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Energy ratio analysis of genetically-optimized potato for ethanol production in the Chilean market

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Abstract

The continuous increase in energy demand, the high cost of imported oil, and the growing concerns about climate change have sparked a number of initiatives from governments around the world to increase production of energy from renewable sources. Along these lines, the Chilean government is analyzing the introduction of a law to set a reference value of 5% of biofuel production to be placed on the market by 2013. The analysis of different options to meet this new regulatory measure needs to consider different alternatives such as biodiesel and bioethanol from crops or lignocellulosic biomass. This paper analyzes the energy ratio of some of the most common crops grown in Chile that can be utilized for ethanol production. Using a methodology adapted to local conditions of agriculture and transportation, the results indicate that a potato cultivar specially bred for high yield, high starch and dry matter content can obtain a positive net energy balance with an energy ratio of 1.8. The results also show yields near 60 tons ha^{-1} which translate to approximately 9,000 L ha^{-1} of ethanol making the genetically optimized cultivar of potato a suitable local source for ethanol production.

Additional key words: biofuel, energy flow, *Solanum tuberosum*.

Resumen

Análisis de la ratio de energía para papa optimizada genéticamente para la producción de etanol en el mercado chileno

El aumento continuo en la demanda de energía, el alto coste del petróleo importado y la preocupación creciente sobre el cambio climático, han impulsado iniciativas de los gobiernos alrededor del mundo para aumentar la producción de energía a partir de fuentes renovables. El gobierno chileno está analizando la introducción de una ley para poner un valor de referencia del 5% de producción de biocombustibles en el mercado para 2013. El análisis de opciones para implementar esta nueva regulación necesita considerar diferentes alternativas como el biodiesel y bioetanol de cosechas o biomasa de lignocelulosa. Se analizó la ratio de energía de algunas de las cosechas más comunes en Chile aptas para su utilización en la producción de etanol. Usando una metodología adaptada a las condiciones locales de agricultura y transporte, los resultados indican que una variedad de papa genéticamente modificada con altos rendimientos, alto contenido de almidón y volumen de la materia seca, puede obtener una ratio de energía neta positiva de 1,8. Los resultados también muestran rendimientos de 60 ton ha^{-1} que producen aproximadamente 9.000 L ha^{-1} de etanol, que hacen una fuente local conveniente a la variedad genéticamente perfeccionada de papa pora la producción del etanol.

Palabras clave adicionales: balance energético, biocombustibles, *Solanum tuberosum*.

Introduction

Energy in all its forms is essential to humanity and is central to the improvement in people's quality of life. The continuous increase in energy demand, the inevitable decline in the availability of fossil fuels, and the growing concerns about climate change have sparked a number of initiatives from governments around

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Abbreviations used: EI (energy inputs), EO (energy outputs), ER (energy ratio), NEB (net energy balance), NEV (net energy value), PG (percent gain).

Table 1. Examples of energy ratios from traditional crops

Feedstock	Energy ratio	Source
Wheat	1.1	International Energy Agency (2004)
Corn	1.34	Shapouri *et al*. (2002)
Beet	1.54	General Motors (2002); International Energy Agency (2004)
Potato	2.89	Álvarez (1982)
Sugarcane	8.3	Macedo *et al.* (2003); International Energy Agency (2004)

the world to increase production of energy from renewable sources (Quintero *et al*., 2008). Biofuels, and in particular bioethanol, *i.e.* ethanol obtained from crops or lignocellulosic biomass, are getting a lot of attention as a possible option for renewable transportation fuel. Countries with tropical whether conditions, such as Brazil, have successfully utilized sugarcane (*Saccharum officinarum*) for decades as the main feedstock to produce ethanol (Wheals *et al*., 1999). However, some studies show a low power density value (Ferguson, 2008). Due to the low cost of sugarcane, other countries in Africa, Latin America, and Asia have plans to increase their production of ethanol from sugarcane (Worldwatch Institute, 2007). In the United States and Europe ethanol is produced mainly from corn and grain (Rutz and Janssen, 2007). Other starchy crops being utilized are sorghum (*Sorghum* sp) grains, cassava (*Manihot esculenta*), and potatoes (*Solanum tuberosum* ssp *tuberosum*) (Liimatainen *et al*., 2004). However, there is currently a substantial amount of research being done concerning the development of cellulosic bioethanol (Milliken *et al*., 2007), but the process for producing it is not yet at a commercial level.

Rapeseed (*Brassica* sp), sunflower (*Helianthus annus*), sugar beet (*Beta vulgaris* var *saccarifera*), wheat (*Triticum vulgaris*), and potatoes have been considered as potential feedstock for the production of biofuels. In addition, several studies have focused in the production of ethanol from sugar cane in Brazil and other countries (Wheals *et al*., 1999). Table 1 shows several examples of energy ratios obtained from the literature for ethanol produced using different feedstock.

Some of the main concerns about the production of ethanol are related to the substitution of land use from food-generating purposes to the production of fuels, with the consequent increase in the price of food. This issue has been pointed out by the directors of institutions such as FAO and the World Bank. However, some recent studies indicate that ethanol is only one of the many factors behind high commodity prices (Urbanchuck, 2008). In addition, other studies have focused on the concerns about the emission of CO_2 to the atmosphere due to the use of additional land to produce ethanol (Patzek, 2004; Searchinger *et al*., 2008). Thus, for ethanol to become a viable transportation fuel, a low cost per liter of fuel, a positive energy balance, a negative or a small impact in the emission of CO_2 to the atmosphere, and minimal impact on food prices need to be assured.

Along the same lines of regulatory mandates implemented by several governments around the world, a new directive is in the process of being approved by the Chilean congress that states that the percentage of biofuels placed in the market should reach 5% by 2013. Table 2 shows current statistics of the Chilean agricultural sector. It is observed that beets and potatoes have the highest yields requiring a relatively small number of hectares to supply the demand of the country. Out of these crops wheat, corn, potatoes, and beets, constitute viable feedstock options for the production of biofuels. Therefore, an analysis of the local options to produce biofuels becomes necessary considering the relevant technical and economical aspects associated with the Chilean agricultural practices. This paper analyzes some possible choices for production of bioethanol considering the type of crops commonly cultivated in Chile with special consideration of native species, such as Chilean potato, that has been shown to reach high percentages of starch content by means of a breeding process.

Table 2. Current statistics of the Chilean agricultural sector (2006/2007)

Feedstock	Surface (ha)	Yield (ton ha^{-1})
Wheat	282,400	4.68
Corn	134,140	11.61
Oats	103,320	5.07
Potato	63,910	22.61
Rice	26,530	5.28
Beans	23,760	2.10
Beet	22,750	79.41

Source: ODEPA (2007).

Ethanol from potatoes

The utilization of potatoes as a feedstock to produce ethanol has been studied in the past. Liimatainen *et al*. (2004) analyzed the production of bioethanol from waste potatoes that correspond to approximately 5 to 20% of crops and are obtained as by-products of potato cultivation. Figure 1 shows a schematic of the process to obtain bio-ethanol from potatoes. Mann *et al*. (2002) used potato by-products to produce biofuel near two French fries plants in Idaho. Zak *et al*. (2006) studying the conventional potato crop management in Slovakia obtained an energy ratio of 2.6 with an output of 26.6 tons ha^{-1}, where input-output energies were 41.11 and 106.7 GJ ha^{-1}, respectively. This research found that the highest energy input belongs to the use of organic and synthetic fertilizers followed by the consumption of combustible and tuber seeds. A study performed by Schneider and Nafus (1980) analyzed the inputs and outputs of energy per hectare for the crop in different potato producing areas in the USA. The regions studied were California, Maine, Idaho and New York, which showed average returns of 36.7, 23.6, 26.7 and 34.5 tons ha^{-1} with energy ratios of 1.64, 1.44, 0.83 and 1.37, respectively. The variations in the amounts of energy used in the various regions are attributable to differences in climate and soils that have a direct bearing on the use of machinery and applications of pesticides. Seyed (2006) investigated the flow of energy in growing potatoes in the six major potato producing areas of Iran. The results of this study showed that the average energy input per hectare of potato was 78.44 GJ and the average yield of this crop reached 25,817 kg ha^{-1}. According to this information the energy ratio obtained was 0.98. Álvarez (1982) performed an analysis in southern regions of Chile and concluded that the highest energy costs of growing potatoes are in descending order: fuel, nitrogen fertilizers, and seeds. In relation to the year 1964, there is a trend of increasing use of machinery and pesticides, and a decrease in the use of animals and manpower. In his study, the energy ratio for the ecosystems of potatoes dedicated to both, producers of potato for human consumption, and for farmers engaged in the production of potato seed, was 2.89.

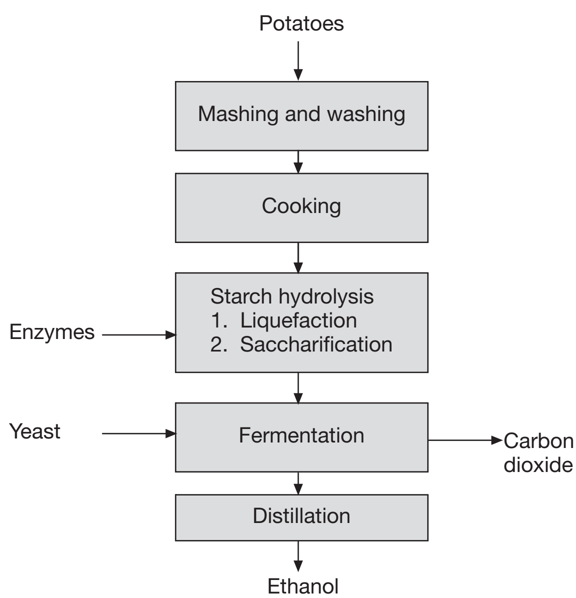

Figure 1. Process to produce ethanol from potatoes. *Source:* Liimatainen *et al.* (2004).

Starch-rich potato

Recent industrial experiments to obtain starch and ethanol from potato have been developed based on utilizing the waste of potatoes destined to human consumption, thereby achieving a very low net energy balance. Although there are examples of genetic engineering approaches to improve production of ethanol from crops (Torney *et al*., 2007), to the best knowledge of the authors, there has been no industrial development based on specific potato cultivars optimized for the ethanol industry. The development of inedible cultivars with high starch and dry matter content and high yield per hectare emerges as a possible option that is complementary to other alternative sources for the production of biofuels in the Chilean market. The Native Potato Germplasm Bank at the Austral University in Chile contains more than 280 cultivars of potato species and a number of wild species (Contreras *et al*., 1993), many of which show desired characteristics for ethanol production. The starch content and the density of solids are closely correlated (Simmonds, 1977) and represent cumulative breeding characteristics that allow good dominant features to remain at the center of the normal distribution curve. The Germplasm Bank at Austral University has a significant number of accessions for which the chemical and agronomic characteristics have been already determined. Existing records show a large potential for a significant number of accessions to contain desired genetic characteristics to be used as parent material in the development of new cultivars with high percentage of dry matter, starch, and high yield (Contreras *et al*., 1979, 1987, 1992; Duran *et al*., 2006). As an example of this potential, yields of almost 60 tons per hectare have been recently obtained in pre-competitive tests performed by farmers associated with this initiative and the current assessments of the results support the goal of reaching 28% of starch content. Table 3 shows the yields (in tons ha^{-1}) for a cultivar of bred potatoes compared with commercial cultivars for five different communities in the South of Chile. The table shows the information for three different cultivation periods, *i.e.* 90-120, 120-140, and 140-160 days. Potato cultivars such as Melita and Piuquemapu reached yields of 56.3 and 55 tons ha^{-1}. In this way, potato cultivars specifically designed for fuel production would allow a substitution of 1.83% of the needs of gasoline in the Chilean market by increasing the potato cultivated surface by 15% or 8,986 hectares. There is a potential production of ethanol up 9,000 L ha^{-1} due to the optimized cultivar of potatoes. It is noted that the idea of breeding potatoes for specific objectives is not new since researchers have used this technique to increase resistance to diseases and pests (Pavek and Corsini, 2001). However, a similar methodology has not been utilized yet for the industrial production of biofuels.

The issue of the concrete contribution of bio-ethanol from crops to the increase in food prices continuous to be a subject of intense debate (Rajagopal *et al*., 2009). However, the prices and availability of food will ultimately be determined by supply constraints of crops (Kostka *et al*., 2009). Also, the impact of biofuel production will be minimized by improving conversion efficiency and performing detailed life cycle analysis studies (Torney *et al*., 2007; Deverell *et al*., 2009). This work does not intend to provide an answer to these important questions.

The main objective of this study is to establish the methodology needed for obtaining the energy ratio for a genetically improved inedible cultivar of potato with high starch and dry matter content. The methodology is used to compare this type of potato with wheat, corn, and beet.

Material and methods

The following sections present a background of the Chilean agriculture and describe the methodology developed for obtaining the energy ratio.

Criteria used for feedstock comparison

A common practice to analyze the feasibility of using a specific feedstock is to calculate its net energy value (NEV). This quantity is equivalent to the total energy outputs minus the total energy inputs (Lavigne

Table 3. Comparison of yields for test cultivar and modified potatoes for five different communities in the South of Chile and three cultivation periods during 1999/2000 season

Potato type/Community	Yield for five different communities (ton ha^{-1})				
	1	2	3	4	5
Cultivation period: 90-120 days					
Atica (test cultivar)	18.9	30.8	27.6	21.4	16.8
2027-1				28.8	
89-3427-3		50.1	45.8	42.1	
1244-221-2		38.4	30.5		
Fueguina 53	27.6				
Fueguina 151					21.7
Fueguina 154		35.9			
Cultivation period: 120-140 days					
Yagana (test cultivar)			35.3	22.2	
Desiree (test cultivar)	20.4	31.3			
84-5-875-14				25.5	
Melita	28.9	56.3			19.3
Cultivation period: 140-160 days					
Piuquemapu					55

and Powers, 2007). However, the total energy inputs and outputs of different feedstock differ significantly in value. Thus, the energy ratio is considered as the quantity utilized for comparison purposes. The energy ratio is defined as the total energy outputs divided by the total energy inputs. It is important to consider the local farming practices, processes, and transportation related energy inputs in order to quantify the local benefits of using a specific feedstock. In the next section, a number of assumptions are stated and the methodology followed to compare different crops for the production of ethanol is described.

Assumptions for energy equivalents

Energy equivalents constitute expressions used to quantify the inputs of energy associated with the manufacture of production means (Hülsbergen *et al*., 2001). There is a wide variation in the values of energy equivalents that have been reported in the literature and their values are heavily dependent on local conditions of transport distances and changes in the manufacture of productions means (Bonny, 1993; Uhlin, 1999). Of particular importance is the consideration of energy equivalents of fertilizers since their application has a strong effect on the energy input (Hülsbergen *et al*., 2001). In this study, the energy equivalents proposed by Yilmaz *et al*. (2005) have been adopted and presented in Table 4.

Methodology to quantify energy flows

A number of methodologies have been reported in the literature to analyze the energy balances of crops. In this paper a methodology adapted to local conditions of agriculture and transportation is utilized considering energy equivalents taken from the literature and rates of application of energy inputs calculated from data obtained from direct surveys to farmers. The total energy input to the farming-ecosystem is quantified but the energy utilized in the ethanol production process has not been considered in this study.

Table 4. Energy equivalents used in agricultural production

Input (unit)	Energy equivalents (MJ unit^{-1})
Pesticides (kg)	101.2
Labor (hr)	1.96
Machinery (HR)	62.7
Nitrogenous fertilizer (kg)	66.14
Fertilizer phosphorus (kg)	12.44
Fertilizer potassium (kg)	11.15
Water for irrigation (m^3)	0.63
Fuel (L)	56.31

Source: Yilmaz *et al.* (2005).

The energy flows were estimated by quantifying the associated energy in MJ ha^{-1} of different contributions involved in growing different types of crops, considering: energy to produce agricultural inputs, in which fertilizers and pesticides are included (E_j); energy used in the manufacture of machinery depreciated during its useful life (E_{de}); energy in the fuel used by motorized machines (E_{co}); energy used by human labor (E_{jh}); energy used by animals labor (E_{ta}); energy input to the farming-ecosystem due the use of irrigation systems (E_{ir}); and energy input due the seed used (E_{se}).

Thus, the total energy input to the farming-ecosystem per hectare, E_T, was determined by means of the sum of the items previously defined, as described by Eq. [1].

$$E_T = E_i + E_{de} + E_{co} + E_{jh} + E_{ta} + E_{ir} + E_{se} \qquad [1]$$

a) Indirect energy inputs

The method utilized to obtain the indirect energy input to the system through fertilizers and pesticides (E_i) considers two categories: fertilizers and pesticides, and was based on the methodology proposed by Romanelli and Milan (2005) and described by Eq. [2].

$$E_i = E_f + E_p, \qquad [2]$$

where E_f is the energy input from fertilizers (MJ ha^{-1}) and E_p is the energy input from pesticides (MJ ha^{-1}).

The energy input from fertilizers was determined based on the rate of application and their enclosed energy, as described by Eq. [3].

$$E_f = C_i \, I_e, \qquad [3]$$

where C_i is the quantity of input applied per hectare (kg ha^{-1}) and I_e is the energy content in a fertilizer in MJ/kg. The values for P_2O_4 and K_2O were obtained from Romanelli and Milan (2005) and Haciseferogullari *et al*. (2003).

The energy input to the system through pesticides was calculated by means of Eq. [4], as:

$$E_p = I_{ep} \, i_a \, q, \qquad [4]$$

where I_{ep} corresponds to the energy index of pesticides on a volume basis (MJ L^{-1}), i_a is the percentage of concentration of the active ingredient in the commercial product (%) and q is the rate of application (L ha^{-1}).

b) Energetic depreciation (E_{de})

The total amount of energy consumed through energetic depreciation was calculated according to the following equations used by Romanelli and Milan (2005):

$$E_{de} = DMM + DMT + DIR, \qquad [5]$$

where DMM is the energy consumed by the energetic depreciation of the tractor and self-propelled machinery (MJ ha^{-1}), DMT is the energy consumed by the energetic depreciation of the machinery and pulled implements (MJ ha^{-1}), and DIR is the energy consumed by the energetic depreciation of irrigation systems (MJ ha^{-1}).

Machinery: The manufacturing of the motorized machinery has a demand of energy of 68.9 MJ kg^{-1}, referred to it as DEE_m. At the same time, the manufacture of pulled machines has an energy demand of 57.2 MJ kg^{-1} and is referred to as DEE_t (Haciseferogullari *et al.*, 2003).

The DMM and DMT were calculated using Eqs. [6a] and [6b]:

$$DMM = \frac{M\ DEE_m}{C_o\ V_u} \qquad [6a]$$

$$DMT = \frac{M\ DEE_t}{C_o\ V_u} \qquad [6b]$$

where M is the mass (kg), DEE_m is the specific demand of energy for the motorized machinery, and DEE_t is the specific demand of energy for the pulled machinery (MJ kg^{-1}), and C_o is the operational work capacity (ha h^{-1}), and V_u is the useful life of the equipment (h) (Romanelli and Milan, 2005).

Irrigation system: The energy depreciation of irrigation system (DSR) was calculated according to Eq. [7]:

$$DSR = \frac{M\ DEE\ U_d\ P_d}{V_u\ A_r} \qquad [7]$$

where DEE is the specific demand of energy in (MJ kg^{-1}), U_d is the average of daily use (h), P_d it is the period of irrigation during the cultivation cycle (days), V_u corresponds to the useful life of the equipment, and A_r is the total of irrigated area by the system (ha) (Romanelli and Milan, 2005).

c) Energy input from seeds (E_{se})

In order to determine the input of energy to a crop, the energy contained in the inputs is not accounted for but the energy involved in its production, processing, and transport is considered. To determine the energy value from the use of one kilogram of potato seed, the method by Kalk *et al.* (1995) was used, for which this was valued at 1.3 MJ kg^{-1}, indicating that this quantity includes the energy used in the production, storage, and sale of this input. The same methodology was utilized for the other types of crops with energy values corresponding to 5.5 MJ kg^{-1} for wheat, 98 MJ kg^{-1} for beet, and 15.45 MJ kg^{-1} for corn (De Freitas *et al.*, 2006).

In this way, the estimation of the energy input through seeds was obtained using Eq. [8]:

$$E_{se} = S_A\ I_s, \qquad [8]$$

where S_A corresponds to the amount of seed applied per unit of area (kg ha^{-1}) and I_s corresponds to its energetic value (MJ kg^{-1}).

d) Tractor fuel consumption: approximate model

The model for the fuel consumption of the tractor and the power requirement to move the tractor and/or implement through the crop was developed following a modified version of the methodology proposed in ASAE (2003).

The soil and crop resistance (R_{SC}) was calculated using Eq. [9]:

$$R_{SC} = T_u\ w_i, \qquad [9]$$

where R_{SC} is the soil and crop resistance (kN), T_u corresponds to the soil and crop resistance specific to the implement per unit of length (kN m^{-1}), and w_i is the width of implement (m).

The internal friction, ground penetration, weight on the wheels, tire pressure, and tire design were considered for obtaining the value of the motion resistance. Thus, we calculate this quantity for an agricultural tractor using Eq. [10]:

$$R_M = W\ f_{RR}\ , \qquad [10]$$

where R_M is the motion resistance (kN), W corresponds to the dynamic wheel load (ton) and f_{RR} correspond to the motion resistance factor (kg ton^{-1}) which varies according to soil type. Another factor that determines the motion resistance and the power required at the drawbar of the tractor is the resistance in the slopes. Depending on the positive or negative value of the slope, the effect on the total resistance should be added or subtracted, accordingly. Thus the draft, D, or the total force parallel to the direction of travel required to propel the implement is:

$$D = R_{SC} + R_M \pm S,$$

where the effect of the slope is considered as;

$$S = 10\ W\ P_S\ , \qquad [11]$$

where P_S is the slope in percentage and the constant 10 has units of (kg ton^{-1}).

Therefore, the drawbar power required by the implements (P_{db}) corresponds to

$$P_{db} = \frac{D\ V}{3.6} \qquad [12]$$

where V is the travel speed (km h^{-1}).

The power-takeoff, or the power required by the implement (kW) from the power-take off shaft (PTO) of the tractor or engine is expressed as:

$$P_{PTO} = P_R\ w_i \qquad [13]$$

where P_R corresponds to the rotary power requirement (kW m^{-1}), and w_i is the implement width (m).

In this way, the total of power, P_T, required for a determined implement is the sum of the components:

$$P_T = \frac{P_{db}}{0.96\ \eta_T} + P_{PTO} \qquad [14]$$

where η_T corresponds to the traction efficiency.

To estimate the tractor fuel consumption the equations proposed in ASAE (2003) were used. These equations estimate the specific volume consumption (L kW^{-h}) at wide open throttle, so expressions developed in Grisso and Pitman (2001) and Grisso *et al*. (2004) were used to obtain fuel consumption for low or partial tractor loads. The specific volume consumption for a tractor with diesel engine at partial loads and full throttle were calculated using equation [15]:

$$Q = (2.64X + 3.91 - 0.203(738X + 173)^{1/2})\ X\ P_{PTO} \qquad [15]$$

where Q is the diesel fuel consumption at different loads (L h^{-1}), X is the relation between equivalent PTO power (P_T) to rated PTO power (P_{PTO}), and P_{PTO} corresponds to the rated PTO power, kW.

The energy used due to fuel consumption (E_{co}) of a tractor was determined with the following equation:

$$E_{co} = \frac{C_c\ I_p}{C_o} \qquad [16]$$

where C_c is fuel consumption per hour (L h^{-1}), I_p is the energy associated with the fuel, which takes a value of 47.8 MJ L^{-1} for the case of fuel oil (Bockari-Gevao *et al*., 2005), and C_o is the operational capacity (ha h^{-1}).

e) Energy cost associated with human labour (E_{jh})

According to Safa and Tabatabaeefar (2002) and Bockari-Gevao *et al.* (2005), the labour input in terms of energy per unit of time corresponds to 2.2 MJ h^{-1}, Yaldiz *et al*. (1993) reports a value of 1.96 MJ h^{-1}, and Baali and Ouwerkerk (2005) indicate a value of 1.93 MJ h^{-1}. Therefore, in the present work the average of these quantities, *i.e.* F_{ce} = 2.03 MJ h^{-1}, was used for the calculations, and the energy consumed by the application of human work was evaluated using Eq. [17].

$$E_{ij} = \frac{H_T\ F_{ce}}{A_T} \qquad [17]$$

where H_T is the total number of hours worked (h), F_{ce} is the energy consumption factor per hour of human labor MJ h^{-1}, and A_T is the area (ha).

f) Energy input due to irrigation systems (E_{ir})

The energy consumed by the irrigation system was calculated according to the following equation:

$$E_{ir} = \frac{I_e\ B_e\ H_u\ N_r}{A_i} \qquad [18]$$

where I_e = 11.4 MJ kW^{-h} corresponds to the index for the energy input for the equivalent electric power used (Meyer-Aurich, 2005), B_e is the power required by the pump (kW), H_u corresponds to the number of hours of operation of the irrigation system (h), and N_r is the number of times that the crop is irrigated, and A_i is the irrigated area (ha).

g) Energy outputs (E_O)

According to Hülsbergen *et al*. (2001), the energy output of the crop is defined as the calorific value of the harvested biomass (main product and/or by-products). In this work the energy output for each crop was calculated as:

$$E_O = M_S\ P_c\ I_e \qquad [19]$$

where M_S corresponds to the dry matter of the harvested product (%), P_c is the quantity of harvested product (kg ha^{-1}), and I_e corresponds to the energy equivalent of one kg of dry matter (MJ kg^{-1}), shown in Table 5.

The main parameters used for the measurement of the energy flow were obtained from Zak *et al*. (2006) and correspond to:

Table 5. Gross energy contents of harvested products

Crop	Energy content ($MJ\ kg^{-1}$)
Potato	17.2
Sugar beet, beets	16.8
Sugar beet, leaves	16.4
Winter wheat, grains	18.6
Winter wheat, straw	17.7
Winter barley, grains	18.6
Winter barley, straw	18.1
Spring barley, grains	18.4
Spring barley, straw	18.1

Source: De Freitas *et al.* (2006).

$$\text{Energy inputs} = \text{EI (GJ ha}^{-1}) \quad [20]$$

$$\text{Energy outputs} = \text{EO (GJ ha}^{-1}) \quad [21]$$

$$\text{Net energy balance NEB} = = (\text{EO} - \text{EI}) \text{ (GJ ha}^{-1}) \quad [22]$$

$$\text{Energy ratio ER} = \text{EO/EI} \quad [23]$$

$$\text{Percent gain PG} = 100 \text{ (ER} - 1) \quad [24]$$

Results and discussion

Comparison of energy ratios

The energy ratio for four different feedstock has been calculated and compared using the methodology described in the previous section. The energy equivalents have been obtained from the literature but the energy inputs and outputs represent local conditions of transportation, processing, and farming practices. The results are shown in Table 6 for corn, wheat, potato, and beets. It is evident that wheat does not represent a viable feedstock since its net energy value is negative. Corn and beet have positive energy values and thus, energy ratios greater than unity, but their magnitudes are lower than for the starch-rich potato which shows a large positive NEV and an energy ratio of 1.8. In the production and processing of the analyzed crops, different amounts of energy are required. Therefore, the sugar beet crop requires the highest level of energy, followed by the potato crop, corn crop, and wheat crop. The most significant inputs in the production of culture in dryland are fertilizers and fuels. Irrigation has a strong effect in the energy inputs for sugar beet compared to the other crops.

In terms of liters of ethanol obtained per cultivated hectare, there is a significant difference between wheat and corn compared to potato and beet. The number of liters per hectare for corn, wheat, potato, and beets corresponds to 3,400, 2,226, 9,280, and 9,720, respectively. Although, the sugar beet crop can produce as much ethanol as the improved cultivar of potato, it uses the largest amount of pesticides because this species is highly sensitive to illnesses in its phonological states.

Table 6. Comparison of energy ratio for different crops

	Corn	Wheat	Potato	Beet
Fertilizer, $MJ\ ha^{-1}$	17,654.1	8,989.9	15,118.3	29,437.2
Pesticide, $MJ\ ha^{-1}$	921.3	0.0	1,498.5	2,496.1
Fuel, $MJ\ ha^{-1}$	7,007.2	7,021.7	7,956.9	39,630.7
Irrigation, $MJ\ ha^{-1}$	563.2	0.0	0.0	23,507.4[a]
Other (Feedstock), $MJ\ ha^{-1}$	507.7	3,891.5	5,726.3	2,765.0
Total (Feedstock), $MJ\ ha^{-1}$	26,653.5	19,903.1	30,300.0	74,329.0
Process steam, $MJ\ ha^{-1}$	33,066.3	36,569.5	75,117.5	110,086.0
Electricity, $MJ\ ha^{-1}$	13,002.5	37,607.6		
Bulk transport, $MJ\ ha^{-1}$	1,197.3		3,947.2	5,540.5
Other (Process), $MJ\ ha^{-1}$	1,305.3			
Total (Process), $MJ\ ha^{-1}$	48,571.4	74,177.1	79,064.7	115,626.5
Total energy input, $MJ\ ha^{-1}$	75,224.9	94,080.2	109,364.7	189,955.6
Energy in ethanol, $MJ\ ha^{-1}$	71,426.5	47,369.3	197,478.4	206,841.6
Co-product credit, $MJ\ ha^{-1}$	13,497.7	0.0	0.0	0.0
Total energy output, $MJ\ ha^{-1}$	84,924.2	47,369.3	197,478.4	20,6841.6
Net energy value, $MJ\ ha^{-1}$	9,699.3	–46,711.0	88,113.7	16,886.0
Percent gain	12.9	–49.7	80.6	8.9
Energy ratio	1.1	0.5	1.8	1.1

[a] The irrigation system works with diesel, human labor, and depreciations which are considered in the Fuel and Other (Feedstock) items, respectively.

Besides, this crop requires large quantities of inorganic fertilizers. In this way, when the sugar beet crop is analyzed in energetic terms (Table 6), it uses double the energy in fertilizers compared to potatoes.

Advantages of potato for the production of ethanol

Within the matrix of species likely to be utilized in the production of biofuels in Chile, the starch-rich potato emerges as a feasible option. From a productivity perspective, this crop can be developed in the southern provinces, not competing for irrigation areas with more profitable crops, such as pasture, wheat, or sugar beet, and can become part of a crop rotation for bioenergy feedstock (*i.e.* potato-wheat-rapeseed). Besides, being a sown crop species, it allows opening the crop rotation after natural grasslands, which are very low in agricultural productivity and low in profitability per hectare. Furthermore, the southern regions of the country are some of the few zones that can expand their crop surface. For instance, the regions of La Araucania, Los Rios, and Los Lagos, have significant potential in terms of availability of surface to establish a system for potato production for bioenergy purposes. The regions of La Araucania and Los Lagos have a potential cultivated area of 1,004,737 and 1,068,365 hectares, respectively. During the 2005-06 season the area planted with potatoes reached 17,980 and 18,700 ha in these two regions. Thus, the area used to grow potatoes is only a small fraction of the total area available for agriculture.

One of the main concerns of producing ethanol from crops is related to the shift in the use of land from food production to biofuels. Due to the high yields obtained by potato growers, especially in the southern regions of Chile, added to the fact that only a small fraction of the total production is exported, there is a large fluctuation in the amount of land used to grow this crop that is mainly based on price expectations of this commodity. Figure 2 shows the variation in the number of hectares utilized to grow potato from 1999 to 2007. The maximum difference corresponds to 8,290 ha which is approximately the same amount of land needed to substitute almost 2% of the needs of gasoline in the Chilean market. The introduction of a cultivar of potato that is specifically bred for the purpose of producing ethanol would stabilize the market by regulating the number of hectares used to grow both types of potato, *i.e.* for human consumption and for ethanol production. The potato market in Chile is irregular and there are large variations in price every year, with a constant demand and a supply fluctuating significantly. The fluctuations in the supply come from a lack of organization of farmers that do not handle the information of how many farms will be producing potatoes. Thus, as the market becomes saturated the price drops and farmers shift to other more profitable crops. If farmers shifted to grow potatoes for biofuels purposes, the price of the cultivar for human consumption would rise and farmers would naturally shift again to this cultivar increasing the supply and lowering the price again. An additional 8,000 to 10,000 hectares utilized for the production of ethanol would not generate a lack of availability of land to grow potatoes for human consumption and would not cause a significant increase in CO_2 emissions due to change in land use.

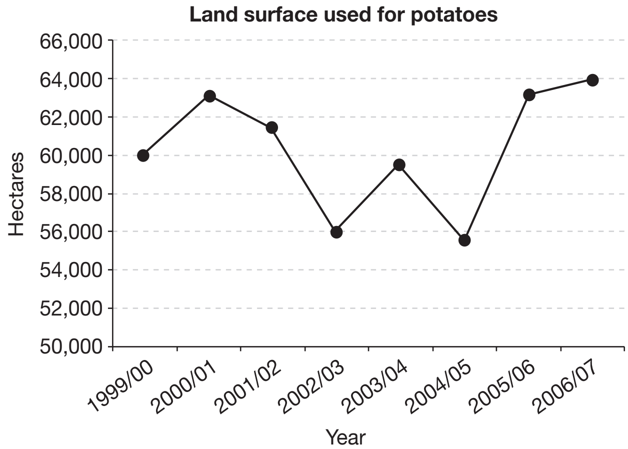

Figure 2. Variation of the number of hectares used to grow potatoes in Chile. *Source:* ODEPA (2007).

Conclusions

New directives from governments around the world are pointing in the direction of increase production of biofuels. Along these lines, the Chilean government is analyzing the introduction of a law to set a reference value of 5% of biofuel production to be placed on the market by 2013. Cellulosic ethanol is currently not at the stage of being a feasible industrial option. This paper analyzes the energy ratio of some of the most common crops grown in Chile that can be utilized for the purpose of producing ethanol. The results indicate that a potato cultivar specially bred for high yield, high starch and dry matter content can obtain a positive net energy balance with an energy ratio of 1.8. In addition to this, current tests performed with farmers associated to this initiative have obtained yields near 60 tons/hectare which translate to approximately 9,000 liters of ethanol per hectare. The introduction of this high-starch content potato cultivar would also help stabilize the price of potato that has traditionally fluctuated significantly with large differences in the amount of land utilized to grow this crop. The solution to the problem of dependency on foreign oil will come as an array of alternatives and is heavily dependent on the local agricultural and energetic resources of each country. The utilization of a genetically optimized potato cultivar for the production of ethanol emerges as a feasible alternative in the Chilean market.

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