Supplementary Information

Agroecosystem energy transitions in the old and new worlds: trajectories and determinants at the regional scale
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1. Detailed description Prince Edward Island, Canada
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1.1. The region
This note outlines research on energy in agro-ecosystems in the Canadian province of Prince Edward Island (PEI) from 1880-1995. PEI is the smallest province in Canada, with only 143,000 residents, one small city, and 5,660 square kilometers of land in the southern Gulf of Saint Lawrence. The island’s level terrain, well-drained soil, and stable climate made it more suitable for agriculture than most parts of Atlantic Canada. Farming and fishing have dominated PEI’s economy since French Acadian settlement in the eighteenth century and intensive British settlement in the nineteenth and twentieth centuries. The island’s dense mixed forest was one of the practical barriers to farm settlement, but used in conjunction with marsh hay and other estuarine resources, the forest provided shelter, feed, and materials necessary for a system of mixed animal husbandry in the organic regime (Hatvany 2001; Bittermann and McCallum 2016). In the late twentieth century, PEI farmers maintained this system of livestock, but they slowly began to replace beef and dairy with hog production. The recent period of industrial agriculture is known for a new focus on intensive crops (Arsenault 2016), but in energetic terms, a more significant transition occurred when farmers began to reduce their own internal cycling of feed from crops and pasture. Building on recent work in PEI’s agricultural history (MacFadyen and Glen 2014; MacFadyen 2016a), this case study examines energy flows in the regional agroecosystem in the period from 1880 to 1995.

The county selected for this comparative research was Queens County, PEI. Queens was the most populated and most agriculturally productive of PEI’s three administrative regions. It was also the home to the provincial capital, Charlottetown, although this city was removed from the energy analysis. The recent research covers the longer period of British settlement and recent modernization, but this study focuses on data gathered from four main time points (1880, 1930, 1950, and 1995) to trace major changes in agroecosystem energetics from early European settlement to recent industrialization and intensification processes.

1.2. Sources and methods
The Canadian Census of Agriculture is the primary resource for this study. These censuses were conducted at the same time as the regular census of population (decennially starting in 1881 and quinquennially starting in 1916). The Canadian census of agriculture provides information on a broad range of scales. Agricultural data were reported from national and provincial down to county (Census Division) and township (Census Subdivision) levels. The census bureaus also changed their reporting practices over time, and toward the end of the study period, data from other agencies like Statistics Canada are required to fill in some key energy flows.
The size and composition of the agroecosystem, including agricultural workforce and population, was determined through the land use data in the Census of Agriculture, where information on land used by farms was reported (Department of Agriculture 1883b; Canada Census Office 1934; Dominion Bureau of Statistics 1953; Statistics Canada 1997, CANSIM database). In addition, land use inventories created by the PEI departments of Forestry and Agriculture were used to trace non-farmed (in particular forested) land (Prince Edward Island Canada 2003a, b; MacFadyen and Glen 2014). Livestock units were determined from the quantity of each animal reported in the censuses and standardized by the historical (Gentilcore et al. 1993) and modern (FAO 2003) weights of each species.

The two primary categories of agro-ecosystem energy outputs are Land Produce (LP), i.e. all plant biomass consumed by the local farmers, sold to markets, or reinvested in the agroecosystem as Biomass Reused (see below), and Livestock Barnyard Produce (LBP), i.e. all final produce from livestock (for definitions of these terms, see e.g. Tello et al. 2016). In Queens County LP from cropland was a relatively straightforward conversion of crop data from the censuses (Department of Agriculture 1883a; Canada Census Office 1934; Dominion Bureau of Statistics 1953; Statistics Canada 1997, CANSIM database), and converted based on historical assumptions available in Guzman et al. (2014).

Woodland produce data was developed using Census of Agriculture reports on products of the forest (especially firewood and fencing/lumber used on the farm, see Department of Agriculture 1883; Canada Census Office 1934; Dominion Bureau of Statistics 1953). We then refined those firewood data according to new estimates in biomass energy history (MacFadyen 2016b). In 1995, the woodland production was determined by provincial forestry and firewood consumption surveys (Smith Green & Associates 1995; Prince Edward Island Canada 2003c). Pastureland produce was determined by a combination of census data on pasture availability and estimates of regional productivity (Department of Agriculture 1938), and results were checked against ruminant consumption based on feed balances from the calculations of Biomass Reused (see below).

LBP is a measure of all the energy contained in livestock products, including butter, milk, and eggs, and in slaughtered animals calculated by the slaughter weight of each species. The Canadian census data allow an accurate measurement of most animal products, and Guzman et al. (2014) provide conversion factors to assess energy flows.

For the calculation of Biomass Reused (BR), we used estimates of the demand for seed, feed, and litter that were based on the available census data on crop and livestock production. We calculated this demand using conversion factors that are informed by historical analysis of the local and regional variations on feeding livestock. After the demands were calculated, they were compared with available litter, forage and feedstuffs to determine if local farms produced enough to account for the demands internally. Any demands that exceeded local production, and even some that did not, were considered as external inputs.

In order to determine cropland BR, the amount of seed needed for sowing the following season’s crop was deduced from Final Produce. For roots that meant 10 percent, but for grains it ranged from 5 to 15 percent, depending on the crop. Determining the Livestock-Barnyard BR is one of the most complex processes of the energy analysis. It involves many historical assumptions about the animals present in an agroecosystem and the sources and varieties of the feed they consumed in the time point under study. In Queens County, it was particularly difficult to understand BR, because of the nineteenth century food and feed shortages outlined in earlier work (MacFadyen 2016a). The solution involved a complex feed
balance that accounted for all of the possible feed types in the county and adjusted for period-specific feeding rates (and animal survival rates) based on historical research. For instance, a significant reduction of pasture land in the late twentieth century meant there would have been a shortage of grazed biomass in 1995. However, increased hay (and some feed grain) production accounted for the difference. Historical estimates of the quantity and apportionment of each feed type were derived from a variety of sources (Armsby and Moulton 1925; Jennings 1953; Statistics Canada 1982; Lucci et al. 2013 CANSIM database).

For **External Inputs** (EI) the most important variable to know in the early periods in Queens County was human labor which was estimated based on the Census of Population (Department of Agriculture 1883a, 1884). Beginning in 1930, additional information is available for hired farm workers (Canada Census Office 1934). Later in the twentieth century, other external inputs become increasingly important, particularly the energy intensive forms such as artificial fertilizers, machinery, and fossil fuels (Dominion Bureau of Statistics 1953; Statistics Canada 1982). These were converted to GJ/ha based on their embodied energy as specified in Aguilera et al. (2015) and other sources (Audsley et al. 1997; Dhungana 2007). The 1995 county-level fertilizer consumption was estimated by the Statistics Canada data on the N, P, & K fertilizers imported for agriculture in 1995/1996 divided by Queens County's share (16%) of the region's total area treated by commercial fertilizers (P.E.I. Statistics Bureau 2013, CANSIM database). Fossil fuel and electricity consumption were determined by the relative amount of expenditure on these inputs by Queens County farmers as reported in the 1995 census.

1.3. References

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2. Data compilation of major energy flows and energy returns
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Table SI1 Major energy flows and energy returns in advanced organic, industrializing and industrialized agroecosystems. Data sources: see text

| Location     | Year | Final Produce | External Inputs | Biomass Reused | Total Inputs Consumed | EFEROI | IFEROI | FEROI |
|--------------|------|---------------|-----------------|----------------|-----------------------|--------|-------|-------|
| Europe       |      |               |                 |                |                       |        |       |       |
| St. Florian (AT) | 1864 | 27            | 3.9             | 68             | 71                    | 6.9    | 0.4   | 0.4   |
|              | 1950 | 20            | 12              | 46             | 58                    | 1.7    | 0.4   | 0.3   |
|              | 2000 | 109           | 42              | 46             | 88                    | 2.6    | 2.4   | 1.2   |
| Grünburg (AT) | 1864 | 21            | 1.6             | 34             | 36                    | 12.9   | 0.6   | 0.6   |
|              | 1950 | 14            | 5.9             | 44             | 50                    | 2.4    | 0.3   | 0.3   |
|              | 2000 | 41            | 64              | 67             | 130                   | 0.7    | 0.6   | 0.3   |
| Vallés (ES)  | 1860 | 22            | 1.0             | 21             | 22                    | 21.5   | 1.0   | 1.0   |
|              | 1956 | 20            | 7.7             | 13             | 20                    | 2.6    | 1.6   | 1.0   |
|              | 1999 | 34            | 138             | 16             | 153                   | 0.2    | 2.1   | 0.2   |
| Santa Fe (ES)| 1904 | 27            | 4.6             | 54             | 59                    | 5.8    | 0.5   | 0.5   |
|              | 1934 | 26            | 5.0             | 53             | 58                    | 5.1    | 0.5   | 0.4   |
|              | 1997 | 81            | 35              | 63             | 98                    | 2.3    | 1.3   | 0.8   |
| North America|      |               |                 |                |                       |        |       |       |
| Queens (CA)  | 1880 | 24            | 2.0             | 26             | 28                    | 11.8   | 0.9   | 0.8   |
|              | 1950 | 24            | 3.9             | 31             | 35                    | 6.1    | 0.8   | 0.7   |
|              | 1995 | 29            | 9.3             | 37             | 47                    | 3.2    | 0.8   | 0.6   |
| Nemaha (USA) | 1880 | 6             | 4.6             | 23             | 28                    | 1.3    | 0.3   | 0.2   |
|              | 1954 | 14            | 3.1             | 35             | 38                    | 4.4    | 0.4   | 0.4   |
|              | 1997 | 32            | 12              | 66             | 78                    | 2.6    | 0.5   | 0.4   |
| Decatur (USA)| 1880 | 0.5           | 0.4             | 2.0            | 2.4                   | 1.2    | 0.3   | 0.2   |
|              | 1954 | 6.0           | 1.3             | 21             | 23                    | 4.8    | 0.3   | 0.3   |
|              | 1997 | 17            | 6.2             | 31             | 38                    | 2.7    | 0.5   | 0.4   |
3. Comparative discussion of temporal trends in energy input and output intensity

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Figure SI1 displays the per-area values of Final Produce and different types of inputs. The dots refer to combinations of energy outputs and inputs in pre-industrial (starting point of arrows) and industrialized agroecosystems (end point of arrows), and the direction of arrows corresponds to changes in energy returns per unit of input. This integrates the perspectives of agroecosystem efficiency and intensity (Erb et al. 2013), and combines flow-flow relations, i.e. unit of output per unit of input, with “flow-fund-relations” (Georgescu-Roegen 1971; Giampietro et al. 2009), i.e. unit of energy per unit of area. Figure SI1a compares Final Produce to Total Inputs Consumed and displays that more output was achieved at equally increasing input (all arrows point up and right). It also reveals that, while FEROI values were comparable among case studies, the levels of inputs and outputs diverged significantly between European and North American case studies throughout the time period.

*Figure 1*: area intensity of energy input (a: Total Inputs Consumed; b: Biomass reused; c: External Inputs; d: Labor) and energy output (Final Produce) in advanced organic and industrialized agroecosystems. Arrows point from pre-industrial to industrial values (for time points in the individual case studies, see main text).
Figures SI1b, SI1c and SI1d show that the type of input changed in the course of the agroecosystem energy transition in Western agriculture. The amount of Biomass Reused changed at levels similar to or below those of Final Produce, while external inputs changed much more (arrows point far right on a logarithmic scale). Finally, labor was not only in relative, but also in absolute terms a decreasingly important energy input (arrows point up). It is worth contrasting land productivity (higher in Europe) and labor productivity (higher in North America, see Table 2): In North America, less farmers worked on larger land areas, and generated more Final Produce per unit of energy invested in labor. In combination with differences in biogeographic conditions, the low input of labor in the North American case studies may provide an explanation to the low area productivity values in North America in the late 20th century (Arizpe et al. 2011). Final Produce per unit of labor energy input was between 820 and 2650 (Nemaha and Decatur, respectively), while in Europe, these values ranged between 70 (Santa Fe) and 613 (Sankt Florian).

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