediate position in terms of energy conversion values. On the other hand, wheat had the lowest energy conversion index. In the vetch case, for soil cover and green manure, there was a reduction in the input of fossil energy, especially that related to nitrogen fertilizers application. The research by Andrea et al. (2014) with energy flows in forage production systems, also partially confirms the energy efficiency of maize and sorghum, together with perennial pastures such as *Panicum maximum* and Tifton 85, in relation to black oat, ryegrass, barley and millet.

In the period from 2010/2011 to 2017/2018, there was a difference in five out of the eight studied years, in the annual energy conversion (winter + summer) and in the mean of the years in between the soil management systems (Table 3). In the 2012/2015 agricultural harvest, the no-tillage system was superior for energy conversion, compared to conventional tillage with moldboard plows, and did not differ from conventional tillage with disc plows and minimum cultivation. In the agricultural crops of 2013/2014 and 2014/2015, the no-tillage system showed a higher energy conversion value than the other soil management types. In the agricultural harvest of 2016/2017, the no-tillage system, conventional tillage with moldboard plowing and minimum cultivation had a higher energy conversion index than the tillage with disc plow. In the 2017/2018 harvest, the no-tillage and the minimum cultivation system stood out regarding energy conversion values, in relation to conventional tillage systems. Hetz & Melo (1997) report that the increase in the grain yield of crops (maize and wheat) and, consequently, the energy efficiency of the no-tillage system has increased over time. These same authors took into account the remaining straw of the studied species. Rising balance values indicate an increase in Mcal yield per Mcal invested, mainly due to increased grain yields, dry matter and nitrogen increases in the system.

In the joint mean of this studied period (from 2010/2011 to 2017/2018), the no-tillage system (12.31) showed a higher energy conversion than that of the minimum cultivation (11.33) and conventional tillage with disc plow (9.94) and with moldboard plow (10.21). Minimum cultivation ranked in an intermediate position for energy conversion rates. According

Table 2. Energy conversion (Mcal ha⁻¹) of dry matter yield and of the winter and summer crops, over the years, in systems of soil management and crop rotation, from 2004/05 to 2009/10. Embrapa Trigo. Passo Fundo, RS.

| Harvest | Crops | | | | | | Mean |
|---------|-----------|---------|---------|----------|---------|---------|-------|
| | White oat | Vetch | Maize | Soybean | Sorghum | Wheat | |
| 2010/11 | 10.71 C | 15.90 B | - | 10.99 C | 21.09 A | 10.32 C | 13.30 |
| 2011/12 | 11.12 B | 23.32 A | - | 4.40 D | 8.97 C | 11.97 B | 10.77 |
| 2012/13 | 9.14 C | 12.65 B | - | 9.30 C | 15.49 A | 6.96 D | 10.29 |
| 2013/14 | 8.01 BC | 6.30 C | - | 12.21 A | 11.06 A | 8.70 B | 9.81 |
| 2014/15 | 11.15 B | 18.21 A | - | 10.16 BC | 8.96 C | 6.63 D | 10.50 |
| 2015/16 | 12.62 AB | 7.45 C | - | 13.90 A | 13.86 A | 7.99 BC | 11.23 |
| 2016/17 | 11.75 C | 5.73 D | - | 15.26 B | 18.05 A | 11.74 C | 12.96 |
| 2017/18 | 10.90 C | 2.51 E | 14.16 A | 12.63 B | - | 7.92 D | 9.88 |
| Mean | 10.68 B | 11.51 B | 14.15 A | 11.11 B | 13.93 A | 9.03 C | 11.09 |

Means followed by the same letter, horizontally, do not show significant differences, by Duncan test, at the level of 5% probability of error.

Table 3. Effect of soil management types on energy conversion (Mcal ha⁻¹), in the harvests (winter + summer) from 2004/05 to 2009/10. Embrapa Trigo. Passo Fundo, RS.

| Harvest | Soil management systems | | | | Mean |
|---------|-------------------------|---------|---------|----------|---------|
| | NT | CTD | CTM | MC | |
| 2010/11 | 14.24 A | 12.77 A | 13.30 A | 13.61 A | 13.48 a |
| 2011/12 | 10.27 A | 10.11 A | 9.98 A | 9.85 A | 10.05 b |
| 2012/13 | 12.11 A | 9.83 AB | 9.28 B | 10.40 AB | 10.41 b |
| 2013/14 | 13.02 A | 8.16 C | 8.16 C | 10.28 B | 9.90 c |
| 2014/15 | 11.45 A | 8.18 B | 8.59 B | 9.23 B | 9.36 c |
| 2015/16 | 11.87 A | 9.56 A | 9.70 A | 13.05 A | 11.04 b |
| 2016/17 | 13.88 A | 11.51 B | 13.46 A | 13.35 A | 13.05 a |
| 2017/18 | 11.67 A | 9.38 B | 9.19 B | 10.92 A | 10.29 b |
| Mean | 12.31 A | 9.94 C | 10.21 C | 11.33 B | 10.95 |

NT: no-tillage; CTD: conventional tillage with disc plow in winter, and no-tillage (direct sowing) in summer; CTM: conventional tillage with moldboard plow in winter and no-tillage (direct sowing) in summer; and MC: minimum cultivation in winter and no-tillage (direct sowing) in summer. Means followed by the same uppercase letter horizontally and lowercase vertically, do not show significant differences by the Duncan test, at the level of 5% probability of error.

to Hetz & Barrios (1997), the energy costs of soil management types with minimal cultivation and no-tillage were notably lower than the values of conventional tillage with disc plows. In the evaluation of the period from 2004/2015 to 2009/2010 (Santos et al., 2011a), the no-tillage system was superior, in terms of energy conversion rates, to the minimum cultivation and conventional tillage. The greater energy conversion in the no-tillage system, in relation to the conventional tillage management, can be partially explained by the reduction of the energy demands caused by the decreasing number of agricultural operations (Santos et al. 2011a; Townsend et al., 2016; Müller et al., 2017). Moreover, it should be considered that in all soil management systems in this study the remaining straw was also computed as produced energy, with it being higher in no-tillage than in the other studied managements.

In most of the studied years and in the analysis of the years joint mean, there were differences between the energy conversions of the different crop rotation systems (Table 4). The highest value in most harvests, with respect to energy conversion, manifested under crop rotation, in the systems II (wheat/soybean and vetch/sorghum or maize) and III (wheat/soybean, white oat/soybean and vetch/sorghum or maize), compared to the system I (wheat/soybean monoculture). In the present study, maize and sorghum produced more straw than wheat. Therefore, crop rotation (systems II and III) was more efficient in energy conversion when compared to the

wheat/soybean monoculture (system I). This efficiency is, in part, due to the amount of remaining maize or sorghum straw, added as produced energy, which in this study was greater than that of winter and soybean crops.

Regarding the energy conversion index, systems II (11.32) and III (11.34) were, in the analysis of the years joint means, superior to system I (9.04) (Table 4). This may be partly due to the cultivation of maize or sorghum, which showed greater energy conversion than soybean and the studied winter species. Hetz & Melo (1997) report maize as an efficient crop (127,218 MJ ha⁻¹) in converting energy, in comparison to wheat (63,250 MJ ha⁻¹). Santos et al. (2011b), when working with production systems with crop + livestock integration from 2003/2004 to 2008/2009, found higher rates of energy conversion in the following systems: I: wheat/soybean and vetch/maize (49.52); and IV: wheat/soybean and pea/maize (52.12), compared to systems II: wheat/soybean and black oat/maize pasture (44.54); III: wheat/soybean and black oat/soybean pasture (39.64); V: wheat/soybean, vetch/soybean and dual-purpose triticale (42.82); and VI: wheat/soybean, dual-purpose white oat/soybean and dual-purpose wheat/soybean (40.71). According to the same authors, it is likely that the difference in favor of systems I and IV is related to the maize crop presence. It was preceded by winter green manure crops, which did not receive maintenance fertilizer, thus consuming less energy and providing more available energy to

Table 4. Effect of crop rotation systems on energy conversion (Mcal ha⁻¹), in the harvests (winter + summer) from 2004/05 to 2009/10. Embrapa Trigo. Passo Fundo, RS.

| Harvest | Crop rotation systems | | | Mean |
|---------|-----------------------|-----------|------------|---------|
| | System I | System II | System III | |
| 2010/11 | 9.29 B | 14.73 A | 14.04 A | 13.48 a |
| 2011/12 | 7.98 B | 10.85 A | 10.21 A | 10.05 b |
| 2012/13 | 7.62 B | 11.03 A | 10.92 A | 10.41 b |
| 2013/14 | 9.77 A | 9.22 A | 10.41 A | 9.90 c |
| 2014/15 | 7.24 B | 9.65 A | 9.88 A | 9.36 c |
| 2015/16 | 8.80 A | 12.31 A | 10.95 A | 11.04 b |
| 2016/17 | 12.75 A | 12.78 A | 13.33 A | 13.05 a |
| 2017/18 | 8.85 B | 9.97 A | 10.98 A | 10.29 b |
| Mean | 9.04 B | 11.32 A | 11.34 A | 10.95 |

System I: wheat/soybean; System II: wheat/soybean and vetch/sorghum; and System III: wheat/soybean, white oat/soybean and vetch/sorghum. Means followed by the same uppercase letter horizontally, and lowercase vertically, do not show significant differences by Duncan test, at the level of 5% probability of error.

the systems and to the maize, grown without nitrogen cover fertilization. This made systems I and IV more energy efficient and had a direct impact on the systems energy conversion.

The evaluated types of soil management and crop rotation showed positive energy conversion rates (above 1.0), which means that all of them produced more energy than what they consumed (9.04 to 12.31). In this case, the studied types of soil management or crop rotation can be considered sustainable from an energy point of view.

In a study of production systems with crop + livestock integration, Santos et al. (2013) found that the wheat/soybean, white oat/soybean and vetch/maize systems, only for grain production (14.74); wheat/soybean, white oat/soybean and vetch/maize after perennial winter pasture (13.99); wheat/soybean, white oat/soybean and vetch/maize after perennial summer pastures (14,19); and wheat/soybean, white oat/soybean and vetch/maize after lucerne (13.80) were more efficient in energy conversion than the wheat/soybean, white oat/soybean system and pasture of black oat + vetch (11.73). According to the same authors, the reason for this difference in favor of systems I, III, IV and V, in reaction to system II, may be related to their maintenance and top-dressing fertilization.

There were differences between the means of each year, of the isolated energy balance of the dry matter yield from winter and summer crops and of the soil management types.

In the period from 2004/2005 to 2009/2010, sorghum was the most efficient crop regarding energy conversion when compared to the other studied crops (Table 5). Comparable results of energy yields were obtained in the maize crop by Hetz & Melo (1997) and Santos et al. (2011a), who compared winter and summer species in types of soil management and crop rotation for several years in Concepción, Chile and Passo Fundo, RS, Brazil, respectively. However, all other studied species (white oat, vetch, wheat, soybean and sorghum), winter and summer alike, consumed less energy than what they took from the system.

When compared, the energy balance means from 2009/2010 to 2017/2018 showed differences between the soil management types, in six of the eight agricultural crops studied and in the years joint mean (Table 6). In the 2010/2011 and 2017/2018 agricultural harvests, the no-tillage system had a higher energy balance than the conventional tillage systems. In the agricultural harvests of 2012/2013, 2013/2014 and 2014/2015, the planting system was superior to the other studied systems regarding the energy balance index. However, in the 2016/2017 agricultural harvest, the no-tillage system, conventional tillage with moldboard plowing and minimum cultivation all showed higher energy balance values, in comparison to the conventional tillage system with disc plow.

Table 5. Energy balance (Mcal ha⁻¹) of dry matter yield and winter and summer crops, in the years mean, in soil management types and crop rotation systems, from 2004/05 to 2009/10. Embrapa Trigo. Passo Fundo, RS.

| Harvest | Crops | | | | | | Mean |
|---------|-----------|----------|----------|-----------|-----------|-----------|----------|
| | White oat | Vetch | Maize | Soybean | Sorghum | Wheat | |
| 2010/11 | 30.909 A | 9.683 D | - | 15.165 C | 25.463 B | 29.262 A | 20.803 b |
| 2011/12 | 25.600 B | 14.370 C | - | 5.797 D | 15.195 C | 27.868 A | 15.960 c |
| 2012/13 | 20.659 B | 8.791 D | - | 15.350 C | 30.405 A | 14.489 C | 16.993 c |
| 2013/14 | 19.796 A | 3.305 B | - | 19.228 A | 21.230 A | 21.706 A | 17.574 b |
| 2014/15 | 25.098 A | 10.631 C | - | 16.570 B | 17.100 B | 19.133 B | 17.020 b |
| 2015/16 | 34.426 A | 7.844 D | - | 19.157 CD | 32.182 AB | 20.792 BC | 21.123 a |
| 2016/17 | 32.903 A | 5.769 C | - | 20.878 B | 34.499 A | 32.741 A | 24.597 a |
| 2017/18 | 29.927 B | 2.012 D | 43.020 A | 18.773 C | - | 20.370 C | 21.349 a |
| Mean | 27.415 B | 7.801 E | 43.020 A | 16.365 D | 25.153 BC | 23.295 C | 19.428 |

Means followed by the same uppercase letter horizontally and lowercase vertically, do not show significant differences by the Duncan test, at the level of 5% probability of error

Table 6. Effect of soil management systems on the energy balance (Mcal ha⁻¹), in the harvests (winter + summer) from 2004/05 to 2009/10. Embrapa Trigo. Passo Fundo, RS.

| Harvest | Soil management systems | | | | Mean |
|---------|-------------------------|-----------|-----------|-----------|----------|
| | NT | CTD | CTM | MC | |
| 2010/11 | 45.559 A | 38.334 B | 39.745 B | 42.791 AB | 41.607 b |
| 2011/12 | 33.647 A | 31.357 A | 30.840 A | 31.839 A | 31.921 c |
| 2012/13 | 41.066 A | 31.062 BC | 29.159 C | 34.658 B | 33.986 c |
| 2013/14 | 47.101 A | 27.851 C | 28.050 C | 37.594 B | 35.149 b |
| 2014/15 | 42.811 A | 28.999 C | 30.467 BC | 33.885 B | 34.040 c |
| 2015/16 | 46.775 A | 35.545 A | 36.289 A | 50.378 A | 44.246 a |
| 2016/17 | 53.379 A | 42.164 B | 49.877 A | 51.361 A | 49.195 a |
| 2017/18 | 49.746 A | 37.823 B | 36.933 B | 46.292 A | 42.698 a |
| Mean | 45.011 A | 34.142 C | 35.170 C | 41.100 B | 38.855 |

NT: no-tillage; CTD: conventional tillage with disc plow in winter, and no-tillage (direct sowing) in summer; CTM: conventional tillage with moldboard plow in winter and no-tillage (direct sowing) in summer; and MC: minimum cultivation in winter and no-tillage (direct sowing) in summer. Means followed by the same uppercase letter horizontally and lowercase vertically, do not show significant differences by the Duncan test, at the level of 5% probability of error.

Table 7. Effect of crop rotation systems on energy balance (Mcal ha⁻¹), in the harvests (winter + summer) from 2004/05 to 2009/10. Embrapa Trigo. Passo Fundo, RS.

| Harvest | Crop rotation systems | | | Mean |
|---------|-----------------------|-----------|------------|----------|
| | System I | System II | System III | |
| 2010/11 | 38.615 B | 39.641 AB | 43.916 A | 41.607 b |
| 2011/12 | 29.612 A | 32.196 A | 32.507 A | 31.921 c |
| 2012/13 | 28.342 B | 33.410 A | 36.252 A | 33.986 c |
| 2013/14 | 39.857 A | 29.791 B | 37.152 AB | 35.149 b |
| 2014/15 | 32.549 A | 32.737 A | 35.406 A | 34.040 c |
| 2015/16 | 34.800 A | 45.676 A | 42.443 A | 42.246 a |
| 2016/17 | 53.078 A | 45.570 B | 50.318 AB | 49.195 a |
| 2017/18 | 35.802 B | 41.184 A | 46.007 A | 42.698 a |
| Mean | 36.582 B | 37.526 AB | 40.500 A | 38.855 |

System I: wheat/soybean; System II: wheat/soybean and vetch/sorghum; and System III: wheat/soybean, white oat/soybean and vetch/sorghum. Means followed by the same capital letter horizontally, and lowercase vertically, do not present significant differences, according to the Duncan test at the level of 5% probability of error.

The energy balance indexes from no-tillage system (45,011 Mcal ha⁻¹), in the joint mean of the agricultural harvests (2010/2011 to 2017/2018), were higher than the other soil management types of minimum cultivation: 41,100 Mcal ha⁻¹, conventional tillage with disc plow: 34,142 Mcal ha⁻¹ and with moldboard plow: 35,170 Mcal ha⁻¹ (Table 6). The minimum cultivation index ranked between the other soil managements and the no-tillage system. In this study, the soil management type that consumed most energy (conventional tillage with disc plow and moldboard plow) obtained the lowest energy return. Santos et al. (2011a) previously found a similar result by using this same experiment, in the evaluation of the harvests from 2004/2005 to 2009/2010.

In most of the studied years and their joint mean, there were differences between the obtained energy balance in the different crop rotation systems evaluated (Table 7). In the 2010/2011 harvest, system III (wheat/soybean, white oat/soybean and vetch/sorghum or maize) showed a higher energy balance than system I (monoculture wheat/soybean); however, it did not differ from system II (wheat/soybean and vetch/sorghum or maize). In the 2012/2013 and 2017/2018 harvests, systems II and III were superior to system I regarding energy balance indexes. In the 2013/2014 and 2016/2017 harvests, system I showed a higher energy balance when compared to system II; however, it did not differ from system III. In the joint mean of the harvests (from 2010/2011 to 2017/2018), system III (40,500 Mcal ha⁻¹) had a higher energy balance index when compared to system I (36,582 Mcal ha⁻¹), but it did not differ from system II (37,526 Mcal ha⁻¹). This may be due, in part, to the sorghum crop, which was the most efficient species in harnessing the available energy.

In the study developed by Santos et al. (2011b) with production systems with crop + livestock integration, from 2003/2004 to 2008/2009, the following systems: I: wheat/soybean and vetch/maize (148,854 Mcal ha⁻¹); II: wheat/soybean and black oat/maize pasture (155,543 Mcal ha⁻¹); and IV: wheat/soybean and pea/maize (159,487 Mcal ha⁻¹), all had higher energy balance indexes than the other systems; III: wheat/soybean and black oat/soybean pasture (122,734 Mcal ha⁻¹); V: wheat/soybean, vetch/soybean and dual-purpose triticale (120,808 Mcal ha⁻¹); and VI: wheat/soybean,

dual-purpose white oat/soybean and dual-purpose wheat/soybean (130,000 Mcal ha⁻¹). According to the same authors, the biggest difference in energy balance when compared to the others is, in part, due to the maize crop, the species with the highest energy return.

When working with production systems that had crop + livestock integration, Santos et al. (2013) found that the wheat/soybean, white oat/soybean and black oat + vetch pasture (42,671 Mcal ha⁻¹) systems were superior, in terms of energy balance indexes, to the system of wheat/soybean, white oat/soybean and vetch/maize after lucerne (39,596 Mcal ha⁻¹). The wheat/soybean, white oat/soybean and vetch/maize systems, only for grain production (42,160 Mcal ha⁻¹); wheat/soybean, white oat/soybean and vetch/maize after perennial winter pasture (40,204 Mcal ha⁻¹); and wheat/soybean, white oat/soybean and vetch/maize after perennial summer pastures (40,688 Mcal ha⁻¹) were in an intermediate position for the energy balance values.

Ferreira et al. (2014) analyzed the energy balance during the production process of main cereals in Rio Grande do Sul, in three production units from Rio-grandense Rice Institute: 1) irrigated rice cultivation with production systems with crop + livestock integration, with soybean cropping under no-tillage system alternating with ryegrass pasture; 2) irrigated rice cultivation with crop-livestock integration, with soybean cropping under no-tillage system and ryegrass pasture; and 3) wheat and soybean cultivation under no-tillage system. The same authors found that soybean activity under no-tillage system with crop rotation attained the highest energy efficiency.

Conclusions

The highest rates of conversion and energy balance occurred in the no-tillage system, in comparison to the other soil management types.

The rotation systems of wheat/soybean and vetch/sorghum and wheat/soybean, vetch/sorghum and white oat/soybean are to be preferred since they are more efficient in energy conversion, in substitution to the wheat and soybean monoculture.

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