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ORIGINAL ARTICLE

From mixed farming to intensive agriculture: energy profiles of agriculture in Quebec, Canada, 1871–2011

Lluis Parcerisas[1] · Jérôme Dupras[1]

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Abstract
This article presents an energy analysis of Quebec agroecoystems at five periods of time: 1871, 1931, 1951, 1981, and 2011, calculating for each year the various energy flows and their resulting Energy Return on Investment (EROI). In the nineteenth century, Quebec agroecosystems were typical examples of historical organic agriculture, with a low dependence on external Inputs but a high dependence on biomass reused, mainly livestock feed and crop seeds. Following the full industrialization of Quebec agriculture by the 1960s, there have been massive injections of external inputs, but also steadily rising amounts of biomass reused due to livestock specialization and the decoupling of domesticated animals from crop farming. As a result of this transformation, the energy efficiency of agroecosystems diminished, despite the significant increases in both final produce and area productivity that were achieved.

Keywords Energy analysis · Energy Return On Investment (EROI) in farm systems · Sociometabolic profiles · Energy transitions · Energy productivity · Sustainability

Introduction

The agrarian sector in Western countries has progressively lost importance in domestic economies during the last 60 years (Grigg 1992; Federico 2005; Mazoyer and Roudart 2006). Loss of land dedicated to agricultural uses is one consequence of this process. Between 1961 and 2012, Western European agricultural lands decreased by 16% and permanent crop areas by almost 45% (FAOSTAT 2013). The agriculture that has survived this trend, having shifted from a domestic and subsistence agriculture to a market-oriented and industrialized agriculture, has though succeed in increasing by large amounts its production, crop yields, and land productivity through improved technology (FAO 2006; Federico 2005). However, industrialized agriculture is also known to have had severe impacts on the type and spatial distribution of agricultural activities. The typical processes of livestock specialization and intensification of the agricultural practices have had major negative impacts on the environment since the Green Revolution adopted techniques such as the massive use of fertilizers and pesticides, as well as unfriendly environmental practices (Mazoyer and Roudart 2006; Pimentel 2009; Krausmann et al. 2013). Moreover, cheap transport since the end of the Second World War has helped to the globalization of agriculture and the disconnection between food and resource production and consumption (Kastner et al. 2011). All this is contributing to the higher use of energy in agriculture, jeopardizing the energy efficiency and sustainability of industrialized agricultures. Hence, it is not strange that some voices stand for a return to certain practices typical from organic agricultures that could help diminish energy inputs in agriculture, enhancing its energy efficiency and reducing global warming and environmental threats (Pelletier et al. 2008; Pimentel et al. 2005).

Recently, new methodology has been developed to calculate Energy Return On Investment (EROIs) in order to assess the energy efficiency and sustainability of agroecosystems

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✉ Lluis Parcerisas
luisparcerisas@gmail.com; lluis_parcerisas@ub.edu

Jérôme Dupras
jerome.dupras@uqo.ca

[1] Institut des sciences de la forêt tempérée (ISFORT), Université du Québec en Outaouais, 58, rue Principale, Ripon, Québec, Canada

(Tello et al. 2015; Tello et al. 2016), adopting the theoretical concepts offered by social metabolism (Fischer-Kowalski and Haberl 2007; González de Molina and Toledo 2014). In this study, we apply this method to calculate the EROIs of Quebec's agriculture in 1871, 1931, 1951, 1981, and 2011 in order to study its energy transition from a traditional organic agriculture to an intensive industrialized one. The election of these years is due basically to the quality of the data of the censuses. At the same time, these years represent well the different stages of the path that agroecosystems of Quebec have followed during the period studied.

It needs to be noted that the distinction we make here between "traditional" or "organic" and "industrialized" agriculture is based on the human-environment relationship established, that is, the socio-metabolic regime. We assess this regime by the importance of energy flows according to its origin. From that point of view, a traditional, or organic, agriculture relies on the solar energy and its area of influence is mainly local, while an industrialized agriculture mostly uses fossil fuels and is connected to and affects distant areas (Fischer-Kowalski and Haberl 2007; González de Molina and Toledo 2014). The transition from a traditional to an industrialized agriculture can be long or short process, and both stages may overlap for a period of time.

Methods and sources

In order to determine the energy flows and basic funds of farming systems in Quebec, we have followed the conceptual and methodological approach proposed by Tello et al. (2015, 2016). A key point of this approach is the adoption of a farm-operator standpoint and the establishment of the agroecosystem boundary in order to calculate the inputs invested by the farm operator, coming from within or outside the agroecosystem, and the outputs produced by the farming system. This agroecosystem boundary includes the farmland (composed by the cropland area, the pasture land, and the woodland area), but also the livestock and the ecological services provided by an associated biodiversity, recognizing this way that the former cannot function alone without the last two (Tello et al. 2015). This methodology also enables us to bring into light the internal loops and processes that occur within the agroecosystems, so allows us to a better understanding of their functioning and links with the internal and external agents, and a better assessment of their sustainability (Guzmán and González de Molina 2015; Tello et al. 2016).

In that sense, the *total produce* (TP) of the agroecosystem, that is the gross production coming from the farmland and the livestock, is divided among the *final produce* (FP)—the part which goes to human consumption or used by the society, the *biomass reused* (BR)—the fraction of farm production which is reinvested in the agroecosystem in order to sustain it, and the *waste* (W)—that fraction not properly used to maintain agroecosystems or used to be consumed by society.

The censuses of agriculture of Canada carried out every 10 years since mid-nineteenth century give quite ample information on the crop extensions, crop yields or production, livestock number and products, and forest products (Statistics Canada 1872, 1935, 1953, 1982, 2012). We used this data to estimate the biomass produced in the farms in 1871, 1931, 1951, 1981, and 2011. Produce from pasture land has been calculated from Petit (1993).The census of 1871 details the cords or cubic meters of wood sold per tree species, and the census of 1931 also provides information on the forest products sold (that we accounted as *final produce*) and the forest products consumed by the farmers (accounted as *biomass reused*). We used the ratio of wood consumed per farm from Census of Agriculture of 1941 for our calculations in 1951 to have the wood consumed in the farms in that year. For 1981 and 2011, we used data from regional syndicates (FPFQ 2016).

All this biomass has been converted into energy units using the conversion, gross calorific value, and water content rates from Guzmán et al. (2014). This source has also been used to calculate the residues of the crops and their gross energy.

The corresponding censuses of agriculture of Canada also provide comprehensive information on the inputs used in agriculture (workers, working animals, machinery, seed imports, fertilizers and pesticides, water used, and others). Electricity used in agriculture is provided for 2011 in the census of the same year. For 1931 and 1951, we estimated it from the number of electric motors, milking machines, and cream separators. For 1981, we used the data and methodology of Dyer and Desjardins (2006), who give values of electricity used in Canada per each type of livestock and crop. Imported animal feeding was calculated as the difference between the livestock needs and the availability in the province.

According to this methodology, indirect and embodied energy have to be calculated as well when dealing with flows coming from outside of the agroecosystem. For that purpose, we took the rates given by Aguilera et al. (2015).

With all this amount of information and data produced, three different EROIS were calculated. First, the *final EROI* (FEROI), relating the *final produce* with the *total inputs consumed* (TIC), which is the sum of *biomass reused* and the *external inputs* (EI). Secondly, the external EROI or *EFEROI* (FP/EI) gives information on how much energy a farm operator has spent in order to generate the *final produce*. Finally, the internal EROIs or *IFEROI* (FP/BR) assesses what amount of the *total produce* has been reinvested in the agroecosystem to get one unit of the *final produce* (Tello et al. 2015; Tello et al. 2016).

Results

Main socio-environmental and agricultural features of Quebec

The province of Quebec is the largest province of Canada with a total area of around 1.5 million km^2. However, not all its territory is suitable for agriculture, taking into account that farming becomes difficult when the number of frost-free days is under 100 (Linteau et al. 1983). For our purposes, here we have used the *ecúmene* area of Quebec of nowadays (calculated in Parcerisas and Ruiz, in press). This area comprises those territories colonized and where population settled along different times of period (Linteau et al. 1983; Boudreau et al. 1997) and totals 118,353 km^2 (Fig. 1). The first period of settlement in Quebec, until circa 1820, was done in the St. Lawrence Lowlands. In a second phase, agrarian settlements extended into the Laurentian and Appalachian Highlands. When the occupation of the highlands was completed, by the end of the nineteenth century, the settlement within some areas of the Canadian Shield (Temiscangue and Saguenay-Lake St. John) had already started. During the first decades of the twentieth century Abitibi region was colonized. All the process of colonization and settlement lasted four centuries and prolonged until the 1940s (Linteau et al. 1983; Boudreau et al. 1997; Hayes 2015).

In the beginning of the nineteenth century, farmland area totaled less than 7000 km^2, being improved[1] and suitable for agriculture only a third of them (Statistics Canada). By the end of the century farms already occupied almost 58,500 km^2, of which more than the half had been cleared and improved. This process of land improvement continued well into the twentieth century, and with the new settlements in Temiscamingue, Lake St. John, and Abitibi, the highest peak of land taken by farms was reached in the 1940s (Fig. A1). Since mid-twentieth century, agriculture has diminished its presence in the territory.

Since the 1940s, cropland area has remained quite stable though, so its proportion in the total farm area has increased up to be around 56% of the farmland in 2011. Cropland area has gained importance at the expense of the woodland area and the pastureland during the second half of the twentieth century (Fig. A2).

Following European traditions and farming, wheat and potatoes, were the most extended crop in Quebec during the first period of settlement. Large part of its production was exported to Britain markets (Courville et al. 1995; Linteau et al. 1991). The crisis of 1830s, due to the exhaustion of soils suitable for wheat and population pressure, provoking the incapacity of Quebec to meet external and internal demands, exposed the inappropriateness of cultivating wheat in Quebec (in contrast to the Western Prairies of Canada) and was used to carry out important changes. Wheat farming was largely substituted by oats, in order to supply feed for increasing local livestock and to be exported to the USA. The depression of 1873 also implied a move towards more suitable crop techniques and the choice by agronomists and politicians of Quebec to redirect agriculture of the province towards dairy industry. Since then, mixed farming, combining extensive animal feed-oriented crops with dairy agriculture, has been traditionally practiced in Quebec (Russell 2012; Courville et al. 1995; Linteau et al. 1991; Hayes 2015). As shown in Fig. 2, ruminants were the main farm animals in nineteenth century. The option of Quebec for a specialization in dairy production is reflected in the increasing number of cattle and milk cows in particular. Along with Ontario, Quebec turned into the main producer of milk and dairy products (mainly cheese and butter) for the rest of Canada and foreign markets, especially the state of New York and Great Britain (Linteau et al. 1991; Hayes 2015).

During the second half of the last century, this situation changed. Since then, livestock specialization focused in pork and poultry industry has gained importance, and dairy cattle industry has lost weight. On the other hand, horses, the main working animal used in the province, have largely decreased since the massive introduction of machinery in the last 50 years. Here, it is worthy to note the slow introduction of machinery in Quebec (Linteau et al. 1991; Hayes 2015): there was not an average of at least one tractor per farm until 1966.

Crop production in Quebec has been linked to each one of these livestock specializations options (Table 1). Wheat and other cereals for human consumption has not been an important crop in Quebec agriculture since wheat crisis in 1830s. During the specialization in dairy production, most part of the cropland area was allocated to animal feeding crops such as oats, hay, and other fodder crops. Since the boom of the pork industry in the 1970s, corn and soybeans, crops oriented to feed the increasing number of pigs and poultry, have strongly appeared in Quebec, especially in Southern Quebec (Jobin et al. 2014). In 2011, these two crops already matched the extension of the total hay and fodder crops. These four crops accounted for 80% of the cropland surface.

Despite this general picture presented here, there have been different realities and different paces within Quebec regions. Since the second half of the nineteenth century, some regions had an important specialization for local economy in other commodities (garden market products, tobacco, livestock

[1] According to the censuses of agriculture in Canada, improved land is defined as the farmland that has been transformed by the settler for agrarian uses. It includes cropland, fallow area, improved pasture land, and other improved area (the area of barnyards, lanes and roads on farms, and idle cultivated areas). This process of clearing the land could take years or decades (Linteau et al. 1983). On the other hand, the non-improved land is defined as an area inside the farm that has not been transformed and used by the farmer for agrarian use. It includes woodland, natural pasture, and other non-improved land (uncultivated hay land, brush pasture, grazing or waste land, sloughs, marsh, and rocky land).

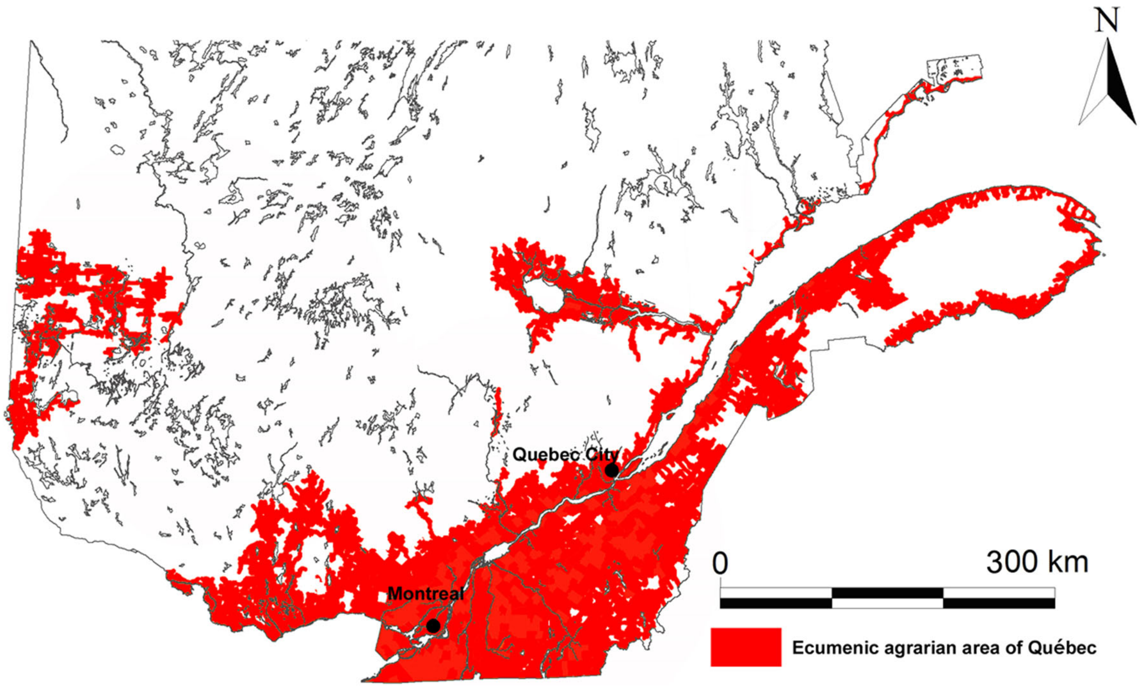

Fig. 1 Ecumene area of Quebec

raising, firewood). As previous research has already demonstrated (Courville et al. 1995; Courville 2000; Hayden 2015), agriculture in Quebec until the late 1960s has been a two-speed agriculture, and smaller holdings on marginal lands turned towards subsistence, especially foothills of the Laurentian shield and Appalachian Mountains, and did not participate in this commercial turn of the farms in the Laurentian Valley. The same way, the hand in hand-intensive specialization in corn and pork production that has taken place in the last decades of twentieth century has concentrated in the south of Quebec, along the Saint Lawrence River. On the contrary, more extensive cropping such as oats, linked to dairy production, has remained in the more remote areas of Quebec (Courville 2000; Jobin et al. 2010, 2014; Parcerisas and Ruiz, in press).

Energy profiles of Quebec between 1871 and 2011

Table 2 shows the main energy flows generated by the agroecosystem of Quebec in each year studied. *Total produce* more than tripled, from 939 petajoules (PJ) to 3006 PJ, during the whole period studied. Among this *total produce*, produce coming from the land (*land produce*) have always been much higher than the produce coming from the barnyard (dairy

Fig. 2 Evolution of selected livestock in Quebec (number of heads × 1000)

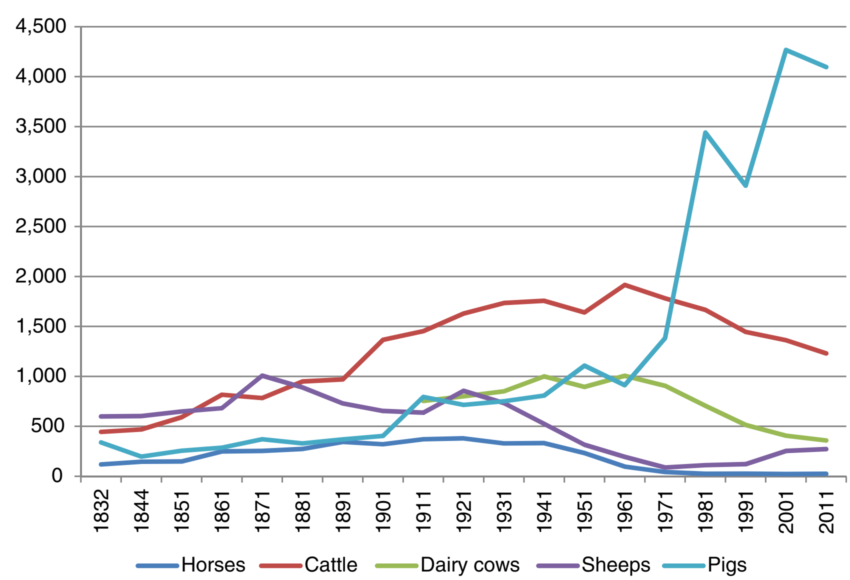

Table 1 Socio-economic indicators, land uses, and main crops in Quebec, 1871–2011

	Unit	1871	1931	1951	1981	2011
Current ecumenic area	km^2	118,353	118,353	118,353	118,353	118,353
Population density	cap/km^2	10.1	24.3	34.3	54.4	66.8
Farm population	%	23.3	10.6	7.7	1.8	1.3
Nr of farms	nr	118,086	135,957	134,336	48,144	29,437
Average farm size	ha/farm	37.8	51.5	50.6	78.5	113.5
Farmland area	km^2	44,619.8	70,027.5	67,932.2	37,791.7	33,413.3
Cropland area	km^2	15,219.3	24,846.2	23,432.7	17,560.4	18,747.6
Fallow	km^2	n.d.	113.9	190.5	530.8	45.3
Woodland and scrub area	km^2	n.d.	24,425.2	23,772.6	10,695.0	10,657.6
Pastureland area	km^2	7,863.8	16,315.8	10,866.7	4,435.6	2,604.8
Built-up and unproductive area	km^2	21,536.7	4,440.3	9,669.6	4,570.0	1,358.0
Wheat and other grains	% cropland	6.5	4.0	5.5	5.6	3.4
Oats	% cropland	n.d.	27.0	24.1	8.5	5.5
Hay and fodder	% cropland	32.2	62.9	67.3	60.7	40.9
Corn and soybeans	% cropland	n.d.	0.8	1.4	14.3	39.3

products, meat, livestock raising, wool, eggs, and honey), despite the continuous increase of the latter during the whole period.

Cropland produce, for its part, has always been the most important source of produce in Quebec's agroecosystems during the period studied. However, until 1931, *woodland produce* was also very important. Its peak in 1931 can be explained by the wood from forest clearing in the new territories colonized during these years in Abitibi, Temiscamingue, and Lake St. John. Also, wood available from forest clearing during the nineteenth century must be part of the huge timber and firewood sold and consumed by the farms in 1871. Since 1931, forest areas have decreased within farmlands, and this process is reflected in the lower amount of biomass produced and consumed.

Cropland produce had a growth of 428% during the whole period. Proportionally, this increase was higher between 1871 and 1951 than between 1951 and 2011. For sure, some agrarian technique improvements and the change towards more suitable crops helped to increase agrarian production during the so-called *The Great Transformation* of Canada's economy between 1891 and 1929 (Hayes 2015; Linteau et al. 1983), but the main reason of this huge augment was the increase of the cropland area. In fact, at the end of this period, the insufficient fertilization had exhausted the soils (Linteau et al. 1983). The productivity per unit area (Table A3) decreased between 1871 and 1931, but has boosted since then.

The other source of *total produce*, *pasture produce*, is of course related to the extension of pasture land. And this, in turn, is related to the socio-metabolic regime of agriculture. In traditional organic agricultures, the lack of access to external animal feeding and fertilizers forced to maintain a minimum extension of pasture in order to feed local livestock and dispose of its manure (Guzmán and González de Molina 2009). The industrialization of agriculture and the massive arrival of external chemical fertilizers and animal feed implied, among other things, the disappearance of pasture land, since then allocated to other land uses. Hence, it had and important and increasing presence between 1871 and 1951, but has sharply dropped since then.

Not all this *total produce* is finally consumed by the society, but some is reinvested in the agroecosystem (*biomass reused*), or is wasted. In 1871, 1931, and 1951, we could estimate the part of *woodland produce* that was consumed by the same farmers (as materials for building construction or firewood). Part of the *cropland produce* is reinvested in the cropland and some in the barnyard for livestock needs. A certain amount of the harvest needs to be kept as seeds for next season, and some is not harvested or is buried in the same fields, and used this way as a soil natural fertilizer. The total amount of *buried biomass* has hugely increased due to imports of animal feed. In traditional agricultures, crop by-products and residues (straw, hulks, steams, and stalks) had an important use as complementary animal feeding. Since the massive use of external animal feed, these products are not used so they are left on the ground and sometimes burned. This explains the substantial increase of *buried biomass* during the period studied, especially since 1951. On the other hand, a part of *total produce* is addressed to livestock needs. This amount will depend on the livestock dimension. Some cultivated crops (corn, oats, soybean, tame hay, beets...) are used to feed local livestock as fodder. The remaining can be exported or sold in the domestic markets, and so, accounted as *final produce* (for human consumption or animal feed). Also, crop

Table 2 Flows of energy carriers (in terajoules) and Energy Return on Investment (EROI) in Quebec, 1871–2011

	1871	1931	1951	1981	2011
Woodland	31,148.1	68,092.0	41,595.3	27,534.1	28,233.0
Cropland	46,317.2	68,094.2	141,241.5	177,584.1	244,470.3
Pasture	13,761.6	28,552.7	19,016.7	7,762.3	6,216.6
Land produce	91,226.9	164,738.9	201,853.5	212,880.4	278,919.8
Barnyard produce	2,739.8	6,319.9	9,687.0	13,623.0	21,740.2
Total produce	**93,966.7**	**171,058.8**	**211,540.5**	**226,503.5**	**300,660.1**
Wood used in farms	4,797.9	45,978.8	15,739.3	...	...
Seeds	1,886.2	3,387.5	4,495.6	3,675.7	3,834.0
Buried biomass	6,081.1	13,035.9	9,950.4	45,717.5	66,633.7
Farmland biomass reused	**12,765.3**	**62,402.3**	**30,185.3**	**49,393.1**	**70,467.7**
Fodder	1,656.2	11,362.4	51,043.9	60,318.7	77,878.0
Crop by-products	96.0	73.1	22,752.5	14,577.1	21,410.5
Stall bedding	7,851.3	17,272.7	15,751.5	16,515.1	14,591.3
Grass	50.8	11,788.3	3,034.1	352.8	857.5
Barnyard biomass reused	**9,654.3**	**40,496.4**	**92,582.0**	**82,839.2**	**114,737.2**
Biomass reused (BR)	**22,419.6**	**102,898.7**	**122,767.3**	**141,156.8**	**185,204.9**
Food	7,510.2	9,326.6	15,762.2	32,163.7	50,586.5
Animal feed	23,861.5	19,896.5	31,047.5	18,323.0	20,909.7
Fiber and tobacco	100.0	40.0	29.9	32.9	0.0
Plants	0.0	0.0	4.8	0.0	132.4
Food, fiber, feed, and plants	**31,471.6**	**29,263.1**	**46,844.5**	**50,519.6**	**71,628.9**
Firewood and timber	**26,350.1**	**22,113.2**	**25,856.0**	**27,300.0**	**27,606.5**
Industrial crops	**0.0**	**0.0**	**0.0**	**36.9**	**972.7**
Final produce (FP)	**57,836.3**	**51,395.7**	**72,970.7**	**77,856.5**	**100,208.1**
Unharvested biomass	**13,710.8**	**16,764.4**	**15,982.6**	**7,409.5**	**5,359.1**
Waste	**0.0**	**0.0**	**0.0**	**80.7**	**9,887.9**
Pasture	50.8	11,788.3	3,034.1	7,762.3	857.5
Crop by-products	96.0	73.1	22,752.5	14,577.1	21,410.5
Main product	1,656.2	11,362.4	51,043.9	60,318.7	46,938.5
Animal feeding	1,803.0	23,223.7	76,830.6	82,658.1	100,145.9
Stall bedding	7,851.3	17,272.7	15,751.5	16,515.1	14,591.3
Barnyard entries	**9,654.3**	**40,496.4**	**92,582.0**	**99,173.2**	**114,737.2**
Manure	30,337.7	109,174.6	57,823.8	104,157.9	46,374.5
Draft power	1,741.5	2,134.7	1,287.2	0.0	0.0
Barnyard services	**32,079.2**	**111,309.4**	**59,111.1**	**104,157.9**	**46,374.5**
Barnyard produce	**2,739.8**	**6,319.9**	**9,687.0**	**13,623.0**	**21,740.2**
Imports for animal feeding	0.0	27,852.3	46,079.0	178,195.3	196,717.8
Electricity	0.0	294.1	3,786.5	5,704.4	32,666.0
Domestic residues	2,707.4	0.0	0.0	0.0	0.0
Barnyard external inputs	**2,707.4**	**28,146.4**	**49,865.5**	**183,899.6**	**229,383.7**
Electricity	0.0	0.0	0.0	4,167.6	11,315.9
Machinery	3,618.4	5,385.8	24,080.9	80,408.9	160,876.7
Fertilizers	0.0	154.7	598.1	10,830.2	17,278.2
Herbicides	0.0	0.0	0.0	1,062.1	165.9

Table 2 (continued)

	1871	1931	1951	1981	2011
Water	0.0	0.0	0.0	12.7	1,209.0
Seeds	0.0	0.0	0.0	0.0	297.3
Greenhouses	0.0	153.4	19.7	94.9	46.8
Cropland entries	**3,618.4**	**5,693.9**	**24,698.7**	**96,576.4**	**191,189.9**
Agroecosystem societal inflows	**6,325.8**	**33,840.3**	**74,564.2**	**280,476.0**	**420,573.6**
Labor	**554.3**	**3,499.0**	**4,477.0**	**782.4**	**404.7**
External inputs (EI)	**6,880.1**	**37,339.3**	**79,041.2**	**281,258.4**	**420,978.3**
Total inputs consumed (TIC = EI + BR)	**29,299.7**	**140,238.0**	**201,808.5**	**422,415.2**	**606,183.2**
External final EROI EFEROI = FP/EI	**8.406**	**1.376**	**0.921**	**0.277**	**0.238**
Internal final EROI IFEROI = FP/BR	**2.580**	**0.499**	**0.593**	**0.552**	**0.541**
Final EROI FEROI = FP/TIC	**1.974**	**0.366**	**0.361**	**0.184**	**0.165**

by-products and grass from pasture land are used as animal feeding (the grass not used is accounted as *biomass not harvested*). And finally, some part of the production (the straw from the cereals) is used for stall bedding for livestock. *Biomass reused* has kept growing up in Quebec, but above all between 1871 and 1951, when it multiplied by four and a half, than between 1951 and 2011, when there has been an increase of 51%.

Final produce, the part of the *total produced* available and addressed to the society out of the farmland, has increased but at a much lower rate than *total produce* and *biomass reused*. This fact says that most *total produce* gains have gone to *biomass reused*, but mainly as buried biomass. If in 1871 *biomass reused* represented 24% of the *total produce*, in 2011, it meant the 62%.

However, its weight in the *total inputs consumed* (*biomass reused* plus *external inputs*) by agriculture has largely decreased, mostly since the 1950s. Meanwhile, in 1871, it represented 77% in 1871 and 61% in 1951; it accounted for 31% in 2011. The reason is not the decrease of its amount, as we have seen, but the huge increases of *external inputs* injected in the agroecosystems. In 1871, only 6.9 PJ was invested in the agroecosystems from external markets, mainly machinery and domestic residues. The machinery used by the time was composed by plows, harrows and reapers, mowers, threshing mills, and fanning mills. We have assumed that food domestic residues were used as animal feeding to complete their diet, especially for pigs and poultry. Great disruptions had to come after 1950s with the total industrialization of agriculture (Linteau 1991; Hayes 2015). Imports of animal feeding, mechanization and adoption of machinery, use of chemical fertilizers and pesticides, imports of selected and modified seeds, and an increase of electricity use have entailed energy imports from external markets to multiply by more than ten between 1931 and 2011, from 37 to 420 PJ.

As expected, and following the same trend of other study cases in Western societies (Tello et al. 2016; Gingrich et al., in press), *FEROI* and *EFEROI* have decreased overall the period to very low values in 1981 and 2011 (Table 2). In 2011, for every unit of energy invested in the agroecosystems, society only got 0.16. For its part, *IFEROI* has also decreased but has remained quite stable since 1951. *EFEROI*, comparing *final produce* with *external inputs*, is obviously very high in 1871 as the only external inputs injected in the agroecosystem were labor, some little basic machinery and domestic residues. The improvement of transport networks and the adoption of the Second Industrial Revolution products allowed the access to external animal feeding (in this case from the Western Prairies of Canada) and the introduction of some fuel machinery and chemical fertilizers in the farms in the beginning of the twentieth century. This implied a drop of this ratio in 1931, but still in values higher than one. *IFEROI*, on its side, presents values around 0.5 during the whole twentieth century.

Discussion

According to the results obtained, we could establish three stages of different sociometabolic profiles of the Quebec agriculture during the period studied. Figure 3 displays on a graph these energy flows from 1871, 1951, and 2011, representative years of each stage. From them, it is easier to glimpse the two last main socio-ecological transitions.

During nineteenth century, we find an “advance organic economy” stage. Agricultural production was already inserted in a growing connected commercial network and markets, thanks to urbanization and industrialization of economies and societies (Linteau et al. 1983). First with wheat production and later with animal feed oriented crops, such as oats and hay (Courville et al. 1995). However, it was still organic, optimizing traditional low-input agrarian systems (Krausmann et al. 2008; Tello and Jover 2014). Production rises were based essentially on increasing the cultivated land and exploiting the soils. Most inputs in agriculture, coming from local

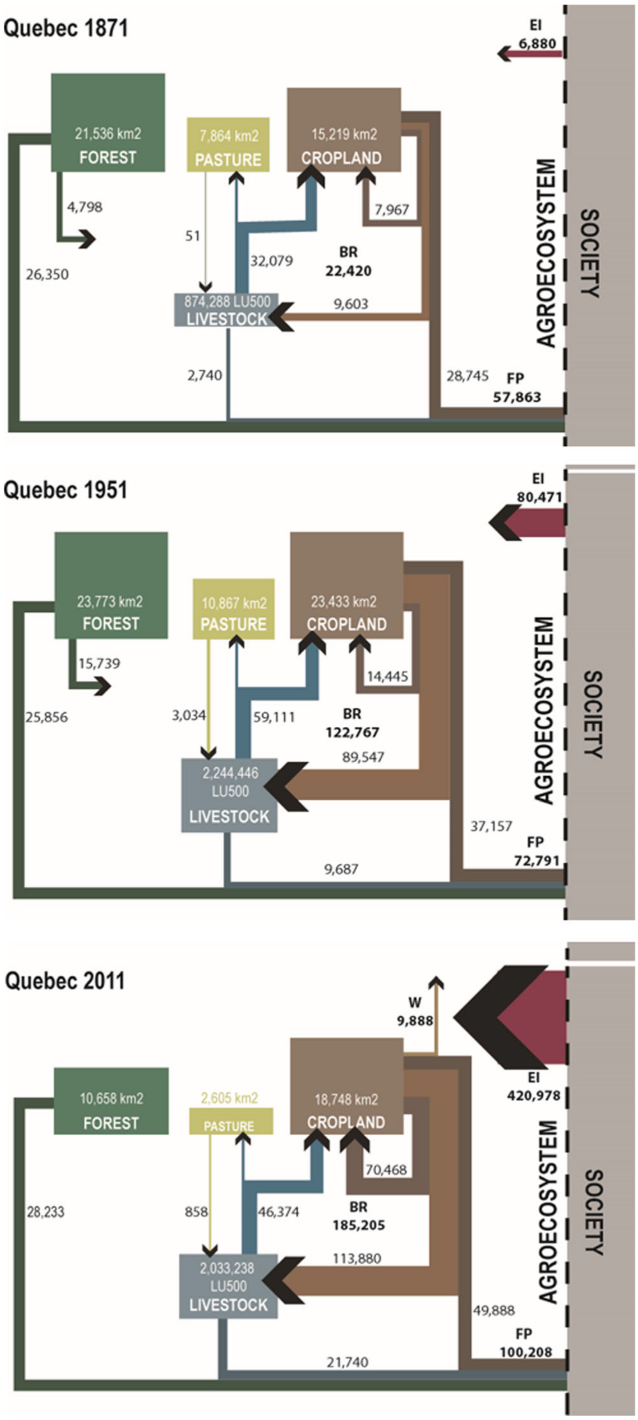

Fig. 3 Energy flows (in terajoules) in Quebec in 1871, 1951, and 2011. *EI* external inflows, *BR* biomass reused, *FP* final production, *W* waste

environments, were solar based, and practically, all of them were reinvested from the same agricultural produce. A distinctive feature of these traditional farming systems was the necessity of having a well-integrated diversity of farm uses (cropland, pasture, and forest) in order to produce, firstly, biomass to be reinvested in the soils and, secondly, to feed and keep (through grass, straw, and animal feed products) the livestock, whose services (manure and draught power) were essential to the functioning of the agroecosystem (Cunfer 2004; Guzmán and González de Molina 2009; Krausmann 2004).

Given the small amount and access to external inputs, these livestock services and biomass reused were the most important way to inject energy inflows into agroecosystems. In that sense, crop by-products and residues were a key component for the household and environmental reproduction in traditional agricultures; despite most of them did not have a market value, they provided very diverse and useful uses. As a result, we find, towards the end of this period, in 1871, the characteristic feature of this type of socio-metabolic regimes: very high EFEROIs, due to the small amount of external inputs invested, and much lower IFEROIs, due to the high quantity of internal reuses forced by the land cost of sustainability of traditional agricultures (Guzmán and González de Molina 2009). In 1871, 5 gigajoules (GJ) of biomass produced by agroecosystems were reinvested per hectare of farmland. On the contrary, only 1.5 GJ of external inputs was injected to 1 ha of farmland (Table A3).

External markets demanding dairy products offered the opportunity to change wheat production specialization for a dairy production combined with animal feed cropping, shaping the mixed farming characterized of Quebec since then. From then on, agriculture of Quebec entered in a period of transition towards an industrialized agriculture based on fossil fuel injections. During this new stage, there was still a combination of organic agricultures with the oil- and electricity-driven technologies of the second Industrial Revolution that fuelled mass production and consumption. It is the time when external and fossil fuel inputs are incorporated to agriculture. In 1931, they already accounted for 27% of the total inputs consumed by agriculture, and in 1951, they represented almost 40%. However, agricultural reproduction still depended on energy reuses. The needs of *biomass reused* per hectare were of 14.7 GJ in 1931 and of 37.4 GJ in 1951, still higher to the 5.3 and 11.6 GJ of *external inputs* per hectare of farmland in those same years.

By 1930s, this stage of agriculture in Quebec seems to be arriving at its limits, as problems of soil exhaustion by lack of fertilization exposed (Lindeau et al. 1983; Guzmán and González de Molina 2009; Tello et al. 2016) and by the high cost of land sustainability and the huge demands of biomass reuses. Due to the latter, in 1931 and 1951, Quebec agriculture produced less energy to be finally consumed by population and markets per hectare of farmland and cropland than in 1871. *Barnyard produce* per hectare and per head increased between 1871 and 1951 (from 0.6 and 3.1 GJ to 1.4 and 4.3 GJ), but probably less than one could expect after the specialization in dairy products. Insufficiency of certain elements in the animal's rations surely affected their low productivity, and the incapacity of farmers to go beyond producing cheese and butter also helped to the slow increase of production, with moments of stagnation (Linteau et al. 1983).

Farmers could face this issue thanks to the last socio-ecological transition, from 1950s, towards the fully industrialization of the farm systems by means of massive fossil energy subsidies (Krausmann et al. 2008; Tello and Jover 2014). On the other hand, in Quebec, the general answer of the agrarian sector to increase productivity and face urban and other economic pressures has been the industrialization of agriculture through a specialization in pork and poultry production.

Certainly, during this last stage, productivity per unit area and *final production* have increased, but *external inputs* have augmented at higher levels. In 1981, 20.6 GJ of *final produce* was obtained by hectare of farmland, and 30 GJ in 2011, tripling values of 1951. But in order to obtain these higher rates of productivity in 1981, it was necessary to invest 74.4 GJ per farm hectare and 126 GJ in 2011. During this stage, FEROIs have decreased to very low values, 0.184 in 1981 and 0.165 in 2011. Also, EFEROIs have largely decreased due to high dependency on external inputs. For its part, IFEROIs in the case of Quebec have remained in similar low values than in 1951, and there has not been an increased because the volume of biomass reused has kept increasing despite to its lower importance.

Hence, this specialization in livestock production is far from being efficient, as already demonstrated in other case studies (Tello et al. 2016; Singrich et al., in press), to a large extent because it is the type of production that consumes more relative energy (Pelletier et al. 2008, 2011; Woods et al. 2010). In 2011, despite 84% of the cropland are dedicated to animal feeding crops (corn, soybeans, and hay), barnyard produce only represented 7% of the *final produce* measured in energy units. The substitution of energy from biomass reused to external inputs entails deep changes in the functioning of the agroecosystems, and ultimately in the damage of the most important natural funds, such as soil life and landscape biodiversity. On one hand, the rupture of the land cost typical of traditional agricultures (Guzmán and González de Molina 2009) has allowed the abandonment of large amounts of farmland (Paquette and Domon 1997, 2001) . Few agricultural areas remaining today in Quebec are isolated, with the consequent reduction of ecological connectivity that threatens local biodiversity (Dupras et al. 2016). The surviving farms have passed from a diversified cropping agriculture mixed with dairy production to the large present-day intensive farming system monocultures of corn and other animal feed crops. Pasture land has disappeared and livestock are stuck and bred in high-energy consumer industrial feedlots (Jobin et al. 2014). Adopting intensive ways of agriculture has also produced negative environmental consequences by reducing landscape patch diversity (Jobin et al. 2014), decreasing wildlife habitat and soil carbon capacity (Eilers et al. 2010), contaminating underground water and watersheds, and causing soil degradation (Levallois et al. 1998; Eilers et al. 2010; Giroux 2003; Acton and Gregorich 1995; Van Bochove et al. 2007).

One characteristic of this energy transition towards a massive fuel industrial agriculture in Quebec is that it was slow and long, not being fully completed until well into the second half of the twentieth century despite the first introduction of machinery, imported animal feed, and fertilizers in the 1910s. Also, *biomass reused* inflows were still very important during this period. In 1951, they were much higher than the *external inputs*, and the latter did not overpass the first until 1981, in the years we have studied. Again, though, we have to stress that this picture may change depending on what area is studied. First results of a more detailed county analysis show that some areas of Quebec, such as the Montreal Metropolitan Region or in the Laurentides, are fully industrialized by 1966, even some by 1951, when EI are already higher than the BR (Table A3; Parcerisas et al., in press). In general, nevertheless, we can affirm that the agroecosystems of the whole province of Quebec became fully industrialized, with a clear prominence of external inflows at some point after the 1960s.

Conclusions

The use of the different three EROIs is revealed as a suitable and positive tool in order to study and assess the energy efficiency of an agroecosystem, giving at the same time valuable information on its internal functioning. Despite we have carried out an analysis at a provincial level and, though, missing different spatial realities and dynamics occurring at a local level, we were able to analyze the case of Quebec's agriculture and detail how and when it transformed from an advance organic agriculture to an industrialized one. Results show clearly how current specialization on livestock production and intensive monocultures is inefficient, consuming much more energy than they provide to society.

Quebec's agroecosystems from nineteenth century until present day have followed a path which is a general trend in most of the international agroecosystems studied so far (Tello and Cattaneo 2017), with some distinctive features. In 1871, agroecosystems of Quebec were the typical ones of a past organic agriculture. During this period, there existed a very low dependence on external inflows, which leaded to very high EFEROIs. On the other hand, agriculture depended mostly on biomass reuses and barnyard services (manure and draft power). As a result, IFEROIs were much lower than EFEROIs, but yet much higher than one, and higher than those found in other parts of the world (Tello and Cattaneo 2017).

A transition from organic to industrial farm systems took place in the twentieth century until the 1960s. This transition occurred at different speeds and ways within the province. As we have seen, in 1930s, this transition was yet in the first stages. External inputs had exponentially grown due to animal feed imports, but agroecosystems still depended largely on the biomass reuses to maintain soil fertility and livestock. In consequence, EFEROIs were still high but the great effort in biomass reused had led to very low IFEROIs. The back-to-the land movement of the 1930s and the massive changes brought during and after World War II shot up external inputs, especially concerning the introduction and use of tractors and trucks, fertilizers, and animal feed imports. These inflows helped to sustain land productivity increases and to alleviate pressures on biomass reused inflows. However, by 1951, biomass reuses were still larger than external inputs. As a result, in these last moments of the transition, EFEROIs had largely decreased but were still higher than IFEROIs.

From 1960s on, farm systems of Quebec have fully industrialized. The high dependence on external input inflows, which multiply by more than four the biomass reused inflows in 2011, has collapsed EFEROIs. Contrary to what one may expect, this fact has not meant the improvement of the IFEROIs. The reason lies in the livestock specialization followed by most of Quebec agroecosystems. In 2011, 84% of the cropland were dedicated to crops to feed livestock, and 62% of the total produce needed to be reinvested, largely as animal feed. As a result, biomass reused flows have kept increasing during the last 60 years in Quebec at very high rates.

On the other hand, this livestock specialization, first in dairy products and since 1970s in swine and poultry, has completely decoupled from farming and has also brought about important changes on local landscape and biodiversity.

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