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Energy life-cycle analysis of soybean biodiesel: Effects of tillage and water management

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ABSTRACT

The purpose of this paper is to carry out an updated energy Life-Cycle Assessment of soybean biodiesel produced in the Pampean region of Argentina and to analyze the influence of different tillage systems on the Energy Return on Investment (EROI). It aims to identify the processes, materials and methodological aspects that significantly affect biofuel EROI. The procedure considers the main processes and operations of both the agriculture and industrial stages of biofuel production system, but the main novelty of this study is linking EROI with farming and conservation practices and not in the chemical processing of the oil. The results obtained represent the current average energetic performance of soy-based biodiesel produced in the considered region. The EROI values are very encouraging, demonstrating that this biodiesel provides a net energy gain. The results also show that conservation agriculture and the implementation of practices that improve crop yield do not always determine better energetic performance. Sensitivity analysis confirms that EROI values of soybean biodiesel are more responsive to methodological choices such as the system's boundary definition and the choice of the allocation method rather than to the physical aspects of the productive system such as tillage and water management practices.

1. Introduction

Two global threats have fostered the development of biofuels, mainly from the beginning of the current century. One is the proximity of the global oil peak, whose exact date of occurrence is unknown, but which will undoubtedly occur. The other is the economic, social and environmental consequences of the global climate change.

Biofuels appear to be an opportunity for tackling these two problems, suggesting a potential for saving conventional fossil fuels while mitigating climate change. However, they are not exempt from controversy, ranging from land/water competition with food production, the threat to biodiversity, and the lack of cost effectiveness, among others [1].

This discussion is of utmost importance, and the controversy should be addressed by science, allowing these negative aspects to be solved or diminished. However, these efforts will only be compensated if biofuels' essential attribute, the capacity for providing net energy, is verified.

One of the indicators commonly used to verify this capacity is Energy Return on Investment (EROI), calculated as the ratio between the energy delivered by the biofuel and the energy required to deliver that energy. If EROI is greater than 1.0, there is a net energy gain; otherwise, the biofuel is an energy sink. Biofuels with an EROI lower than 1.0 cannot substitute fossil fuels; on the contrary, they accelerate their depletion. Clearly, biofuel sustainability (as any other energy source) relies on the size of the margin between EROI and 1.0 [2–4].

Many studies have been performed to evaluate the EROI of biofuels, with the aim of demonstrating their high-energy value and the important role they can play in the energy sector [3]. However other studies show only modest energy advantages which do not compensate others environmental and social drawbacks [5], and others report EROI which suggest that more energy is required to produce the biofuel than is contained in the biofuel itself [6]. These are just a few of the many studies illustrating the important role that EROI plays in the decision-making process regarding energy sources and vectors.

Soybean (*Glycine max*) is one of the most important feedstocks

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for biodiesel production, as indicated by the huge amount of soybean biodiesel EROI studies that can be found in literature [7–12]. There are few studies on the cumulative energy demand and the energy balance of Argentine biodiesel [13–16]. These studies have been developed for different regions of the country, analyzing different technology levels and following different methodological considerations. However, no studies linking EROI with farming and conservation practices have been found.

No-tillage is a widespread conservation agricultural practice in Argentina that consists in the absence of plowing and in the presence of a permanent soil cover with previous crop stubble. According to the United Nations Food and Agriculture Organization, no-tillage is one of the main factors that favored the global boom in soybean production in the last decade [17]. Currently, about 135 million hectares are cropped around the world under no-tillage [18] concentrated in a few countries: the United States, Brazil and Argentina among them.

The aim of this study is to determine the EROI of soybean biodiesel produced in the Pampean region of Argentina, considering different practices in crop management: a) conventional tillage; b) no-tillage; c) rainfed cultivation and d) cultivation under supplementary irrigation. In addition, the influence of system boundaries and different allocation methods commonly used is studied.

1.1. Soybean biodiesel production in Argentina

Over eighty-six percent of Argentine soybean is produced in the Pampean region situated in the east central region of the country. This region is home to the main vegetable oil and biodiesel hub of Argentina and has specific infrastructure for export through the Parana-Uruguay waterway.

In the Pampean region, 88% of the total cultivated area is under no-tillage [19]. This agricultural technology does not harm the soil, often improving its physical, chemical and biological conditions, thus increasing productivity levels per hectare of occupied land. Around 70% of the area under no-tillage is sown between October and November (early soybean), and the remaining area during December (late soybean). Typically, the late soybean is planting after a winter crop and develops its cycle during a limited period, exposing itself to unfavorable environmental conditions (such as early frost, insufficient incident solar radiation or temperature). Therefore, crop yields are usually lower for late soybean than for early soybean.

In addition, some production schemes respond to conventional tillage, which involves disking, plowing, and other methods of tilling up crop stubble left behind after harvest. This technology reduces the presence and incidence of pests and diseases, but increases the risk of soil erosion.

The rainfall rate of the Pampean region allows soybean cultivation under rainfed conditions. However, there is an increase in the land area occupied by soybean under supplementary irrigation, usually supplied from groundwater sources [20], which allows achieving more stable yields, advancing the planting date and implementing an Integrated Pest Management (IPM) system. The IPM system allows for a more rational use of pesticides, which are applied to remove only target organisms.

At harvest time, soybean moisture content is 16%, which should be reduced up to 10% to optimize storage and subsequent entry into the oil-milling process. Solvent extraction is the most common technology for production of vegetable oil in Argentina [21]. This process includes the extraction of soybean oil, soybean meal desolventization, micelle (oil solution in solvent) distillation, gas condensation and solvent recovery. Later, the refined soybean oil is subject to alkaline transesterification to obtain soybean oil Methyl Ester (MEs) and glycerol.

2. Methodology: Life Cycle Assessment and energy return on investment

Life Cycle Assessment (LCA) is a tool for evaluating the potential environmental impacts generated by products and services during their whole life cycle, from raw material acquisition through manufacturing, use, end-of-life treatment, recycling and final disposal. The International Organization for Standardization (ISO) has standardized this method in ISO 14040:2006 [22] and ISO 14044:2006 [23]. An LCA provides comprehensive evaluations of all upstream and downstream inputs and multimedia environmental emissions. The environmental impact information provided by an LCA can be connected to many impact categories, such as abiotic resource depletion, global warming potential, energy consumption or human toxicity, to name just a few. Many LCA studies consider only a single environmental issue instead, like for instance global warming potential (known as the product's carbon footprint), the impact of water use (known as the product's water footprint), or the amount of energy required for the creation of a given product.

There are different useful indicators that have been devised for estimating product energy efficiency from a life cycle perspective. Their calculation methodology includes an energy balance, where the energy inputs and outputs are compared through arithmetic operations. EROI is the most widely used indicator, calculated as the ratio between the energy obtained and the total energy spent to obtain it. The concept was coined by ecologist Charles Hall for the metabolism of fish [23]. Later on, its use was extended to human activities such as fuel production [2–4]. An EROI of 1.0 is the cutoff point for an energy source [24].

Of the many impact categories that can be included in a product's LCA, only energy will be examined in this paper, using the standard energy return on investment ratio ($EROI_{ST}$) indicator, calculated as the ratio between the energy output and the sum of the direct and indirect energy consumed to generate that output [4] (Eq. (1)).

$$EROI_{ST} = Energy\ \ output/(Direct\ energy\ input + Indirect\ energy\ input) \tag{1}$$

Since both the numerator and denominator of Equation (1) are expressed in the same energy units, the result is dimensionless. The numerator of the EROI formulae, i.e. the energy that the biofuel can provide (usually expressed as Lower Heating Value), does not present significant variability, when the same biofuel produced from the same feedstock is considered. The denominator - the energy consumed to obtain the biofuel - presents a wide variability instead, some of them due to the intrinsic characteristics of the system, and other to methodological choices.

The main characteristics of the system that influence EROI are the crop yield, the amount and type of fertilizers and pesticides applied, the farming and harvest technology, the origin of the inputs, the transportation distances, the climatic conditions, the irrigation system and the processing technology among others.

The methodological issues are related with the calculation procedure, which includes some conceptual and practical choices such as the definition of the functional unit, system boundaries, data collection and allocation procedure.

In the following, both the intrinsic characteristics and the specific methodological issues of the system under study are described.

2.1. Description of the system

The production of soybean biodiesel is composed of two main stages: agricultural and industrial (Fig. 1). In general terms, the agricultural stage includes site preparation, seed inoculation,

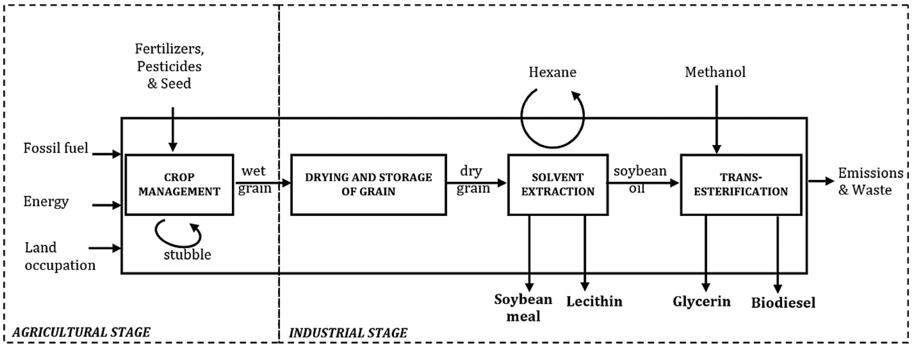

Fig. 1. Process flow diagram of soybean oil biodiesel considering the most widespread technologies in Argentina.

sowing, fertilization, management of crop pests and diseases, irrigation and harvesting. Depending on the farming scheme, some of these processes may or may not appear. For instance, in no tillage schemes the site preparation is not carried out, and stubble from the previous season is left on the soil surface; while in the conventional tillage the site preparation consists of the deep plowing of about 20 cm, followed by the refining of the soil, without stubble on the surface. The water requirement of the soybean is completely supplied by the precipitation, except in the areas under supplementary irrigation in which underground water is distributed using center pivot equipment.

Four agricultural production schemes implemented in the Pampean region are considered in this study: early soybean in no-tillage under rainfed conditions (hereafter referred to as no-till early); late soybean in no-tillage under rainfed conditions (hereafter referred to as no-till late); early soybean in no-tillage under supplementary irrigation (hereafter referred to as no-till irrigated); and early soybean in conventional tillage under rainfed conditions (hereafter referred to as till-early). Each of these farming schemes present a substantial variation in soybean yields. Technical reports from *Instituto Nacional de Tecnología Agropecuaria* (Argentina's National Institute of Agricultural Technology-INTA) attribute falls of up to 20% in crop yields under conventional tillage compared to no-tillage and increases of more than 30% in systems that incorporate supplementary irrigation [16,25,26]. Based on these studies, the crop yields adopted for each production scheme are: 2800 kg ha^{-1} for no-till early, 2200 kg ha^{-1} for no-till late, 3800 kg ha^{-1} for no-till irrigated, and 2380 kg ha^{-1} for till-early.

The mean distance from the agricultural to the industrial area is approximately 330 km. The first 300 km 80% of the grain is transported by road and the remaining 20% by rail. The last 30 km it is transported by short freight [15].

The industrial stage includes grain drying and storage, extraction of soybean oil, and production of MEs (Fig. 1). The grains are dried using different types of fuel (diesel, natural gas and liquefied gas) and cleaned through physical methods. Later, the grains are reduced to 1/8 of the original size over mechanical rolls. The crushed material is heated up to 80 °C and sheets are formed using flat rollers. The sheets are then expanded by addition of steam and transported to the oil extraction system, where they are brought into contact with the solvent (hexane). The micelle (oil solution in hexane) is treated with steam to separate the vegetal oil from the solvent. The hexane is recovered by condensation and re-entered into the system. The vegetal oil is degummed and deodorized, bleached, and neutralized, obtaining refined oil and lecithin. The solid waste is subjected to a desolventizing-toasting process, obtaining soybean meal. Subsequently, the refined oil is submitted to an alkaline transesterification process in which an alcohol (methanol) and a catalyst (sodium hydroxide) are used. Because the transesterification reaction is reversible, methanol is used in excess to shift the chemical equilibrium towards the product side. The soybean oil, methanol and sodium hydroxide mixture is centrifuged to remove excess methanol, glycerin and impurities. Finally, the mixture is washed with a water acid solution and dried, obtaining the MEs. Some companies further refine the glycerin in order to achieve pharmaceutical grade glycerin.

The main inputs for both the agricultural and industrial stages are produced in Argentina, including 100% of seeds, 17% of inoculants, 66.1% of nitrogen fertilizers, 18.7% of phosphate fertilizers, 88% of pesticides and 100% of hexane, bentonite, methanol, sodium hydroxide, phosphoric acid, and sulfuric acid [27–30]. They are transported 150 km on average from the manufacturing zone to the retail site, and then 30 km to the agricultural or industrial site. The rest of the inputs, imported from the United States, Belgium, Brazil and other countries, are transported from the manufacturing area to the Port of Rosario, then 300 km from the port to the retail area, and finally, 30 km to the agricultural area.

2.2. Methodological choices: functional unit, boundaries definition and allocation procedure

The functional unit (FU) provides a reference to which the inputs and outputs of the system are related. Functional units vary among different systems and research objectives, and this hinders the comparison of results. In the case of biofuels most studies use 1 MJ as a FU. However, if different fuels are to be compared for transportation purposes, there could be a difference on the engines' mechanical efficiencies, thus resulting in a dissimilar travelled distance for the same amount of energy consumed. In this article, the focus is in one type of fuel: soybean biodiesel. Therefore, the FU defined as “1 MJ of energy obtained from soybean biodiesel” is appropriated.

This work considers the main processes of both the agriculture and industrial stages of a soybean biofuel production system. The distribution and use of biodiesel and co-products are excluded from the system boundaries.

Foreground inventory data for agricultural inputs have been extracted from Donato et al. [16]; Martelloto et al. [31] and Ferraris et al. [32]. The data about industrial inputs have been obtained from Huerga et al. [14] and Jungbluth et al. [33].

The European Union was the main destination market for soybean biodiesel until 2012. This is why the LHVs used by the European Commission [34,35] have been adopted for the assessment of energy output. The energy embodied in agricultural and industrial inputs during their life cycle has been taken from Ecoinvent [36].

In many product-systems, more than one product is obtained. As mentioned in the previous paragraph, in the product-system considered in this work, soybean oil, meal, lecithin, biodiesel and glycerin are obtained (Fig. 1). The total environmental load produced by the system must be allocated among those products.

The ISO suggests that allocation should be avoided whenever possible, subdividing or expanding the system [22,37]. The subdivision approach is the partition of the unit processes into two or more sub-processes in order to isolate the input and output flows directly associated with each sub-process. The system expansion approach takes into account the additional functions of the related co-products. This procedure assumes that co-products completely replace one or more outputs produced in other product-systems, avoiding their environmental loads. When it is not feasible to subdivide or expand the system, the input and output flows are allocated among the different co-products according to a measurable physical relationship between them (such as mass or heat value). When the physical relationship cannot be established, the inputs and outputs of the system are allocated according to other relationships existing between the co-products (such as market value).

The European Renewable Energy Directive-RED 2009/28/EC has indicated an alternative hierarchy to ISO for selecting methods for handling co-products, preferring energy allocation over other approaches.

This paper analyzes different methods for handling co-products following the hierarchy established by ISO. Firstly, the expansion approach is applied. The soybean meal obtained in the oil extraction process is used as a replacement of rye in livestock feeding, with a protein content ratio of 1:1.23 [38]. The glycerin obtained in the MEs synthesis has a degree of purity similar to that of glycerin for industrial uses (75–80%). Therefore, in this study soybean glycerin replaces propylene glycol as an anticoagulant. It is assumed that the amount of lecithin obtained during the production of soybean biodiesel is not enough to satisfy the growing demand for this product. Consequently, lecithin is excluded as co-product in the expansion approach. Table 1 shows the inventory data for system expansion.

Secondly, allocation based on two physical relationships is performed: mass and energy. In the mass approach, allocation is done considering the amount of mass of each product and co-product obtained when they leave the system. In the energy approach, the allocation is performed by considering the LHV of each product and co-product.

Thirdly, the economic approach is applied. This allocation is a function of the international trade values (FOB-Free on Board Prices), taking into account that demand is the main driving force of the production system. Table 2 shows the allocation factors for mass, energy and economic approaches.

Table 1
Inventory data for system expansion.

Avoided product	Inventory data (kg/MJ)
Soybean oil extraction	
Rye feed	1,73E-01
MEs synthesis	
Propylene glycol	3,2E-03

3. Results

In this article, four production schemes are studied, considering the energy incorporated in the agricultural and industrial inputs, the average transported distances of these inputs from their manufacturing sites to the agricultural or industrial zones, and the product's average transported distance from these zones to the retail site. The energy approach is chosen for allocation purposes.

3.1. Manufacture and transportation of inputs and manufacture of farm machinery

Table 3 presents the energy consumed during the production and transportation of agrochemicals and industrial inputs, and for the manufacturing of farm machinery. In general terms, the manufacture of agricultural and industrial inputs is more relevant than their transportation.

For all the considered productive schemes, the methanol is the most energy demanding industrial input, followed by the agrochemicals: fertilizers in the conventional and in irrigated schemes, and herbicides in no-till early and no-till late schemes.

In no-till irrigated scheme, farm machinery production is the most significant contributor to the total energy consumption because it requires extra equipment to apply the irrigation water.

3.2. Production of soybean

The energy consumed in the soybean production differs considerably among the different production schemes studied (Table 4). Due to pre-sowing soil preparation, the conventional scheme requires more energy than the no-till schemes, except for the irrigated scheme, which is the most energy demanding system during the production stage.

No-till late soybean uses the residual nitrogen from the predecessor crop, saving the fuel required for the fertilization process. However, in relative terms this scheme consumes more fuel than no-till early during sowing and harvesting practices, due to the lowest crop yield per hectare of occupied land. The irrigated scheme increases water availability for crop development and allows advancing the planting date and implementing an integrated pest management system, thus resulting in a 35% crop yield increases compared to the rainfed schemes. The more rational use of pesticides also reduces 51% of the amount of energy required for pest management compared to no-till early. However, the irrigated scheme consumes energy for pumping irrigation water, which accounts for 84% of the total energy consumed during the soybean cultivation. The energy savings are not enough to compensate the energy requirements for irrigation.

Table 2
Allocation factors for products and co-products.

Product/Co-product	Mass allocation	Energy allocation		Economic allocation	
	Factor (%)	LHV (MJ/kg)	Factor (%)	FOB (U$/ton)	Factor (%)
Soybean oil extraction					
Refined soybean oil	17.42	32.2	28.43	862	25.30
Soybean meal	81.89	17.0	70.56	526	73.45
Lecithin	0.69	29.0	1.01	807	0.95
MEs synthesis					
Soybean oil biodiesel	89.30	37.5	94.99	621	89.80
Glycerin for industrial uses	10.70	16.5	5.01	586	10.20

Table 3
Energy consumed (in MJ/MJ of biofuel) in the manufacture and transportation of inputs and in the manufacture of the farm machinery, used to produce soybean biodiesel.

	No-till early	No-till late	No-till irrigated	Till early
Manufacture of agricultural inputs				
Seed	3.22E-02	4.38E-02	2.21E-02	3.54E-02
Inoculants	1.11E-02	1.54E-02	8.94E-03	1.23E-02
Fertilizers	1.52E-01	0.00E+00	2.41E-01	9.65E-02
Herbicides	2.13E-01	1.57E-01	8.55E-02	6.32E-02
Fungicides and insecticides	2.39E-02	1.14E-02	6.38E-02	3.56E-02
Total	4.32E-01	2.28E-01	4.21E-01	2.43E-01
Manufacture of industrial inputs				
Phosphoric acid	6.15E-04	6.15E-04	6.15E-04	6.15E-04
Bentonite	1.58E-04	1.58E-04	1.58E-04	1.58E-04
Methanol	3.84E-01	3.84E-01	3.84E-01	3.84E-01
Sodium hydroxide	3.78E-03	3.78E-03	3.78E-03	3.78E-03
Sulphuric acid	3.90E-04	3.90E-04	3.90E-04	3.90E-04
Water	1.35E-04	1.35E-04	1.35E-04	1.35E-04
Total	3.89E-01	3.89E-01	3.89E-01	3.89E-01
Manufacture of farm machinery				
Tillage & Seeding	9.61E-03	1.23E-02	7.08E-03	6.66E-02
Spraying	1.18E-02	1.50E-02	4.91E-03	1.38E-02
Irrigation	0.00E+00	0.00E+00	3.85E-01	0.00E+00
Harvesting	3.50E-02	4.46E-02	2.58E-02	4.11E-02
Total	5.64E-02	7.19E-02	4.23E-01	1.22E-01
Transport of inputs				
Agricultural inputs	1.13E-01	9.43E-02	9.06E-02	8.07E-02
Industrial inputs	5.54E-03	5.54E-03	5.54E-03	5.54E-03
Total	1.19E-01	9.98E-02	9.61E-02	8.62E-02

Table 4
Energy consumed (in MJ/MJ of biofuel) in the soybean production.

	No-till early	No-till late	No-till irrigated	Till-early
Site preparation	0.00E+00	0.00E+00	0.00E+00	7.80E-02
Sowing	1.57E-02	1.99E-02	1.16E-02	1.55E-02
Management of pest and diseases	3.02E-02	2.56E-02	1.48E-02	1.49E-02
Fertilization	3.17E-03	0.00E+00	2.34E-03	3.14E-03
Irrigation	0.00E+00	0.00E+00	2.72E-01	0.00E+00
Harvesting	3.05E-02	3.87E-02	2.25E-02	3.58E-02
Total	7.96E-02	8.42E-02	3.23E-01	1.47E-01

3.3. *Transportation and drying of soybeans*

The transportation of soybeans to the industrial site is far more energy demanding than the drying. Almost 80% of the energy consumed during transportation is generated in road transportation by trucks, followed by rail (15%), and the remaining is due to short freight.

3.4. *Oil extraction*

The solvent oil extraction requires 0.028 MJ/MJ of biodiesel, of which 86% corresponds to the use of natural gas and the remaining 14% to the use of electricity.

Three different products are obtained in this process: soybean meal, oil and lecithin, representing an energy output of 3.54 MJ/MJ of biofuel, of which 2.42 MJ correspond to the soybean meal, 0.96 MJ correspond to the oil, and 0.16 MJ to the lecithin.

3.5. *Transesterification process*

The energy consumed during the transesterification process is 0.033 MJ/MJ of biofuel, of which 72% corresponds to the use of natural gas and 28% to electricity. Two different products are obtained in this process, representing an energy output of 1.053 MJ/MJ of biofuel, of which 1.0 MJ correspond to the biodiesel and the rest to the glycerin.

3.6. *Energy return on investment of soybean biodiesel*

As described in the previous subsections, each productive scheme may require different amounts of agricultural inputs (implying different transportation loads) and the utilization of different farm machinery. As a consequence, the corresponding EROI are quite different: 1.77 for no-till early; 3.10 for no-till late; 1.86 for no-till irrigated and 2.83 for till-early. These results should be interpreted as an average energetic performance for soybean biodiesel, based on current, publicly available data in the country.

The relative contribution of each input and output in energy

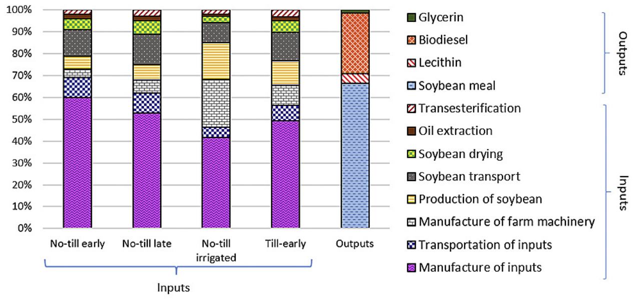

Fig. 2. Energy inputs and outputs contribution to the EROI of soybean biodiesel in Argentina, considering different agricultural schemes and the energy allocation approach.

terms can be seen in Fig. 2. Most of the energy is consumed during the production of inputs, ranging between 40 and 60% of the total. There is no clear prevalence among the other energy inputs (transportation, farm machinery manufacture, soybean production, drying, etc.), except for the no-till irrigated scheme in which the energy consumed for the manufacture of the farm machinery and during the production of soybean are higher than in the other schemes, mainly due to the energy embodied in the irrigation equipment and the energy consumed for water pumping.

Regarding the energy outputs, 72% is associated with co-products. The largest share (67%), corresponds to soybean meal, while the contribution of lecithin and glycerin only represent 4% and 1%, respectively, due to the small production volumes.

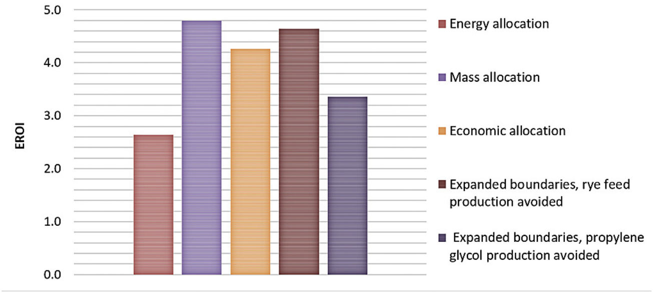

Fig. 4. EROI of soybean biodiesel for different allocation procedures. The agricultural production scheme corresponds to no-till early.

3.7. Sensitivity analyses

Different sensitivity analyses have been performed, in order to obtain an insight into the main parameters and methodological choices affecting biodiesel's EROI. The effect of the origin of the agrochemicals and industrial chemicals used in the system has been explored considering three scenarios. The first one, named “domestic and imported inputs”, considers the real transportation distances for all agricultural and industrial inputs detailed in Sections 3.3 and 3.4. The second one, termed “domestic inputs”, analyzes the case in which all agricultural and industrial inputs are manufactured in Argentina. The last one, termed “boundaries excluding the production of chemical inputs”, simply ignores the embodied energy of agricultural and industrial inputs. These scenarios show that EROI is more sensitive to the exclusion of the chemicals production from the system boundaries than to the accuracy in determining the transportation distance of these inputs (Fig. 3). The embodied energy of methanol, glyphosate and fertilizers represents a large proportion of the total energy consumption during biodiesel production (more than 52%). Therefore, discarding the production of chemicals from the system boundaries (like in Ref. [19]) produces a big increase in the EROI results: by 68% for no-till irrigated, 86.5% for till-early, 96% for no-till late and 135% for no-till early. Under this scenario, the most favorable production scheme is no-till early instead of no-till late, since the former requires the application of fertilizers (in addition to pesticides), while the latter does not. Besides, the energy consumption of the agricultural stage is reduced by 58.7% for no-till early and 38.5% for no-till late, thus increasing their respective EROI figures up to 6.2 and 6.08. With these boundaries, the more energy-demanding processes in both schemes are grain transport from the farm to the industrial area, the transport of chemicals, and fuel consumption in farming activities. For the domestic inputs scenario, EROI is only 5% higher than the corresponding value for the domestic and imported inputs scenario. Although a large number of agrochemicals used in the production of soybean biodiesel is imported from different countries, the transport of agrochemicals is not a critical process, representing only 1% of total energy consumption. The three scenarios considered for this first sensitivity analysis would suggest to always including the production of chemical inputs in the study, even if the real transportation distance is unknown.

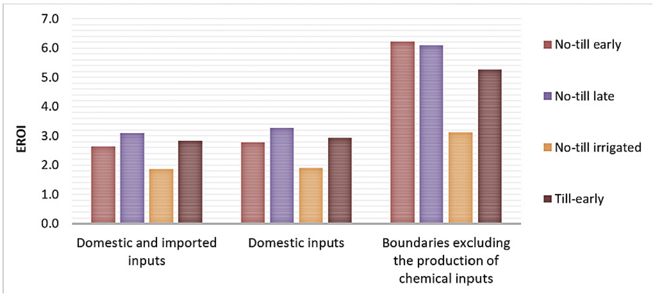

Fig. 3. EROI of soybean biodiesel using different system boundaries.

The effect of the allocation procedure is studied considering four alternatives: mass, economic, energy and boundaries expansion methods (Fig. 4). When using attributional methods, the highest EROI is obtained using the mass allocation approach (4.79) followed by the economic (4.26) and energy methods (2.64). When using the expanded boundaries approach, the system that avoids the production of rye feed is clearly the most favorable (EROI: 4.64), since an energy demand of 0.63 MJ per FU is avoided, which represents a reduction of 45.6% of the total energy consumed when compared to the energy allocation procedure. When the boundaries expansion method avoids the production of propylene glycol, there is 24% of energy reduction compared with the energy approach.

Due to the strong influence of the allocation method and of the boundaries definition on EROI results, the executor of the study must carefully take into consideration the aim and scope of the study prior to perform the calculation. It is convenient to use more than one method, and to analyze their implications before taking conclusions.

4. Discussion

The EROI values obtained for soybean biodiesel produced in the Argentine Pampean region are very encouraging, similar to those calculated by Brondani et al. [7] (3.08); Garza E [9]. (4.24); Cavalett and Ortega [10] (2.48); Carraretto et al. [11] (2.09) and Ahmed et al. [12] (2.51). Other authors such as Pimentel and Patzek [6] or Sheehan et al. [39] suggest that soybean biodiesel represents a net primary energy loss, ranging between 8% and 24% per MJ of biodiesel. The large differences between these values and those found in this study are explained by differences in the amount of required agricultural inputs (e.g., rate of phosphorus, potassium, lime and fuel consumed in agricultural management), in crop yields, and in the energy efficiency of the industrial technologies considered.

The energy inputs considered in this study are higher than those reported in previous Argentine reports [13,14,16], due to differences in system boundaries, in the amount of inputs to the industrial stages, and in the energy required for the production of inputs. For instance, Huerga et al. [14] omit the manufacture and transport of agricultural inputs and consider lower amounts of methanol in the transesterification of MEs (about four times less than the value used in this study). Huerga and Donato [12] and Donato et al. [16] consider lower values of energy required to manufacture agricultural and industrial inputs.

In the three rainfed production schemes, the agricultural stage consumes less energy (49.7% for no-till early, 41% for no-till late and 46% for till-early) than the industrial stage. For the irrigated scheme (no-till irrigated), the energy consumed in the agricultural stage amounts to 64.9% of the total energy requirement. This figure coincides with the values reported by Hill et al. [40] for soybean biodiesel produced in irrigated regions of the United States (66.2%).

The energy demand of no-till early is higher than till-early and no-till late, the latter being the less energy-intensive scheme. The results obtained by Donato et al. [16] also show higher energy demand for the no-till early scheme, but they found the till-early was the least energy-demanding system, which can be explained by a 17.6% higher crop yield according to the authors. Their article reports that an increase in crop yield reduces the total energy demand of soybean biodiesel if the same inputs are maintained, as reported by Panichelli et al. [15]. However, this is a hypothetical situation, since in many cases an increase in crop yields involves changes in agricultural management practices. These practices may include additional flows of materials and energy (e.g. higher amounts of fuel due to a more intensive use of farm machinery or higher doses of agrochemicals). For instance, the implementation of an irrigation scheme increases the crop yield, but requires the consumption of additional energy for water pumping, which worsens the value of the EROI. Another example is the late soybean, which is exposed to unfavorable environmental conditions (such as early frost, insufficient incident solar radiation or temperature). Consequently, low soybean yields are obtained, but since no fertilizers are required because it uses the residual nitrogen from the predecessor crop, the highest values of EROI are obtained.

Results show also that soybean biodiesel EROI can vary up to 80% depending on the allocation method used. Similar trends have been reported for energy balances of other biofuels such as wheat ethanol [41,42], sugar beet ethanol [42], and corn ethanol [43,44].

It can be observed that within certain limits, when the amount of a given co-product is small, its inclusion or exclusion from the EROI calculation does not introduce major changes in the outcomes, irrespective of the allocation method applied. For instance, the EROI of soybean biodiesel using economic allocation when including lecithin as one of its co-products is 2.53 for no-till early, 2.96 for no-till late, 1.78 for no-till irrigated and 2.7 for till-early, quite similar to the values obtained when lecithin was not included.

The continuous increase in the production of soybean biodiesel has prompted an increase in the supply of glycerin for industrial use, causing a fall in prices due to market saturation. For this reason, some industrial plants market pharmacopoeia glycerin (purity 99% or higher) instead of industrial glycerin, since it demand is in constant growth despite a 15% increase in price. This tendency has a negligible effect over the EROI of biodiesel, which is 4.28 considering pharmacopoeia glycerin or 4.26 considering industrial glycerin using the economic allocation approach, or 2.61 and 2.64 respectively using the energy allocation method. Likewise, by extending the system boundaries to consider that soybean glycerin replaces synthetic glycerin obtained from the reaction of epichlorohydrin with sodium hydroxide in aqueous solution for pharmaceutical use, EROI is 3.31. Energy savings for this system (0.32 MJ/FU) are similar to the system that avoids the production of glycerin for industrial use (0.34 MJ/FU).

5. Conclusions

Soybean-based biodiesel produced in Argentina is clearly a net energy carrier. Tillage and water management strongly influence the results of the biofuel's EROI, but for every analyzed scheme, very good EROI are obtained. This study shows that agricultural practices that increase crop yields do not always lead to an energy improvement, as additional flows of materials and energy may be needed to optimize productivity.

Of all the production schemes considered, the higher EROI are obtained with no-tillage, the most widespread soybean practice in the country. The best results are obtained for the rainfed production scheme in which soybean crops are planted during December (late soybean), although the productivity is lower because grain filling usually occurs under unfavorable environmental conditions. This is due to the lower requirement of herbicides and the absence of fertilizers. If higher EROI values are sought, the best option seems to be expanding the production of late soybean in the Pampean region where suitable agroecological conditions are found.

The results show also that the impact of the manufacture of agrochemicals and industrial inputs chemicals influence the EROI outcomes, much more than the origin of these inputs. Therefore, in the absence of specific information regarding the production of chemical inputs, it is highly advisable to use generic data rather than to exclude them from the life cycle inventory, even ignoring their transportation.

It is strongly recommended to explore different scenarios of system boundaries and allocation methods, taking into consideration the aim and scope of the study. The European Commission recommends using the energy approach to handling co-products. This study shows that the adoption of this procedure produces the lower EROI figures for the Argentinean soybean biodiesel. Due to the sharp fluctuations detected in recent years in the market prices of products of the soybean complex in Argentina, as well as in the global energy market, the authors suggest avoiding the adoption of the economic allocation procedure in assessing the lifecycle of national soybean biodiesel. A system expansion approach following ISO 14044, including all the additional functions provided by co-products, is suggested instead. The adoption of this method requires a deep understanding not only of system processes, but also of markets related to products, co-products and their substitutes.

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