Report
Energy and Climate Partnership of the Americas (ECPA) project

EVALUATING THE SUSTAINABILITY OF POTENTIAL AGRO-INDUSTRIAL CHAINS (SWEET SORGHUM, GRAIN SORGHUM, SWEET POTATO AND FORESTRY) FOR AGROENERGY PRODUCTION

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Abstract
Uruguay, a country highly dependent on foreign fossil fuels, recently began developing agro-industrial chains oriented toward renewable bioenergy sources. However, the large number of potential technologies for biofuel production does not provide clear information on production under neotropical conditions or on their potential environmental impacts. Therefore, the National Agricultural Research Institute proposed the first methodological approach for assessing potential agro-industrial chains oriented toward bioenergy production. The effort focused, in the long term, on applying Life Cycle Assessment as the main tool to define sustainability and, in the short term, on estimating the energy return on investment (EROI) and identifying potential feedstocks for biofuel technologies in Uruguay. This project analysed the Uruguayan feedstocks with the highest energy potential (eucalyptus wood, grain sorghum, sweet sorghum, and sweet potato). The energy assessment was based on spreadsheet calculations. The life cycle inventory (LCI) was developed based on agronomic mean data collected from the main forest/agriculture companies and the main Uruguayan agronomist researcher for each crop. Similarly, the average of rate/dosages was obtained for each step. The energy conversion factors utilised were obtained from international publications when primary data were not available in the national survey. The assessment of eucalyptus wood, sweet potato, grain sorghum, and sweet sorghum for bioenergy generation showed EROIs of 0.56, 1.2, 3.5, and 7.2, respectively.

Keywords: forestry, grain sorghum, sweet potato, sweet sorghum, bioenergy, bioethanol

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University of the Republic
ALUR, Alcoholes del Uruguay (www.alur.com.uy)
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1. Introduction

Uruguayan energy production depends mostly on imported supplies: oil accounts for over 50% of the energy consumed. National Energy Policy (available at www.miem.gub.uy) promotes the diversification of energy sources. In particular, it promotes the production of energy from renewable sources, including liquid biofuels and biomass-based electricity production. This strategy will diminish oil dependence and minimise environmental impacts. The objectives for 2015 are for liquid biofuels and bioelectricity to account for 3% and 5% of the Uruguayan energy matrix, respectively.

The lack of local energy sources may be partially mitigated by the use of agroenergy. Agricultural production plays an important role in the Uruguayan economy, accounting for 71% of gross domestic product (DIEA, 2009). Government policies are oriented toward sustainable production, leading to the conservation of natural resources. As an agricultural products exporter, Uruguay is promoting the certification of processes and products. In the framework of potential bioenergy sources based on agricultural production systems, Uruguay has many options, including biomass for electric power generation (e.g. energetic forestry cultivations and forest residue) up to liquid biofuels (e.g. biodiesel or bioethanol from different sources, like sucrose from sweet sorghum and sugar cane or starch from sweet potato or grain sorghum). However, it is highly important to establish a methodology capable of identifying the adequate combination of “feedstock production-bioenergy production” with a positive energy balance. For this goal, the objective of this project was to determine the energy return on investment (EROI) of the main agroindustrial chains that could be used for short-term bioenergy generation.

Sweet sorghum and grain sorghum

Both sweet and grain sorghum (*Sorghum bicolor L. Moench*) are well adapted crops for all national regions. The first one produces up to 120 tons of biomass per hectare. Their plants have thick stems that contain high amounts of sucrose-rich juice, making them very similar to sugar cane. Since the sweet sorghum harvest is a little bit earlier than the sugarcane one, they are likely to be a very good complement for distilleries. Grain sorghum is very attractive to farmers, since it is a summer crop with high tolerance to water stress, a common problem in Uruguay. Besides, its production supports soil sustainability by increasing soil organic matter. The main constraint of this crop today is the lack of stable markets.

Sweet potato

This is a starchy root crop with a broad range of adaptations, grown in more than 100 countries across temperate and tropical regions. Foliage and roots could have alternative uses for food and feed. Roots could be used fresh or processed for various products. It is tolerant to suboptimal growing conditions because of the deep rooting and long root enlargement period. Normally, it requires lower inputs than most other crops.

In Uruguay, it is a traditional crop, grown mainly for fresh consumption until now. Around 2,500 ha are planted each year by small-scale growers, depending on the size of the domestic market. The crop is planted from spring to early summer, limited by frosts at the end of fall. Being a rain-fed crop, it may benefit from some complementary irrigation during establishment and the bulking stage. In the northern region of the country, higher potential yields could be achieved because of a longer growing season (8 months), greater solar radiation, and higher rainfall compared to the south. Besides, one or two crops per season could be obtained there if desired.

There is extensive crop knowledge from previous research, including locally developed varieties for specific purposes, crop management and storage. Additional information and more appropriate varieties are being developed to establish mechanisation across most crop stages.
There are several advantages for choosing this crop as a source of fermentable material for ethanol production. First of all, the industry could be supplied year-round, with low risk of crop failure. Once the crop reaches commercial yield, it can be harvested at any time. In the northern region, it could usually be processed directly from the field by harvesting during six months or it could be stored at farm level for as long as another six months. Under improved growing conditions in that region, this is the highest yielding crop in terms of alcohol per area (10.000 l/ha), provided a long growing season is secured. Additionally, oversized, cull roots or oversupply production from small-scale operations could be diverted for processing. Industrial residue could be valuable for feed use in various ways.

Local experimental data have confirmed a reasonably high efficiency of the hydrolysis and fermentation processes (85-90%) in fresh roots. High content of fermentable free sugars was observed, in addition to starch (20 and 50% respectively, dry weight basis) (Lareo et al., 2011). Dried roots improve practical handling during transport, storage, and industrial processes, although they require much higher energy consumption.

The main constraints to developing this crop for industrial purposes are its bulkiness and perishability if not handled properly. Besides, for competitive production, it would be necessary to mechanise most crop operations. Lastly, fermentation efficiency could be improved.

Forestry

The afforested area in Uruguay has grown significantly since the forestry law provided legal and tax incentives to the sector in the final part of the 1980s. Until that moment, the country had nearly 40,000 ha planted with commercial species, maintaining this area more or less stable during many decades before 80's. But after the Government incentives, the forest area increased to the current 800,000 ha or more. It is expected that this growth rate would continue at the same rate (DIEA, 2009).

For the most part, this surface is planted with *Eucalyptus* and *Pinus* at a ratio of 65% and 35%, respectively. The *most commonly planted Eucalyptus* species are *E. grandis, E. globulus,* and *E. dunnii, which* are used mainly for pulp mills. In this scenario, approximately 80,000 ha of *E. grandis* in Rivera, Tacuarembó, and Paysandú are intended for the solid wood market. The species of P*inus* (*P. taeda* and *P. elliottii*) are planted in the North zone and in the Western zone (Tacuarembó, Rivera y Paysandú), and so is *E. grandis*. Those species are planted for obtaining sawlogs and plywood. The soils that qualified as of forest priority by law, and therefore have the potential to be under commercial forest plantations, have undergone changes in the last decade. Currently, the mentioned area is 4,420,000 ha, 25% of the national agricultural soils. The current area under commercial forest plantation is 6% of the total. The main destinations of wood are elemental chlorine-free (ECF) pulp mill production (for cellulose and paper), sawlogs, plywood, and bioenergy (thermoelectric generation). Most of the products obtained from sawmills and pulp mills, as well as plywood and logs, are exported. This fact increased the sector's income relative to traditional products from other sectors.

EROI

The EROI is the ratio of energy output to energy input. This value gives how much energy is obtained from the invested energy. This methodology is an incomplete Life Cycle Assessment (LCA). It is incomplete because we only considered the energy exchange involved in each operation: machinery, fuel, fertiliser, and pesticide use. Other environmental impacts (such as freshwater eutrophication, ecotoxicological impacts, and biodiversity loss) were not included. For this task, each rate/dose is converted to its energy equivalence, and the energy input and output values are then obtained.

Although an LCA is a desirable scientific goal for decision-makers promoting an agroindustrial chain for bioenergy, the current situation in Uruguay does not allow a complete LCA of biofuels, mainly due to a lack of information on national ecosystems and their carrying capacity (resilience and resistance ranges). Therefore, at this moment, the LCA application in Uruguay is limited to partial LCA forms (e.g. carbon footprint or energy balance). For this reason, the present study must be considered a first approach to defining potential agroindustrial chains for bioenergy production. In this approach, we did not consider environmental impacts because international ecotoxicological databases, mainly developed in the Northern Hemisphere, are inadequate for inferring environmental impacts in neotropical zones.

2. Materials and Methods

To reach the main objective, the strategy of this project was to assess the net energy balance of each of the four bioethanol options (sweet sorghum, grain sorghum, sweet potato, and wood cellulose) under Uruguayan conditions. This energetic assessment was carried out based in a conceptual framework of life cycle assessment. It considered three steps: inventory, impact assessment, and improvement assessment. These tasks were oriented by the main criteria suggested by SETAC (Barnthhouse et al., 1998; Fava et al., 1992), US EPA (2006), and the approach of similar studies (Bergand Lindholm, 2005; Fore et al., 2011; Hill et al, 2006; Landis et al., 2007). This strategy is a partial LCA because it will not consider certain topics, such as biodiversity impacts or ecotoxicological changes (UNEP, 2000). But it is a good solution to generate first approximate answers for four questions: (1) what is the best net energy balance? (2) what are the scientific gaps? (3) what are the research priorities for each source of bioenergy? (4) where do we have the opportunity to improve the bioenergy generation process? This strategy will be complemented by the establishment of scientific cooperation between Uruguayan organisations and US scientific groups. It will establish a scientific basis for developing access to knowledge and know-how to improve results in a second phase, beyond the project's duration.

The components of this project were:

<u>Workshop</u>

USA visitors, partners, and relevant guests held a 2-day meeting at the beginning of the project to define project details. American specialists helped to identify which information was needed and how to interpret it. Local participants contributed information on what was available and how to obtain it. The workshop output included a general consensus on the assumptions used in the study.

<u>Life cycle inventory (LCI)</u>

The LCI was defined using common boundaries and a similar strategy to analyse each component and process across the four production chains. As common criteria, human labour was not to be included as an energy input. Infrastructure, machinery, chemicals, fertilisers, fuels, and transportation were included, as well as co-products that avoid the use of oil energy. The agroindustrial chain was divided into two main components: the agriculture phase and conversion phase. The LCI of the agriculture phase considered the following sub-phases: seed production/nursery, field preparation, planting, post-planting, harvest, and transportation. In the case of the conversion phases of the different agroindustrial chains, the industrial process was analysed as a black box, in which the specific performance of energy/biofuel generation and potential co-products were defined. When possible, additional credits for the energy balance were considered (e.g., co-products that avoid the consumption of fossil energy).

Life cycle assessment (LCA)

The LCA determines the energy of each component and process (e.g., engines and machinery, pesticides, fertilisers) (Roy et al., 2009). It is determined by their corresponding rates, converted to energy units (megajoules). Moreover, the quality of the estimation for each chain was assessed based on the quality of the data source. This task prioritised the national rate data whenever possible. But if these were unavailable, they were estimated from similar regional situations (Coltro et al., 2006; 2009; Mourad et al., 2007; Smaling et al., 2008). At the worst situation, the information required was estimated from international databases (e.g. USA, Ecoinvent or other international databases) (Berg, 1997; Berg and Karjalaien, 2003; Ecoinvent, 2007; FAO, 2003).

Energy balance assessment for each chain

A spreadsheet was developed for the energy balance assessment, expressed as EROI (Hall et al., 2008; 2009). This spreadsheet had a separate tab for the phase seed production/nursery, field preparation, planting, post-planting, harvest, transportation and industrial conversion steps. In each tab, there are columns for LCI, rates, conversion factors, energy equivalences and reference data. The resulting energy obtained was summarised in the summary tab of the file, which also included the EROI assessment.

3. Results

Productive scenarios considered for the energy balance

For each agro-industrial chain studied, a potential production scenario was developed. These scenarios were built on the expertise of the main national agronomists and focused on research into the agricultural systems under study. Although the following summaries of each agroindustrial chain are specifically for potential bioenergetic crops, these scenarios assume cultivation within a crop-rotation framework at the farm scale that allows the maintenance of soil organic carbon (SOC), soil nutrient balance, and economic profit. Further comments are available in the discussion.

Grain sorghum

Field preparation, planting and post-planting treatments were assumed the same as for sweet sorghum. Estimated yield was 5 tons per hectare. The industrial phase assumed was the ALUR projected distillery in Paysandú (www.alur.com.uy/images/galerias/2012/paysandu/nueva-planta-bioetanol-pay.php). Fields were localised up to 100 km from a distillery, which used 50% of its energy from hydroelectricity and the rest from fuel oil. The distillation residues were not dried (Table 1).

Sweet sorghum

No tillage soil management was assumed. This system required a prior glyphosate application using a self-propelled row-crop sprayer. The planting date was proposed for October or

November to achieve the best yield at harvest, i.e., April. An application of atrazine and alfa-metolaclor was suggested at planting time. Two fertilisations were proposed: 180 kg per hectare of diammonium phosphate at planting and 180 kg per hectare of urea post-planting. No further management was assumed. Estimated harvest was 80 tons of green matter per hectare. The juice obtained contained 16% sucrose. Fields were assumed to be at 30km or less from the actual ALUR sugar cane mill (Bella Unión, Artigas). After juice extraction, bagasse was burned to generate electricity and steam (Table 2).

Sweet potato

The scenario used considered a sweet potato culture at North zone, close (50 km) to the sweet sorghum crop and the main ferment reactor facility in Bella Unión or Artigas City, both in Artigas Department. For this product, it was assumed a design of industrial culture. In a first approach, some international works were considered as guidelines to build the LCI (Shabbir and Savitrigarivait, 2007; Ziska et a., 2009). But since the scenarios proposed for this differed significantly from the international ones, most of the data came from INIA's database and from studies and experience developed for the National Vegetable Crop Production Research Program (INIA). Most of this information was presented in the FPTA 266 project report (Lareo et al., 2011). Additionally, information from the University of Tocantins (Brazil) was considered, since at this institution sweet potato research for biofuels has made important advances both at the crop level and in the conversion phase (Patent p10801439-6). All the LCIs were developed with national data, and their respective rates in the same way. Only for the conversion factors was the use of international sources required, mainly the works of Hill et al. (2006), Nagy (1999), and Green (1987).

Forest

The goal was to assess the energy balance of a fast-growth commercial forestry culture for energy. The conversion phase considered was the thermoelectric power. Data from *Eucalyptus* cultures for the pulp mill industry, at a density of 1000 plants per hectare, with a mean growth rate of 30 m3/ha/y and a harvest time of 8 years, were used as an approximate model for the agricultural phase. Plantations were assumed to be situated 50 km or less from the 10 MWh Fenirol thermoelectric power plant. Available data from a national power plant (FENIROL 2008; 2009) was used. This scenario is a mixture of two forest production scenarios: a thermoelectric power plant that typically uses wood discarded from *Pinus* production, and the agricultural phase of Eucalyptus for an ECF-bleached pulp mill. Currently, the power plant mentioned above works with residues from forest harvest and pruning activities, which are normally left aside or on the harvest roads in *Pinus* plantations. Forestry cultures focused on solid wood production. The pieces of wood used by the thermoelectric power plant have a diameter less than 15 cm. The main option for energy production based on wood is short-rotation forestry (rotation time less than 4 years), but these plantations are now being established at an experimental scale in Uruguay. The conversion phase was limited to thermoelectric power generation because there was no usable data for other options, such as those based on second-generation processes at full scale (Kemmppainen et al., 2010; Klein-Marcushamer et al., 2010; Kukkonen, P., 2010). The structure of LCI was developed primarily using information from national forest companies, because operations, management, and the mean growth rate of forests differ across countries. A Brazilian productive situation (Romanelli and Milan, 2010) shows the greatest similarity to the Uruguayan productive system at the productivity level, but not all LCI components are the same; however, the Brazilian system has additional steps (liming and additional fertilisation) that are not present in Uruguayan production. Where national information was not available, the data were obtained for: nursery, from Heller et al. (2003) and national companies; machinery from Heller et al. (2003), Tigercat and/or John Deer company's websites; pesticide from Green (1987); and for energy conversion factor from Nagy (1999) and Hill et al. (2006).

Fig.1: Map of Uruguayan territory and its administrative divisions (Departments).

In general, the agricultural phase of all studied feedstocks has lower energy consumption than the corresponding conversion phase (bioethanol production, power generation), except for sweet sorghum's bioethanol production. In the agricultural phase, planting, post-planting, and harvesting are the most important tasks for grain sorghum and sweet potato. Sweet sorghum production showed that planting, post-planting, and harvest were the steps with the highest energy demand. Forestry showed an energy consumption pattern different from the other feedstock productions, with field preparation, planting, and harvest as the highlighted steps.

In terms of energy output per hectare, sweet potato and *Eucalyptus* wood produced the highest values of energy produced, if it is considered the energy estimated on the basis of the chemical composition. However, in the current situation (a thermoelectric power plant and an 8-year crop rotation), the EROI and energy balance are inadequate for the hypothetical forest energy scenario. The situation could be improved with a short crop rotation (less than 4 years) and a higher-density forest, if the energy inputs are assumed to be similar to those in the scenario studied. In the case of sweet potato, the chain has a very demanding conversion phase, or the national technology available does not allow its conversion into liquid fuel.

As a counterpart, sorghums have lower energy production per hectare, but their bioethanol production requires less energy. Therefore, the energy balance is higher for these crops.

The energy consumption analysis, organised by the main agricultural components (agricultural machinery, pesticides, fertilisers, fuel), is shown in Tables 1 and 2. In this case, the analysis showed that the use of fertilisers and pesticides is important for both kinds of sorghum cultures, and that fuel is also required for sweet sorghum. In sweet potato production (Table 3), only the fertilisers and fuel are important in energy demand; and for forestry, the most important are the fuel, machinery and pesticides.

Table 1: Energy inputs and energy output of agro-industrial grain sorghum chain. All values are expressed in megajoules/ha/year.

	Seeds	Field preparation	Planting	Post-planting	Harvest	Transport	Industrial process	Total
Agricultural machinery	3	5	18	0	52	39		117
Fuel	42	30	298	37	449	86		942
Electricity	0	0	0	0	0	0	7527	7527
Pesticides	76	588	545					1209
Fertilizers	312	19	2242	3103				5676
Total input energy	432	643	3103	3140	501	124	7527	15470
Total energy output (MJ/ha)								**47177**
Crop rotation time (years)								**1**
Net energy (MJ/ha)								**31706**
EROI (MJ/MJ)								**3.05**

Table 2: Energy inputs and energy output of agro-industrial sweet sorghum chain. All values are expressed in megajoules/ha/year.

	Seeds	Field preparation	Planting	Post-planting	Harvest	Transport	Industrial process	Total
Agricultural machinery	3	5	18	5	416	178		625
Fuel	41	30	299	37	2878	394		3679
Electricity							1322	1322
Pesticides	81	588	596					1265
Fertilizers	307	19	2247	3103				5676
Total input energy	432	643	3160	3146	3294	572	1322	12567
Total energy output (MJ/ha)								**90674**
Crop rotation time (years)								**1**
Net energy (MJ/ha)								**103242**
EROI (MJ/MJ)								**7.22**

Table 3: Energy inputs and energy output of agro-industrial sweet potato chain. All values are expressed in megajoules/ha/year.

	Seeds	Field preparation	Planting	Post-planting	Harvest	Transport	Industrial process	Total
Agricultural machinery	101	202	241	101	47	14		706
Fuel	1	1078	1144	792	2622	510		6146
Electricity							85714	85714
Pesticides			160	1037				1196
Fertilizers	80	0	2997	7563				10640
Total input energy	1155	1279	4541	9509	2145	524	85714	104867
Total energy output (MJ/ha)								**121486**
Crop rotation time (years)								**1**
Net energy (MJ/ha)								**16618**
EROI (MJ/MJ)								**1.16**

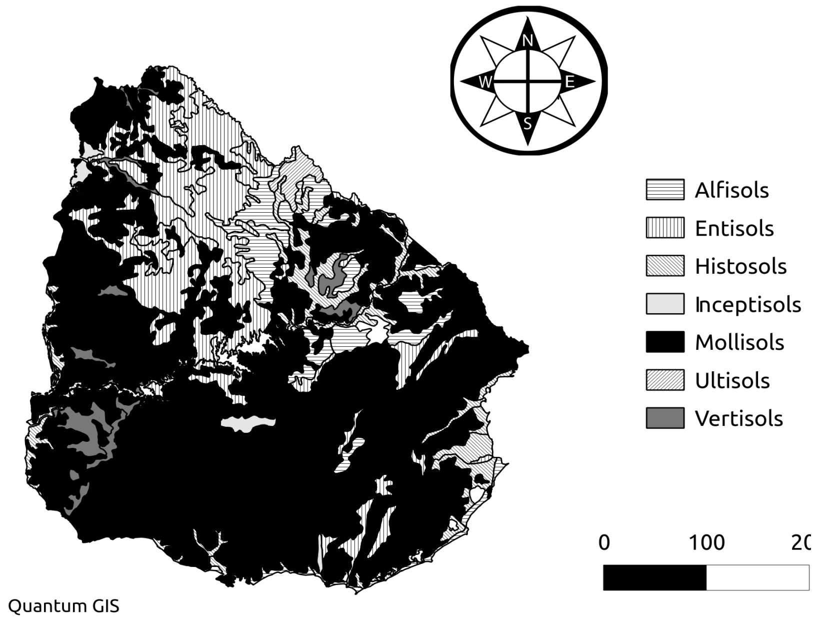
Table 4: Energy inputs and energy output of agro-industrial forestry chain. All values are expressed in megajoules/ha/year.

	Seeds	Field preparation	Planting	Post-planting	Harvest	Transport	Industrial process	Total
Agricultural machinery	0	146	106	17	3685	271		4224
Fuel	90	1760	440	1408	4434	2225		10356
Electricity	180						29690	29870
Pesticides		3710	3718	1628	1200			10255
Fertilizers	114	1201	873					2188
Total input energy	383	6817	5136	3051	9319	2495	29690	56892

Energy output from thermoelectric power plant		Energy output from calorimetric power of wood	
Total energy output (MJ/ha)	**30927**	Total energy output (MJ/ha)	**1782000**
Crop rotation time (years)	**8**	Crop rotation time (years)	**8**
Net energy (MJ/ha)	**-25965**	Net energy (MJ/ha)	**167918**
EROI (MJ/MJ)	**0.54**	EROI (MJ/MJ)	**4.06**

4. Discussion

In general terms, the production of biofuels and biomass from different feedstocks could be a potential solution to reduce fossil fuel consumption. However, this solution can be illusory if only the favourable aspects of bioenergy production are considered. In this framework, the current results are only a first approach to an integrated assessment of four agroindustrial chains that can produce bioenergy using limited national technological options. The current situation of the country and the process engineering expertise do not allow us to assess or to think in the potential EROI results with second-generation fuels processes (e.g. liquid fuels from wood as the new UPM's full-scale plant, or China's semi-solid fermentation process). As a counterpart, the agricultural information for each agroindustrial chain, although it concerned theoretical scenarios, was strongly based on agronomic research conducted over the last fifty years.



All the scenarios assessed were based on a theoretical situation in which the crop rotations that contain the target crop under study do not involve additional changes to the other land uses considered in those rotations. This assumption is very important for annual crops, such as sorghum and sweet potato, where the soil nutrient and carbon balances depend on the structure and composition of all crop rotations at the farm scale (Ernst and Siri-Prieto, 2009; Salvo et al., 2010). This is particularly important with grain sorghum cultures, which are part of some crop rotations, normally on Mollisols. These agricultural soils are not more than 1,400,000 hectares (DIEA, 2009), whose maintenance depends on many climatic (e.g. strong rainfall events), agronomic (e.g. crop rotations) and edaphic conditions (e.g. presence of a Bt horizon) (Ernst and Siri-Prieto, 2009; Salvo et al., 2010).

For grain sorghum, future LCA assessments must consider crop rotation alternatives. Grain sorghum culture can be part of three different crop rotations, in which it is possible to maintain organic carbon levels in the soil, soil nutrient balance, and farmers' economic profit (Ernst and Siri-Prieto, 2009; Salvo et al., 2010). These potential crop rotations are: (a) wheat/2nd soybean/grain sorghum/barley/2nd soybean; or (b) wheat/ 2nd grain sorghum/ 1st soybean/wheat/ 2nd grain sorghum; that allow at least 8 tons of slash per hectare per year. This is a condition able to ensure a neutral Soil Organic Carbon (SOC) balance, and a sustainable use of the soil. But if the agronomic system must work in a strategy more focused on grain sorghum culture, it will be necessary to increase the biological nitrogen fixation; then the crop rotation must be as: (c) wheat/ 2nd soybean - winter cover (annual leguminous) - grain sorghum, and so on. Although incorporating grain sorghum into crop rotations with other crops can maintain SOC in a neutral balance in highly intensive agriculture, it is too difficult to eliminate soybean crops from these rotations for economic reasons (J. Sawchik, personal communication).

Considering the high economic profit of soybean, commercial obstacles for the use of grain sorghum in cattle production, sorghum grain cost, transport costs and the necessity of using some of the crop rotations mentioned above (a or b), the grain sorghum at most could be at the same farm once every three years. Or in other words, in three summers we have two soybean cultures and one grain sorghum culture. And the most likely crop rotation must be: wheat/2nd grain sorghum - 1st soybean - wheat/2nd soybean. In the hypothetical case of an ethanol industrial plant at a reasonable price, there are two scenarios. In one, big farmers may introduce sorghum in a crop rotation as wheat/2nd soybean – winter culture (leguminous) /grain sorghum – wheat/ 2nd soybean, or soybean instead of grain sorghum, because there is no crop that can compete with the economic profit of soybean (J. Sawchik, personal communication).

For small farmers, they should be close to the bioethanol plant, with low transport costs (like the sugar cane mill model), and work under contract with the distillery. In a basic crop rotation with leguminous crops as the winter crop and wheat, there may be two grain sorghums in three summer seasons. It cannot be a large area, and it will depend on the industrial plant's location (e.g., Paysandú). However, in the case of a large industrial plant, the scheme mentioned will not be sufficient, and the grain sorghum must come from farms at greater distances. Then, the main problem to solve is that 90% of farmers have a strong preference for soybean crops over grain sorghum production for economic reasons (J. Sawchik, personal communication).

In the case of sweet sorghum, all the biomass is removed. Then, for sustainable soil use, the sweet sorghum culture must include a rotation of two years of sweet sorghum with winter cover, followed by at least two years of prairie to recover soil organic carbon (two sweet sorghums in four years). Or an agricultural scheme, with more sweet sorghum but with some leguminous crop, oats, and/or *Lolium perenne*.

The sweet potato production chain can exhibit high variability depending on soil type and condition, history of use, and other agronomic characteristics (Diaz Rossello, 2003; Ernst and Siri-Prieto, 2009; Salvo et al., 2010). This crop grows well under many farming conditions, including lower-fertility soils, and is considered a drought-tolerant crop (Indira and Kabeerathumma, 1988; Kays, 2004; O´Sullivan et al., 2001). Sweet potatoes are considered to require minimal inputs such as fertiliser, irrigation, and pest and disease control, thus reducing environmental impact. Additionally, because of the crop's rapid development of foliage cover, it helps reduce soil erosion and competes well with weeds. One anatomical reason for sweet potatoes' reported drought tolerance would be their deep rooting capacity. Another reason would be their very plastic storage sink. The plant translocates photosynthetic products to the storage roots throughout most of the growing season. Thus, adverse production conditions during part of the growing season are unlikely to have a significant effect on crop yield (Kays, 1985). The main requirement would be good drainage to avoid waterlogging, especially at harvest time.

The sweet potato harvest is the intervention with higher impact on soil and SOC. In general, a crop rotation with reduced tillage should be assumed.

This crop is considered a summer crop, planted in spring and harvested during the fall. The crop growth cycle could be adjusted to meet rotation requirements, ranging from approximately 4 to 6 months. Yield potential would depend on crop duration. Annual winter forage crops, such as oats, could be grown sequentially to provide soil cover and some grazing for cattle. Besides, most winter annual crops, including grains, could also be grown.

Alternating with other summer grain crops, such as sorghum, may benefit both crops due to reduced tillage adaptation, different nutrient extraction profiles, and stubble contribution. Both crops share some characteristics, such as drought tolerance. On some conditions, after several of these cycles, a permanent pasture period would contribute to maintaining and eventually enhancing soil carbon, while obtaining relatively high productivity on both crops. This would depend on the original soil fertility status.

At this moment, and given current agronomic knowledge of national ecosystems' capacities, the most important elements to consider in any case are the protection of soil and SOC (Ernst and Siri-Prieto, 2009; Salvo et al., 2010). It is clear that any one of the agro-industrial chains, with the exception of the forest, cannot be present on the same farm each year, both for SOC/nutrient balance and for economic profit at the farm scale. However, the demand for biofuel and its pressure on the economic system can create new conditions in which those without current economic profit could be viable. In this scenario, a change in the pricing policies of the studied feedstocks, or a new willingness to pay driven by changes in the international fuel market, can promote better economic conditions for these crops (grain sorghum, sweet potato). This scenario must handle these changes carefully, with new land planning for agricultural production, both for the protection of soil as a natural resource and for the management of the country's unique 1,400,000 ha for agriculture.

Finally, the conversion phase examined in this study must be treated as a baseline, not as the best option for the country. Throughout the project, it was clear that there were significant limitations in this area, as well as in the national expertise in industrial processes oriented to biofuel generation. The regional experience in bioethanol (University of Tocantins, Brazil; EMBRAPA's biofuels), or maybe the private company experiences (liquid fuel from wood at Finnish UPM full-scale plant) can be adequate technologies and expertise for the local reality in the future.

Both grain and sweet sorghum results support INIA's previous assumptions about the suitability of these chains. In particular, sweet sorghum's EROI is very high (over 7), confirming that it is the most promising energy crop in the short term. However, it has several logistic issues that limit its application as a complement to sugar cane ethanol production. The results help support the use of sweet sorghum at the ALUR Bella Unión industrial plant.

The results of this project are very important for the country because they provide the first data on agricultural feedstocks for bioenergy. In the case of sweet potato, this study was a good approach, but the potential yield considered was incorrect, and there were important information gaps regarding process performance, which affected the EROI value for this agroindustrial chain. Therefore, the current estimated EROI value cannot be considered the potential value. Nonetheless, the industry has decided to use the sweet potato as feedstock for ethanol production. In this framework, ALUR will develop small-scale distilleries for ethanol production using sweet potato from farmers in the Artigas Department. This will imply INIA's involvement in both agronomic research and sweet potato breeding for bioethanol production. Surely, this project could help generate national data in the future on industrial processes that use sweet potato as the main feedstock for bioethanol production.

At the same time, grain sorghum EROI is not as high as that of sweet sorghum, but it is still high enough to encourage its use. Since the agricultural system needs to include grain sorghum in rotation systems and ALUR is planning a grain-based ethanol industrial plant, this result will help promote its cultivation.

This is the first energy balance study based on information on Uruguayan forest performance. This kind of information is important for both the public and private sector. The compiled information and analysis were based on private databases from forestry surveys and will be available for public access and for future similar studies. Both the EROI concept and the results obtained will help improve communication with decision-makers and enhance the forestry chain's performance for energy production. After this project, the LCA analysis was already included in new project proposals for the INIA Forestry Program. From these proposals, one already has a grant approved from the National Agency of Research and Innovation (ANII, Uruguay). A second one is among the 8 proposals preselected from a group of 38 by the Fondo de Cooperación México-Uruguay (Mexico-Uruguay Cooperation Fund). Additionally, the INIA's Forestry Program has included the LCA as a standard methodology for environmental sustainability, and it will be included in future proposals. In this framework, the program developed new proposals for forestry production linked to the carbon footprint, the relevance of nutrient export from forestry biomass assays, and the management/logistic assessment of forestry production. All these topics will be studied under an LCA methodology. At the forestry production level, this project did not create a new focus, because these topics have been studied before. However, the project results add value because factors not previously considered were included. This project covered a wide view of forestry production, not only the traditional agronomic analysis. For the Uruguayan forestry production sector, the generated information will have a high impact at the national policy level, because it is a key piece of information that can be used to define agroenergetic policies.

Conclusions

The energy balance of the agroindustrial chains expressed as EROI showed positive values for all the studied cases.

In hierarchical order, the agroindustrial chains with the highest EROI were: sweet sorghum, 7.2 of EROI, considering continuous cultivation every year; eucalyptus wood, 0.56 of EROI from a culture of 8 years on forest land; grain sorghum, 3.5 of EROI considering continuous cultivation every year; and sweet potato, 1.2 considering as part of a crop rotation each year.

These results provide a basic structure for completing an LCA of future forest energy use and a first definition of the energy balance for each of the considered chains.

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