Regional Environmental Change (2018) 18:1033–1045
https://doi.org/10.1007/s10113-018-1315-9

ORIGINAL ARTICLE

Energy in a woodland-livestock agroecosystem: Prince Edward Island, Canada, 1870–2010

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Received: 31 July 2017 / Accepted: 1 March 2018 / Published online: 15 March 2018

Abstract
This article presents historic energy profiles in order to understand the changing roles of three critical energy flows in eastern Canadian agroecosystems. The first flow is the societally useful energy that farms produced in crops, animal products, and forest resources. This flow stabilized after colonization and then intensified with the introduction of fossil fuel inputs. The second flow consists of these external inputs, including human labor and the energy embodied in machinery, fuel, and fertilizers. The final flow is the biomass from within the agroecosystem itself. Farmers removed this biomass from their final produce and recycled it as feed for animals, seed for crops, and fencing for livestock management. This article presents evidence on these energy flows from a set of case studies in Northeastern North America. Prince Edward Island (PEI) offers a study of energy transitions in a frontier agroecosystem at the farm, township, county, and the bounded provincial scales. This study uses time points from the 1881, 1931, 1951, and 1996 censuses, as well other statistics. The energy in land produce remained stable during the socio-ecological transition because of the importance of forest products. Results at the sub-county scale demonstrate complementary components within the larger provincial system, and the example of one farm (1877–1892) illustrates specialized energy strategies within the advanced organic regime. After the socio-ecological transition, external inputs remained lower than expected, but together with the steady growth of livestock, they ensured that biomass energy inputs were more productive in the mineral regime than they had been in the organic period.

Keywords Agroecosystem energy · Canadian agriculture · Agri-forestry · Long-term socio-ecological research · Energy transition

Introduction

The transition from organic to mineral-based energy systems has defined life in developed countries over the last two centuries. The dramatic changes in land use and the corresponding flows of material and energy have been described as a "socio-ecological transition" (Fischer-Kowalski and Haberl 2007; Krausmann et al. 2008), and many geologists and historians claim it heralds a new epoch, the Anthropocene (Steffen et al. 2007). The development of the modern food system was central to this transition. The current system relies on fossil fuel inputs for production and transportation, but more comprehensive energy profiles at the regional scale illustrate the changing roles of energy across agroecosystems. This article uses energy flow accounting and multi-scale historical analysis of Prince Edward Island (PEI), a Canadian island in the Gulf of St. Lawrence, to examine and illustrate the general features of the agricultural energy transition.

Recent studies of the shift toward a fossil fuel-based energy system have shed new light on the importance of biomass during and after the socio-ecological transition (Krausmann 2001; Kuskova et al. 2008; Soto et al. 2016). Energy historians pointed to the scarcity of wood and the rise of coal as the critical stage in industrialization (Chandler 1972; Barca 2011; Jones 2014; Kander et al. 2014; Melosi 1985; Sieferle 1982; Watson 2016; Wrigley 2004). Indeed, coal represented an

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10113-018-1315-9) contains supplementary material, which is available to authorized users.

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important turning point in the history of British and Northeastern US industrial development, but, in Canada and other predominantly rural developed countries, a shift from wood to coal does not fully explain changes in the rural economy (Gentilcore and Matthews 1993; Sandwell 2016). New research on material and energy flows has produced a more accurate understanding of the transition from organic to mineral-based energy regimes in many regions (Gales et al. 2007; Gingrich et al. 2013). In Canada, cold climates and large forests meant the consumption of biomass energy continued to rise until after WWII. By the 1940s, city dwellers had switched to coal, but firewood remained the primary fuel for heating and cooking in rural homes until well into the postwar period (MacFadyen 2016a).

In converting the sun's energy into societally useful forms, agriculture provided the energy necessary for humans in the form of food, and for work and transportation in the form of animal power, not to mention the numerous materials used to manufacture goods. Understanding the socio-ecological transition requires measuring material and energy flows in agroecosystems. Standard economic approaches have treated surplus cereal exports as the most important energy sources from Canadian agriculture (Russell 2012). Indeed, exports from the Canadian Prairies accounted for 40% of the world wheat market in the early twentieth century (Sandwell 2016). However, studies of the physical flows within and between agroecosystems showed that staples were only a small part of the sum of agricultural products that circulated in the nineteenth century (McCalla 1993; McInnis 1984). The energetic impact of regionally cycled biomass is unknown, and the role it played in local agroecosystems, including the efficiency of energy inputs, requires further investigation. This article measures three critical energy flows in eastern Canadian agroecosystems: societally useful outputs, external inputs, and biomass reinvested within the local agroecosystem. We examine consistent evidence on agroecosystem energy flows in a small island province at multiple scales, including provincial, county, and sub-county scales, in order to investigate the changing role of energy in periods of settlement, consolidation, and socio-ecological transition.

Methods, concept, and data

PEI is the smallest province in Canada, with only 143,000 residents, one small city, and 5660 km^2 of land in the southern Gulf of Saint Lawrence (Fig. 1). The island's level terrain, well-drained soil, and stable climate made it more suitable for agriculture than most parts of Atlantic Canada. The region's dense Acadian forest was one of the practical barriers to farm settlement, but together with marsh hay and other estuarine resources, it provided shelter, feed, and materials for mixed animal husbandry. In the late twentieth century, PEI farmers maintained a ruminant livestock system, but they supplemented beef and dairy with pig production and increasingly intensive crop production (Arsenault 2016). PEI was selected as a study site because it maintained a consistent agricultural population, and because its islandness makes it a useful laboratory for studying material and energy flows in bounded systems. Furthermore, PEI agriculture has been the subject of excellent work in historical geography (Clark 1959) and environmental history (Bittermann and McCallum 2016; Hatvany 2001; MacDonald et al. 2016; MacDonald 2016; MacFadyen and Glen 2014).

This paper examines the ways geographic scale and social and environmental history shaped the energy regimes of settler agroecosystems across four time points (1880, 1930, 1950, and 1995). Recent methodological advances in long-term socio-ecological research allow us to examine regional agroecosystem energy flows throughout this period. The methodology stems from "social metabolism" theory and research on long run patterns of material and energy use (Gingrich et al. this issue; Gonzalez de Molina and Toledo 2014; Haberl et al. 2006). Social metabolism research combines traditional land use histories with a rigorous examination of the material and energy flows associated with intensification (Erb et al. 2013), and it distinguishes between three flows: societally useful outputs, external inputs, and biomass reinvested within the local agroecosystem. Examining the effect of biomass and fossil fuel inputs at county and farm-level study sites within a single region enables comparative analysis at different scales (Erb et al. 2013; Giampietro 2003).

We compare the energy content in the products of cropland, pasture, forest, and barnyard with the energy from locally reinvested biomass and the energy added from outside the agroecosystem boundary (Galán et al. 2016; Tello et al. 2016). This approach draws a system boundary between the local agroecosystem and its external non-solar energy sources, including the local farm community and the rest of society. Solar energy was a constant input to the system, but the other energy inputs changed over time and pose a historical problem. Farmers generally sought to increase gross and net agroecosystem productivity. In energetic terms, this meant increasing the energy produced by cropland, pasture, and forest (represented here as Land Produce or LP) and the energy available from livestock products. Livestock-Barnyard Produce (LBP) is the energy in produce such as milk, eggs, and meat. Together, LP and LBP create the Total Produce (TP) available from the agroecosystem.

The full amount of Total Produce rarely leaves the agroecosystem, because the energy processes of agroecosystems are non-linear. They are looped systems that include the internal cycling of energy, an important but often overlooked energy flow. Farmers removed significant sections of Total Produce and reinvested that biomass to various purposes on their farms, such as seed for next year's crop, feed for livestock, and straw for bedding. Even forest produce had an annual energy function

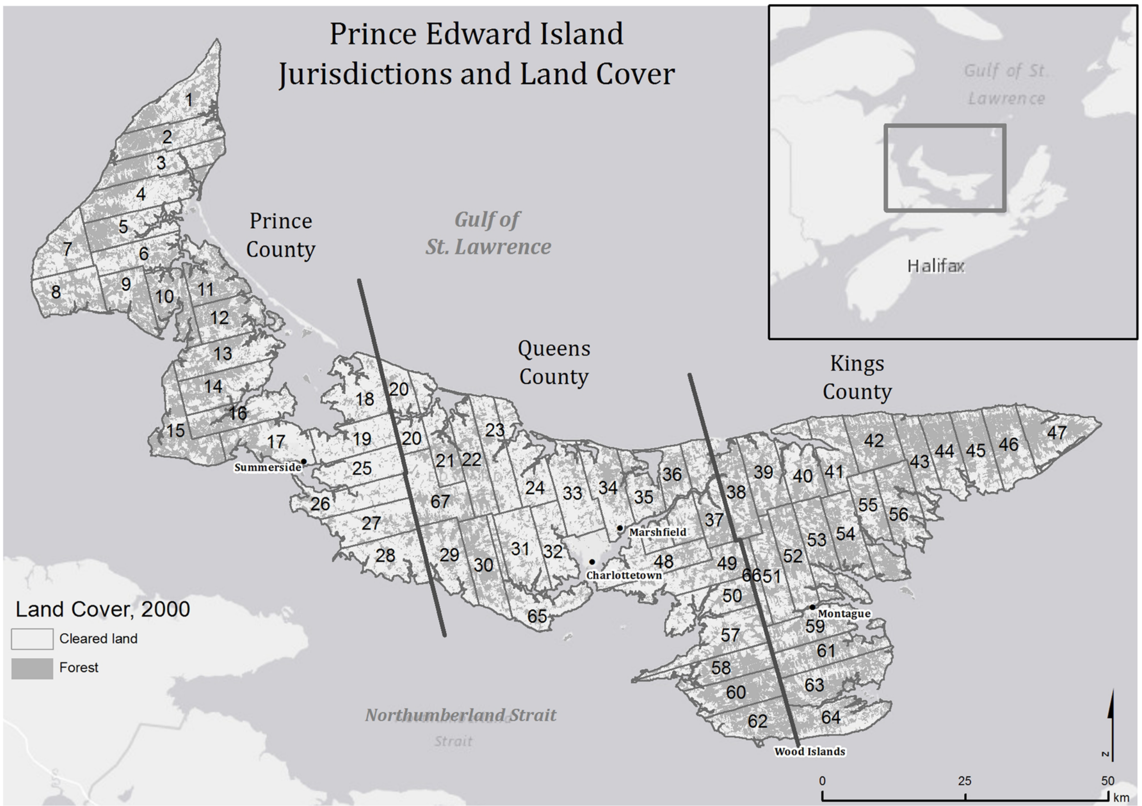

Fig. 1 Jurisdictions and Land Cover, Prince Edward Island (PEI), Canada, 2000. Map by J. MacFadyen. Land Cover data from PEI, Department of Environment, Energy & Forestry, Forests, Fish & Wildlife Division, 2000 Forest Outline, Coastline, last modified 30 November, 2010

as feed and litter for animals and fencing materials for separating crops from pasture. The energy content of these flows is represented here as Biomass Reused (BR) and the remaining flows consumed by humans become Final Produce (FP).

Labor (L) was generally the smallest energy input, but it created an important base load. Together with Labor, farmers added a range of Agroecosystem Societal Inputs (ASI) that accounted for direct and embodied energy in building materials, machinery, fuel, synthetic fertilizers, pesticides, herbicides, lime, and imported feed and litter for livestock. These inputs were relatively small in the nineteenth century because consuming fossil fuels was technologically complex and biomass was more readily available. In pioneer settings, farmers occasionally imported small quantities of feed and litter. In coastal environments like PEI, water transport made this feasible. Combined with Labor, ASI flows accounted for all External Inputs (EI), and combined with Biomass Reused they created the Total Inputs Consumed (TIC) within the agroecosystem. We converted all of the energy flows to gigajoules and normalized by the total hectares of farmland in the agroecosystem (GJ/ha).

Energy quantity matters, but farmers also sought energy quality, i.e., energy that benefitted farm families. In northern climates, highly energetic firewood had a much lower monetary value than grains, per unit of energy. But until other fuels became available and affordable in the mid-twentieth century cordwood was extremely important for local consumption. Similarly, some of the most energy-rich products of the land were not what Oltjen and Beckett have called "humanly edible energy" (1996). This energy reflected the priorities of a system focused on livestock, a less efficient source of food energy. Energy choices were thus shaped by preferences and demands in regional systems. In Northeastern North America, livestock were valued for meat products, manure, and the work they performed. This influenced system efficiencies, which are presented here as the ratios of the agroecosystem's final output to its external and internal system inputs. In the 1970s, energy scholars noted that the increasing productivity of agriculture (rising output per unit of labor) came at the cost of energy efficiency. The energy of corn produced per unit of fossil fuel energy consumed in the USA declined steadily over time (Smil et al. 1983), and subsequent national studies of agricultural energy efficiency have found fluctuating trends (Cleveland 1995; Hamilton et al. 2013). The methodological approach used in our analysis establishes a set of three Energy Returns on Investment (EROI) indicators by dividing Final Produce by the three main energy inputs: internal (BR), external (EI), and total (TIC or BR + EI). The indicators present a measure of the efficiency by which all human-activated energy inputs were used in agroecosystems.

Estimating the three energy flows and indicators requires calculating the energy content (gigajoules) of all harvested plant and animal biomass as well as the energy content of the External Inputs. The Canadian *Census of Agriculture* recorded full count information on land use, the number of animals, and the area and yield of crops since the mid-nineteenth century. We converted the flows of biomass into energy units by using historically specific research on the energy content of plant biomass and animal products (Guzmán et al. 2014; Cunfer and Krausmann 2016). In cases where External Input data were not available at the county level (e.g., pesticide, fertilizer, and electricity ASI), we used national and regional information and downscaled it to each county. We accounted for embodied energy in other inputs, such as fuels, using historically specific estimates for mechanized agriculture (Aguilera et al. 2015). More information about specific calculations is available in the Supplementary Online Material.

Livestock feed, litter, and grazing were the most important components of reinvested energy flows (Biomass Reused) in PEI. We developed these estimates by producing livestock-specific feed and litter balances for each county, which rest on the assumption that farmers attempted to supply animals with locally available biomass. We created feed balances by subtracting the energy demand of all livestock in the county from the seasonal energy supplies available in the Land Produce (i.e., fodder crops and other crop residues). We compare these results between counties, and with historical data on feed imports and exports for the province. Because of the centrality of livestock in our case studies, Biomass Reused flows were often larger than Final Produce or External Inputs, even though the energy from livestock products (LBP) was small.

Since energy flows are normalized by the total area of farmland in each system, it is useful to compare energy profiles at different geographic scales. This article presents data for all time points at the provincial and county scales, and it considers a selection of smaller agroecosystems at the sub-county (township level and farm level) scales. Examining the same energy flows across multiple scales reveals that farmers pursued many different energy strategies, and these strategies often complemented other parts of the larger provincial system. At the township level, it is easier to see how certain geographic anomalies and extremes developed during the socio-ecological transition, and at the farm level, the records of a family farm like Roderick Munn's can help ground truth the higher-order results, if only for a comparatively short period of time.

Results and discussion

Overview and periodization

The four energy profiles in Table 1 and Figs. 2, 3, 4, 5, and 6 present the energy stocks, flows, and indicators for all three PEI counties (Prince, Queens, and Kings) and for the overall province across four time points. The city of Charlottetown is excluded from the study. By examining the energy profiles at these scales, we see the emergence of three overlapping historic trends. The first was the period of extensive British settlement, from 1805 to 1930. The second was a period of farm abandonment and consolidation from 1931 to 1970. The third period was the socio-ecological transition, which was most evident from 1971 to 2010.

In the first period, the desire to expand agricultural settlement, and in particular a commitment to developing agroecosystems that focused on feed and livestock production, shaped energy flows. PEI was an agricultural frontier in the nineteenth century, and by 1911, British settlers had cleared two thirds of the island. Queens County farms expanded the fastest, followed by Prince and then Kings. Queens settlement peaked in 1891, but this was followed by two "second fronts" as expansion continued briefly in West Prince and East Kings. The county profiles and one farm-level case study show how farmers attempted to increase productivity through a mix of extensive clearing, intensive livestock management, and soil treatments, particularly on Queens and East Prince hay land.

In the second period, interwar population decline and outmigration led to demographic aging, farm consolidation, and farmland abandonment. The frontier agroecosystem experienced massive land use change as PEI farmers abandoned 110,000 ha or 35% of their "improved land" (cropland and fenced pasture) between 1931 and 1971. Most abandoned land returned to forest, and forest cover on PEI increased 50% between 1935 and 1990, especially in Kings County and the poorly drained sections of West and Central Prince County. Farms in the "second fronts" were some of the last to appear and the first to fail. Abandonment was mainly on marginal pastures, and cropland remained remarkably stable in the island-wide system (PEI farmland was 40, 40, 36, and 36% cropland across the four time points). Livestock systems changed as well, with sheep disappearing between the 1930s–1960s, and horses between 1950 and 1965. This did not affect the overall number of livestock units (units of 500 kg), nor the ability of farms to recycle most of the energy required by livestock. But the changing quality of the herds leads farmers to shift their feed regimes from pasture to hay and grain. The farmers who remained in this second period continued to use organic methods to increase land productivity, but the early signs of a socio-ecological transition appeared as farmers began to adopt fossil fuel-based fertilizers and machinery in the 1950s.

The final period is the closest to what other scholars have called a socio-ecological transition. A series of government agricultural policies encouraged modern land use and farm management, and a market response to export commodities in the 1970s and 1980s, particularly for potatoes, introduced new influences to the island's farm economy (Arsenault

Table 1 Agroecosystem energy flows (GJ/ha) in Prince, Queens, and Kings Counties and PEI (1880, 1930, 1950, 1995). See Supplementary Online Material

	Prince (total area 2015 km^2)				Queens (total area 1981 km^2)			
	1880	1930	1950	1995	1880	1930	1950	1995
Population density (cap/km^2)	17.0	15.6	18.7	22.1	24.3	18.9	21.6	36.5
Farmland area (km^2)	1647	1729	1703	1665	1702	1843	1668	1645
Percent cropland	*37*	*45*	*40*	*42*	*48*	*44*	*41*	*43*
Percent pasture	*13*	*21*	*17*	*5*	*17*	*25*	*22*	*9*
Percent woodland	*49*	*34*	*44*	*52*	*35*	*31*	*37*	*48*
Livestock density (LU500/km^2)	18.3	24.0	25.1	18.8	26.2	28.7	30.3	37.3
Land Produce, LP	45.2	44.2	42.2	55.6	47.3	46.8	49.8	57.7
Percent of LP from cropland	*24*	*35*	*38*	*64*	*34*	*37*	*45*	*61*
Livestock-Barnyard Produce	0.2	0.8	0.7	1.6	0.1	0.8	0.4	1.7
Total Produce, TP	45.4	45.0	42.9	57.1	47.5	47.6	50.3	59.4
Biomass Reused, BR	16.3	22.4	21.8	16.7	23.8	24.4	26.2	28.4
Final Produce, FP	29.1	22.6	21.0	40.5	23.6	23.2	24.1	31.0
Labor, L	0.2	0.1	0.1	0.0	0.2	0.1	0.1	0.0
Agroecosystem Societal Input	2.3	2.1	3.2	7.9	1.4	2.2	3.8	9.3
External Inputs, EI	2.5	2.2	3.3	7.9	1.6	2.4	3.9	9.3
Total Inputs Consumed, TIC	18.9	24.6	25.2	24.5	25.4	26.8	30.1	37.6
Final EROI	1.5	0.9	0.8	1.6	0.9	0.9	0.8	0.8
Internal final EROI	1.8	1.0	1.0	2.4	1.0	1.0	0.9	1.1
External final EROI	11.5	10.3	6.3	5.1	14.8	9.8	6.1	3.3
	Kings (total area 1660 km^2)				PEI (total area 5657 km^2)			
Population density (cap/km^2)	15.9	11.5	10.8	11.8	19.3	15.6	17.4	24.1
Farmland area (km^2)	1386	1460	1357	1381	4735	5032	4728	4692
Percent cropland	*32*	*31*	*26*	*21*	*40*	*40*	*36*	*36*
Percent pasture	*11*	*20*	*12*	*3*	*14*	*22*	*17*	*6*
Percent woodland	*56*	*49*	*62*	76	*46*	*37*	*47*	*58*
Livestock density (LU500/km^2)	18.0	18.8	15.8	9.8	21.0	24.1	24.2	22.6
Land Produce, LP	38.4	37.5	32.9	34.4	44.0	43.2	42.2	50.1
Percent of LP from cropland	*25*	*32*	*35*	*48*	*26*	*32*	*38*	56
Livestock-Barnyard Produce	0.1	0.8	0.9	1.6	0.2	0.8	0.7	1.6
Total Produce, TP	38.5	38.3	33.7	36.0	44.1	44.0	42.9	51.7
Biomass Reused, BR	13.9	17.1	14.4	8.2	18.3	21.6	21.2	18.3
Final Produce, FP	24.6	21.2	19.4	27.8	25.8	22.4	21.6	33.4
Labor, L	0.2	0.1	0.1	0.0	0.2	0.1	0.1	0.0
Agroecosystem Societal Input	3.5	2.1	2.5	4.6	2.3	2.1	3.2	7.4
External Inputs, EI	3.7	2.2	2.6	4.6	2.5	2.3	3.4	7.4
Total Inputs Consumed, TIC	17.6	19.3	17.0	12.8	20.9	23.9	24.6	25.6
Final EROI	1.4	1.1	1.1	2.2	1.2	0.9	0.9	1.3
Internal final EROI	1.8	1.2	1.3	3.4	1.4	1.0	1.0	1.8
External final EROI	6.6	9.7	7.3	6.1	10.2	10.0	6.5	4.5

2016). The new surge in potato production helped reverse the abandonment of farmland for the first time after 1971, and by the 1990s, farmers began to clear (or re-clear) new cropland. A decline in overall livestock units was hastened by the near disappearance of horses as well as the decline in milk cows after the introduction of supply management in the 1970s. This was partially offset by the rise of grain-intensive pig production. These industrial-era agroecosystem qualities are consistent with the energy intensive socio-ecological transitions in other regions. Final Produce energy increased significantly in every county between 1950 and 1995, nearly doubling in Prince (from 21 to 41 GJ/ha). Much of the increase was in cropland LP, where fertilizer and other External Inputs had a multiplying effect on yields. However, PEI's livestock density remained high in 1995 (23 units/km^2), and in Queens, it increased 23% to 37 units/km^2. This

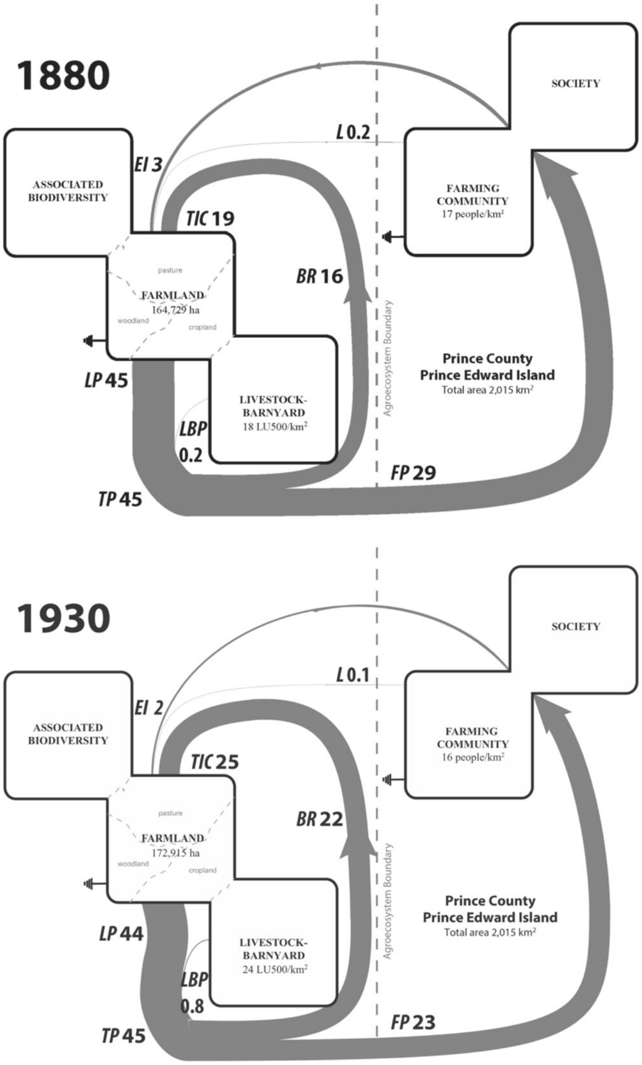

Fig. 2 Agroecosystem energy profile, Prince County, PEI, 1880–1930. LP, Land Produce; LBP, Livestock-Barnyard Produce; TP, Total Produce; BR, Biomass Reused; FP, Final Produce; L, Labor; ASI, Associated Societal Inputs; EI, External Inputs; TIC, Total Inputs Consumed. See Supplementary Online Material

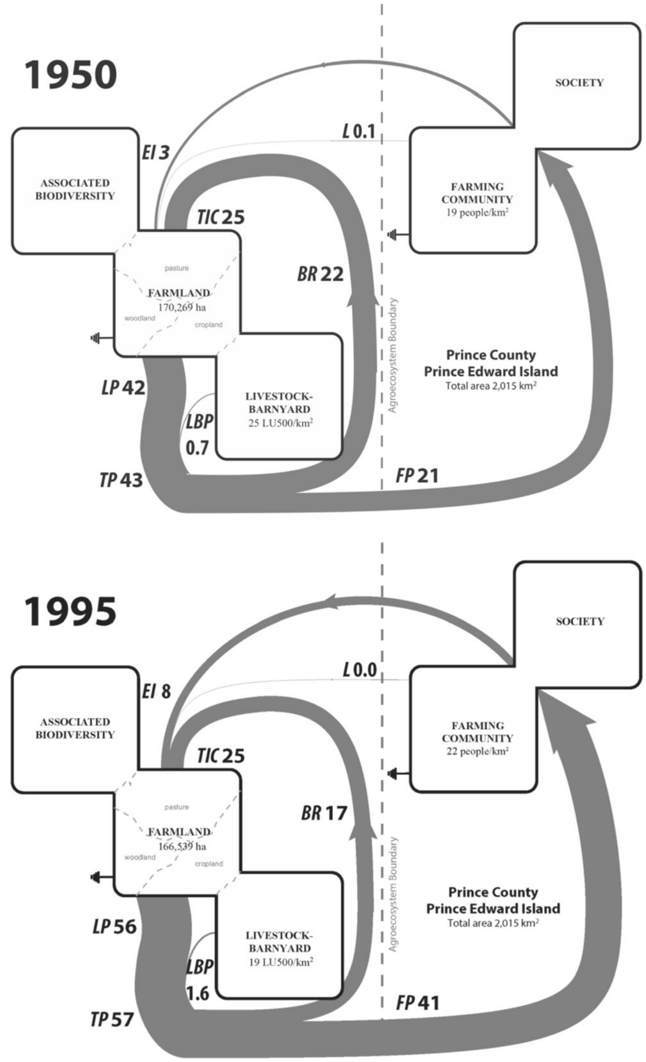

Fig. 3 Agroecosystem energy profile, Prince County, PEI, 1950–1995. LP, Land Produce; LBP, Livestock-Barnyard Produce; TP, Total Produce; BR, Biomass Reused; FP, Final Produce; L, Labor; ASI, Associated Societal Inputs; EI, External Inputs; TIC, Total Inputs Consumed. See Supplementary Online Material

ensured that energy from Biomass Reused remained larger than External Inputs by a factor of two (in Prince and Kings) or even three (in Queens). The persistence of biomass cycling in PEI suggests both that the woodland-livestock agroecosystem was balanced and resilient, and that the socio-ecological transition is far from complete. Examining energy flows at multiple scales points to complementary aspects of the system as well as some of the historical roots of the livestock economy.

Energy strategies at the farm scale

A single farm level energy profile from the first period (settlement) provides evidence of organic intensification and the centrality of livestock in a woodland agroecosystem. Roderick Munn was a gentleman farmer who moved from Wood Islands, near the border of Queens and Kings in Southeastern PEI, to Marshfield, just outside of Charlottetown in the township of Lot 34, Queens County (Fig. 1). Born in 1835 to some of the province's earliest Scottish immigrants, Munn benefitted from early access to PEI's settler economy. He recorded his crop types, planting, location, and output in great detail in his ledgers (Munn 1912). He kept horses, sheep, and cattle, but his ledgers focused primarily on the variety and productivity of crops on his new farm in Marshfield.

The farms that Munn and his immigrant cousins pioneered in Wood Islands were poorly drained and vulnerable to harsh weather. However, by 1880, Munn and his wife Jane (nee Robertson) could afford to trade up. Like many other farmers in this period looking for ways to expand their holdings for the

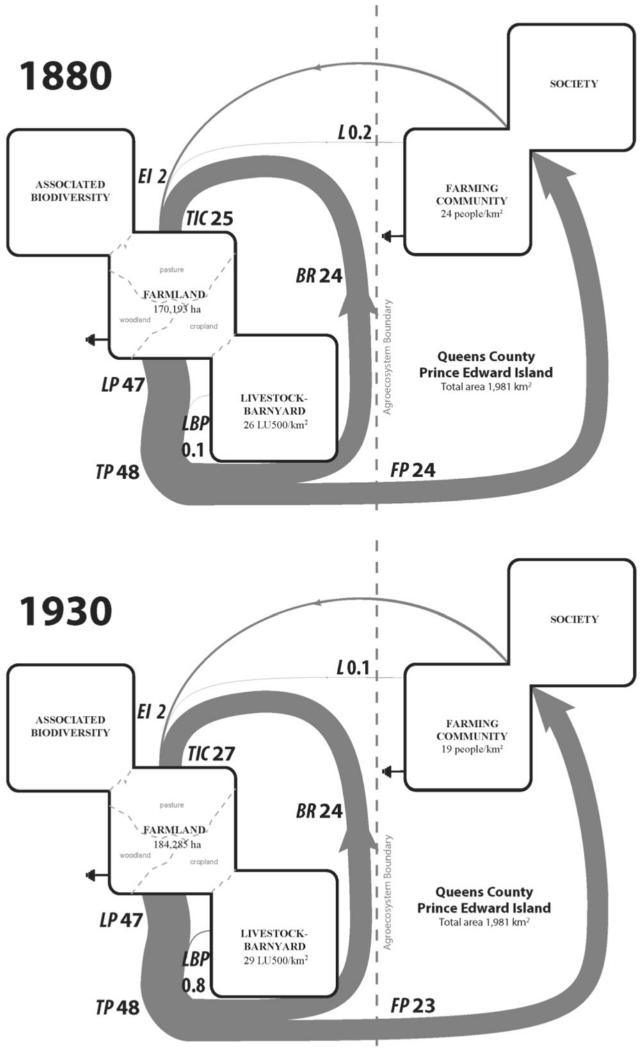

Fig. 4 Agroecosystem energy profile, Queens County, PEI, 1880–1930. LP, Land Produce; LBP, Livestock-Barnyard Produce; TP, Total Produce; BR, Biomass Reused; FP, Final Produce; L, Labor; ASI, Associated Societal Inputs; EI, External Inputs; TIC, Total Inputs Consumed. See Supplementary Online Material

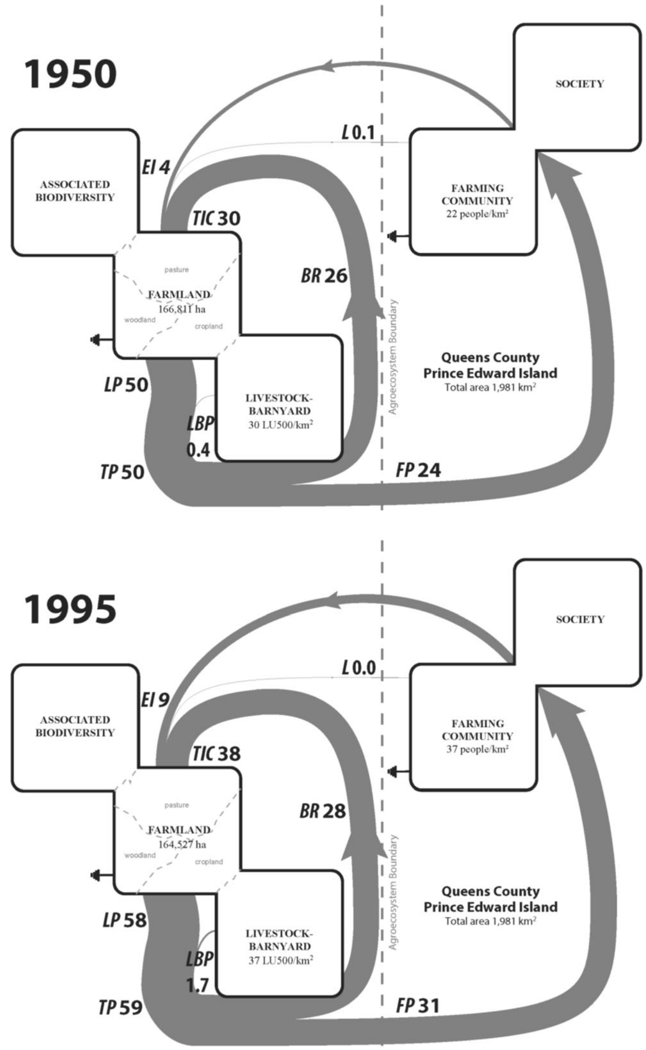

Fig. 5 Agroecosystem energy profile, Queens County, PEI, 1950–1995. LP, Land Produce; LBP, Livestock-Barnyard Produce; TP, Total Produce; BR, Biomass Reused; FP, Final Produce; L, Labor; ASI, Associated Societal Inputs; EI, External Inputs; TIC, Total Inputs Consumed. See Supplementary Online Material

next generation, the Munns could have followed the last wave of settlers into the nearby but more marginal farmland of Kings County. But they decided to move against the flow and buy a well-developed farm with excellent land and good access to urban markets. Jane's family connections in Marshfield provided another incentive to move. Marshfield received its name from the many small streams and estuaries that ran in and out of its border with the Hillsborough River. Rather than a sign of poor land, the name reminded farmers of the rich resources that this riverine environment had to offer. Indeed, by leaving the boggy fields of Wood Islands, and moving to Marshfield, Munn gained access to a property that was close to the water but far enough upland that almost every acre was ideal for growing crops and producing animal pasture and fodder. At 100 acres (40 ha), it was exactly the average size farm in the township of Lot 34 in 1880.

The Munns had financial and social capital, acquired in part from Roderick's years in provincial politics (1874–1882), and they immediately began to improve the farm in Marshfield. In the first few years, they built a new house and barn, they spread hundreds of loads manure on the land, and they began to clear additional land from the forest. Roderick and Jane had six young children when they moved to Marshfield, and the eldest, Robert Fergus, had just turned 15. This put the family in an ideal situation to intensify farm productivity through labor. Between 1881 and 1891, there were always between four and five working age adults on the farm, and they all helped haul manure and clear new land. Eventually, all of the children left except the youngest son, John R., who eventually inherited the farm (Harding 2006). There are no records of the early land clearing, but by the early twentieth century, the Marshfield property was fully

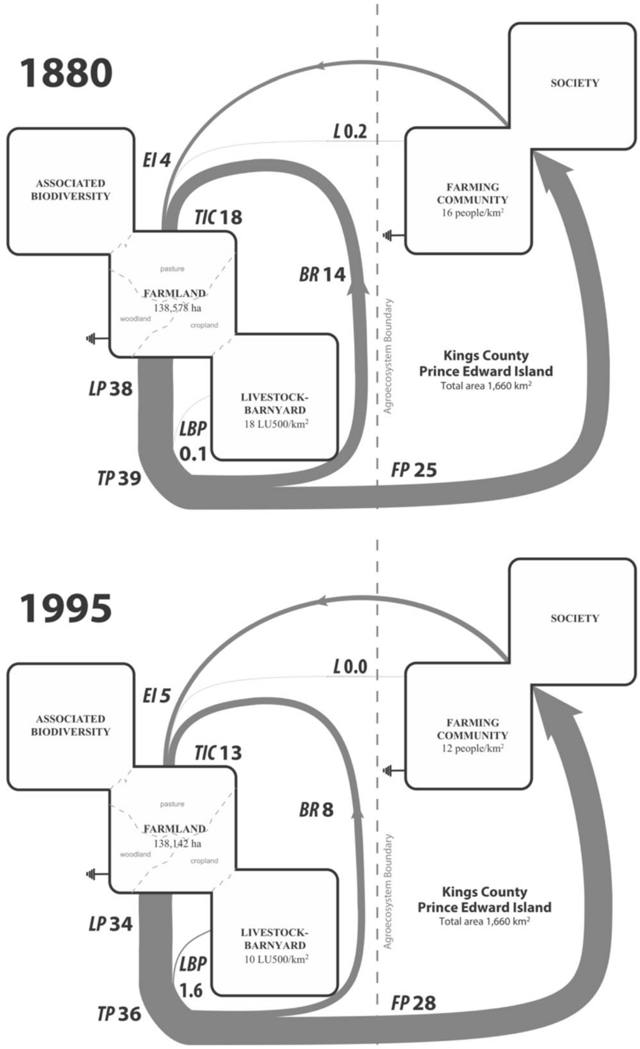

Fig. 6 Agroecosystem energy profile, Kings County, PEI, 1880–1995. LP, Land Produce; LBP, Livestock-Barnyard Produce; TP, Total Produce; BR, Biomass Reused; FP, Final Produce; L, Labor; ASI, Associated Societal Inputs; EI, External Inputs; TIC, Total Inputs Consumed. See Supplementary Online Material

developed with only 10 acres (4.2 ha) remaining in the forest. We assume they began clearing the 25 acre (10 ha) parcel of hilly land at the back of the lot when they arrived. The amount of land cleared each year would have contributed to the energy of woodland LP.

Products of the forest had been easy to find in Wood Islands where ample woodland was available in Southern Kings. When Roderick and his family arrived in Marshfield, they had to develop a new strategy for accessing wood. Marshfield did not have much unsettled forest or public lands to draw from, and Munn's own parcel was down to between 10 and 35 acres of woodland (4.2–14.2 ha) in 1881. In the nineteenth century, Canadians enjoyed access to a large amount of forest products in all but the most densely settled areas. The most important was firewood, and the normal annual consumption rate for PEI farmers in this period was at least 17 cords per household (MacFadyen 2016a). One cord is equivalent to 3.6 cubic meters. In Marshfield, there was only enough woodland left to produce 6.8 cords per year, including the wood from clearing. The production from his woodlot would have been lower (we assumed closer to five cords), and that was almost certainly supplemented with purchases of wood and even coal for home heating and cooking. PEI farmers also harvested other products from their woodlots, especially posts and poles for fencing. This would have been minimal for the more established Munn pastures, but we allot a small amount (425 kg) for annual upkeep and expansion. We estimate that the Marshfield farm's woodlots would have produced 11 GJ/ha in the early years, which declined to less than 7 by the end of the period, and likely almost zero by the early twentieth century (Table 2).

Woodland energy flows were an essential part of living in a cold climate, but farmers like the Munns cleared land and developed cropland and pasture so they could redirect their attention to the energy of livestock. Munn's journal shows that he dedicated most of his time to identifying the best yields and soil treatments for his cereal and root crops. However, an energy profile of his farm's Land Produce demonstrates that the primary aim of this effort was to improve the farm's ability to feed livestock. Overall, cropland productivity rose significantly during Munn's first 12 years in Marshfield, from around 28 GJ/ha in the first three full years to 33 GJ/ha in the last three. The largest increase was not in the energy of comestible crops, but rather hay—the fodder required to bring livestock through the winter. The energy of cereal and root crops increased only slightly over the 12 years in Marshfield, but hay output increased 85%. This was one reason the Munns moved to an established farm. The output of various crops fluctuated with markets and growing conditions. In most years, potatoes were the largest crop in terms of energy output, and Munn also grew small quantities of wheat, barley, oats, and turnips; like hay, oats and turnips were almost entirely for animal consumption. Combined with the output of his pasture, Munn's cultivated land was first and foremost a livestock production engine.

The Marshfield farm included extensive pastures, covering around 28% of the farm at first, and rising to around 36%, depending on the annual cropland requirements. The energy output from this form of Land Produce was metabolized by ruminants and horses, although pigs and poultry benefitted from it as well. Without knowing the exact number of Munn's livestock, township averages are used to estimate the number of each animal type. A grazing feed balance reveals that Munn's pasture contained ample feed to cover the average amount grazed by Lot 34's livestock units. We assumed that Munn's herd started at 10 livestock units (500 kg) and that it grew at various rates, from 1% per year for horses to 20% annually for his beef herd. The output of Munn's grazed pasture averaged almost 17 GJ/ha in the first

Table 2 Land produce energy flows (GJ/ha) on the farms of R. Munn, PEI (1877–1892). Munn, R (1912) Ledger of Roderick Munn. See also Supplementary Online Material

Land produce energy flows (GJ/ha) on the farms of R. Munn, PEI

Wood Islands (1877–1880) Marshfield (1880–1892)	1877	1878	1879	1880	1881	1882	1883	1884	1885	1886	1887	1888	1889	1890	1891	1892
Woodland LP	–	–	–	3.2	11.0	10.7	10.4	10.1	9.8	9.5	9.2	8.9	8.6	8.3	8.0	7.7
Pasture LP	8.0	8.0	8.0	4.9	10.3	11.1	11.9	12.8	13.9	15.0	16.4	18.0	19.0	21.9	24.3	27.1
Residues LP	2.5	2.5	2.5	1.5	3.2	3.4	3.7	2.1	3.3	4.7	5.1	5.6	3.3	2.2	5.6	0.8
Cropland LP	3.1	3.0	2.6	3.6	8.6	12.0	12.2	10.3	13.5	12.5	18.7	8.1	22.8	15.3	17.0	15.7
Corn		–	–	–	–	–	–	–	–	–	–	–	–	0.1	0.2	–
Wheat	0.3	0.5	0.4	0.4	0.2	1.0	0.3	0.1	0.8	0.9	0.7	0.1	0.3	–	0.5	–
Oats	1.6	1.4	0.8	0.7	2.2	2.5	2.0	0.9	0.5	1.7	1.6	2.8	1.2	0.7	1.9	–
Barley	–	–	–	–	0.3	0.3	0.3	–	–	1.2	–	–	–	0.4	0.1	O.4
Turnips	–	–	0.1	–	–	0.8	1.0	0.8	0.9	0.9	0.8	1.8	1.9	–	2.5	1.9
Potatoes	1.2	1.2	1.2	0.6	1.3	2.2	1.8	1.7	3.2	1.5	1.9	2.3	1.3	2.0	1.3	1.2
Hay		–	–	1.7	4.6	5.2	6.9	6.9	8.1	6.3	13.7	1.2	18.2	12.1	10.5	12.1
All land produce	13.6	13.5	13.1	13.1	33.1	37.1	38.2	35.2	40.4	41.7	49.4	40.5	53.7	47.7	54.8	51.2

12 years at Marshfield, roughly as large as the produce of crops (14 GJ/ha) and litter (4 GJ/ha) combined. Similar to the rise in cropland productivity, this estimate accounts for an increase in pasture productivity, as well. Fertilized pasture produced 5.7 tons per hectare, whereas poor pasture land produces only 2.3. We assumed that Munn's pasture began at the lower end, but it increased with intensive soil management.

As some farmers moved to clear new land in East Kings and West Prince, others like Roderick Munn focused on continued clearing and intensive crop and livestock management. Munn achieved productivity gains because he increased manuring and other soil treatments. He occasionally recorded manure-spreading activities, such as in 1884 when he hauled 245 loads of manure and one barrel of phosphate to various fields. But most of his time in Marshfield was spent applying extensive amounts of "mussel mud," a commonly used sea manure. Mussel mud was a highly calcareous soil treatment that farmers dug from the ancient deposits of large oyster beds in the rivers and bays of PEI (MacFadyen 2016b). "Mudding" was a localized activity. Oysters only inhabited certain estuaries, and they had to be dug through the ice in the winter and hauled over the snow by horse and sledge. Many coastal areas like Munn's previous farm in Wood Islands had limited supplies, and by moving to Marshfield the Munns gained access to 1366 loads of the mud.

The impact of soil treatments on crop and pasture land was evident in the energy profiles produced from Munn's ledger. Most frontier crop yields quickly decreased after pioneers depleted the original soil nutrients. In Marshfield, however, cropland energy stabilized or increased over the 1880s, and the total energy output of fodder rose significantly. Munn's decision to treat hay and pasture is consistent with recent research on the importance of livestock in PEI (MacFadyen 2016b). The strategies demonstrated at the farm level are also consistent with larger patterns of organic intensification at the county and provincial levels. Farmers in Queens and Eastern Prince Counties applied calcareous soil treatments like mussel mud to hay crops first, because the labor they invested had a multiplying effect in energetic terms. Improvements from new clearing, soil management, and wildland resources multiplied the agroecosystem's ability to produce more energy from feed, but intensification was not universal in PEI.

General trends at the county scale

Compared to the rapid energy gains attained on the Munn farm over 12 years, the provincial level energy profiles in Table 1 appeared relatively static or even stagnant over 115 years. Between 1880 and 1950, Final Produce declined from 25.8 to 21.6 GJ/ha, and by 1995, it had only increased to 33.4 GJ/ha. The island's overall Land Produce increased only 10%, from 44 GJ/ha in 1880 to 50 GJ/ha in 1995. However, at the county and township levels, the profiles reveal dynamic and complementary energy strategies. Land Produce in Prince and Queens Counties advanced by 10 GJ/ha, but Kings County's actually decreased by 4 GJ/ha. Larger differences appeared in the amount of Biomass Reused, which is partly what caused Final Produce in all three counties to align more closely than Land Produce. Queens County's Land Produce was highest, but it also reinvested more energy than the other counties. Kings County's Land Produce was lowest, and it reinvested a much smaller amount. As a result, these two very different agroecosystems delivered similar amounts of societally useful energy (Final Produce).

Final Produce was also stable at the provincial scale because so much of Land Produce consisted of woodland LP (the high-density energy from firewood and other forest products). Half of PEI's agroecosystem energy came from the forest, and roughly equal parts came from cropland (26%) and pastureland (24%) in 1880. The stabilizing effect of woodland LP did not negate the other energy flows. Rather, it was a critical aspect of an economy that operated with little or no fossil fuels. Living in a cold northern climate, farmers spent a great deal of their time harvesting wood for home heating and cooking. Moreover, forests contribute to higher Final Produce because they are perennial resources that do not require Biomass Reused or other inputs in order to grow (Erb et al. 2013). Woodland LP was such an integral part of PEI agroecosystems that its contribution to Final Produce helped make the island's energy returns on investment (particularly the Final EROI and Internal Final EROI described above) the highest in a comparative study (Gingrich et al. this issue).

Woodland's share of Land Produce was eventually matched and surpassed by other land uses, and as its share declined (reaching 30% in 1995), livestock was the first to benefit from the new land. The energy from pasture grazing increased in 1930 and plateaued by 1950. Then, farmers abandoned pasture, and by 1995, pasture LP had fallen to a mere 14% of the province's Land Produce. The new dominant source of Land Produce was cropland; 56% of the province's Land Produce came from crops, and in Prince County that reached as high as 65%. Cropland LP for the island increased in both relative and absolute amounts (from 12 to 31 GJ/ha).

The land use transition from forest to pasture and then cropland usually reflected the livestock economy. In 1880, Queens County produced just enough summer pasture and winter grain and fodder for its livestock (26 units/km^2). Prince and Kings farms had fewer animals (18 units/km^2), but they still operated in a fodder deficit and likely had to import feed and export some animals. By 1930, livestock density had not changed in Kings, but it increased significantly in Prince and Queens (24 and 29 units per km^2). All three counties now produced enough fodder to carry their expanding herds through the winter. Queens farmers produced their largest pastures ever (25% of farmland) to accommodate the livestock, and the biomass available from grazing increased sevenfold between 1880 and 1930. Even though Land Produce dropped slightly between 1880 and 1930, the proportion of energy from cropland LP increased in every county in both 1930 and 1950. In Queens, it rose as high as 45%, especially because of the highly productive hay and silage crops.

External Inputs remained negligible throughout the first and second periods, and most energy gains were won through the land clearing and organic intensification illustrated by farms like the Munns. However, energy productivity does not always create economic growth, and the twentieth century productivity gains were not enough to expand or even hold the province's farm population when an entire continent of better options enticed many farmers to leave. As outmigration increased and population declined, even the children of advanced farmers like Roderick and Jane Munn pursued opportunities in Western farms and US cities. In more agriculturally marginal lands like the "second fronts" of East Kings and West Prince, farmers rapidly abandoned crop and pasture land after 1930. The proportion of farmland in crops and pasture in Kings County dropped from 51 to 24% between 1930 and 1995.

By the period of socio-ecological transition, the county profiles suggest that livestock was beginning to have less uniform influence on farmland composition and productivity. Cropland LP increased in every part of PEI (doubling in Queens and Kings), but Prince County's quadrupled between 1880 and 1995. Over half of that increase appeared in the late twentieth century, owing mainly to increased potato production. Prince County's Final Produce was the highest in the province in 1995 (40.5 GJ/ha) because of high Land Produce and declining livestock density. Export crops had always been important in Prince County, but the crop composition changed significantly. In 1880, 53% of Prince County's cropland LP came from cereals, and mostly oats. Fodder crops were the next largest at 32%, and the remaining 15% came from root crops. By 1995, that had reversed. Slightly more than half of the county's cropland energy came from roots, virtually all potatoes. Cereal crops dropped to 29%, and fodder accounted for just under 20% of LP.

Many of the gains that appeared after 1970 were from relatively small amounts of Labor and Agroecosystem Societal Input (ASI) energy. Labor energy was most important in the late nineteenth century when the agriculturally active population was largest. By 1931, it dropped significantly due to mechanization and outmigration, and Labor's contribution became negligible by 1995. We calculated ASI as early as 1880 when farmers imported small inputs in the form of lime (an essential soil treatment in the province's acidic soil). But ASI was most important in 1995, particularly in Queens (9.3 GJ/ha) and Prince (7.9 GJ/ha) and to a lesser extent in Kings (4.6 GJ/ha). The three main forms of ASI on PEI were imported feed for livestock, fertilizers for crops, and fossil fuels for tractors and other engines. Diesel fuel was the most significant component of ASI in all three counties. Synthetic fertilizers were the second most important in Prince and Kings, and imported feed was the second largest component of ASI in Queens.

Livestock and the socio-ecological transition

In energetic terms, agroecosystems modernized when they began to incorporate large amounts of external energy inputs (Smil 2000; Soto et al. 2016). In PEI, farmers imported feed supplements in all time points, but the energy that crossed the agroecosystem boundary was minimal, even during the socio-ecological transition. The number of pigs grew over the twentieth century, and the amount of feed they consumed tripled between 1931 and 1996. Pigs surpassed the number of cattle for the first time in 1981, but as an element of the province's livestock units, pigs were always less than half of the equivalent bovine units. Although pigs did have a considerable effect on energy flows, the total consumption of grain by livestock declined over the twentieth century and much of it was supplied locally (Statistics Canada n.d.).

One aspect of the global socio-ecological transition in agriculture occurs when livestock are densely concentrated and supplied by mostly external energy inputs, particularly grain (Cussó et al. 2006; Tello et al. 2016). This decoupling of feed and livestock systems occurred in PEI, as well, but it appeared differently depending on scale. At the provincial level, PEI experienced remarkably stable livestock density across the four time points (21, 24, 24, and 23 units/km^2). However, this became increasingly concentrated in Queens County. In the settlement period (1880–1930), livestock density stabilized in Kings, grew slowly in Queens, and increased rapidly in Prince. After 1930, livestock began to further concentrate in Queens County, and by the end of the century, livestock density in Queens was twice as high as in Prince and almost four times higher than Kings.

At the provincial level, most of the feed for livestock emerged from within the system, but feed balances at the county level indicate that Prince's and Kings' livestock faced a minor shortage of hay and grazing, the two most critical sources of fodder during the settlement period. Two thirds of new clearing were converted into pasture, but grazing shortages were common as livestock density increased. PEI farmers relied on pasture to supply their cattle with 45%, and their milk cows with 33%, of their annual feed requirements. The early feed shortages suggest that some inter-county trade was necessary. At the sub-county (township) level, livestock concentrations and feed markets are even more evident, although the "decoupling" of livestock and Land Produce at this scale promoted feed energy strategies that the local agroecosystem could accommodate.

PEI is comprised of 67 townships, also called "Lots." In the nineteenth century, the intensity of land clearing and livestock density varied significantly across all three counties depending on the age and size of settlements, but most townships increased their cropland in proportion to livestock density. Individual townships, such as Lot 31 in Central Queens and Lot 56 in East Kings, show the extreme differences in agricultural intensification that developed in the twentieth century. In 1871, the townships were quite similar; both had limited amounts of livestock and improved land. Like much of Kings County's "second front" townships, Lot 56 was recently settled and had only cleared 18% of the township area. Lot 31 was an older township with access to markets in nearby Charlottetown, but it had still only cleared one quarter of its total area. However, by 1951, those urban markets encouraged Lot 31's farmers to clear three quarters of the township and feed over 4300 units of livestock. The most Lot 56's farmers ever cleared was 30% of the township in 1911, and by mid-century, they raised less than 1300 livestock units and had abandoned all but 23% of the township to the forest. This reduced to 900 units and 12% of the township in 1991. In Queen's County, by contrast, Lot 31's agroecosystem contained almost 6400 livestock units in 1991.

As land use declined across the province, livestock increased incrementally in many Queens County townships, especially in Lots 31 and 32, two contiguous townships directly west of Charlottetown. Until after WWII, no decoupling of land and livestock was evident at the township level. However, in the period between 1971 and 1995, the first clusters of townships to specialize in either livestock or cropland began to appear. Three clusters are evident in the 1990s. The number of livestock units increased to over 4000 in seven townships, all of them in Queens County. Four of these (including Lots 31 and 32) could be considered specialized livestock areas, because farmers use less than half of each township to produce crops and pasture. These specialized livestock areas import feed from surrounding townships and beyond; they are the closest examples PEI has to a concentrated animal feeding operation.

Conclusion

Energy profiles of Canadian woodland-livestock agroecosystems at the level of province, county, township, and farm demonstrate the energetic processes that shaped modern agriculture and society. The main energy flows appeared relatively stable across the province and over time, particularly when considering the entire island as an agroecosystem. Despite major changes in land use (from forest to pasture and back), livestock type (increasingly grain-fed), and energy flows (decreasing woodland LP), the island-wide agroecosystem experienced remarkably stable livestock density and consistent levels of Biomass Reused. A multi-scale approach shows that the three counties (Prince, Queens, and Kings) are becoming decoupled, but they have always been in some ways complementary. At the sub-county scale, livestock concentrations appeared in some Queens County townships during the socio-ecological transition and certain townships specialized in either livestock or cropland. A farm-level case study shows how one family increased land productivity in both pasture and cropland long before mechanical or fossil fuel intensification. We identify three general periods in the island-wide agroecosystem (settlement, consolidation, and socio-ecological transition), although each county experienced these historical trends in somewhat different ways.

From early in the settlement period, PEI farmers were committed to raising livestock. Feed shortages often presented an energy bottleneck, but farmers tried different strategies including "second front" expansion, "mussel mud" and other intensive soil treatments, and eventually fossil fuel-based mechanization. Crop and pasture energy flows were initially offset by the large and important energy content of forest products. By the second period (1930–1970), each county contained highly productive pastures capable of delivering large summer surpluses. Increasing hay yields also produced enough for winter feed, especially in Queens County. All of this was accomplished with very few additional External Inputs and during a period of consolidation and outmigration. During the socio-ecological transition (1971–2010), PEI farmers introduced new ASI inputs that pushed cropland LP past the organic energy bottlenecks. The transition reinforced the livestock economy in Queens and ensured that Biomass Reused remained the system's largest energy input. In Prince County, commodity crops decoupled from the woodland-livestock system, and farmers gradually increased ASI energy investments, especially fuel for mechanized equipment and synthetic fertilizers.

PEI's agroecosystems experienced a socio-ecological transition, and the agroecosystem is still in flux. Kings County is becoming post agricultural. Prince County focuses on export crops (most recently potatoes, but other commodities could displace it) and its farmers want to adopt deep-well irrigation. Queens County continues to increase its livestock density and local forms of Biomass Reused, but this system relies increasingly on feed for supply-managed livestock (dairy/poultry) and cheap fossil fuel inputs to maximize the yields of fodder and other feed crops. External market pivots could disrupt the system balance and create new instabilities in many ways. A variety of factors could decrease biomass cycling by outsourcing the feed supply, and increased demand for local feed crops, export commodities, or forest products could cause extensive new land use development.

Acknowledgements We thank Simone Gingrich and other members of the Sustainable Farm Systems energy working group, the editors of the "Energy in Agroecosystems" special issue, and the two anonymous reviewers for their valuable input. We thank Geoff Cunfer for his help developing the energy model diagrams.

Funding information We acknowledge the support from the Canadian Social Science and Humanities Research Council ("SFS", Partnership Grant 895-2011-1020).

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