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EHES Working Papers in Economic History | No. 55

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Abstract

The late nineteenth century Danish agricultural revolution saw the modernization and growth of the dairy industry. Denmark rapidly caught up with the leading economies, and Danish dairying led the world in terms of productivity. Uniquely in a world perspective, high quality micro-level data exist documenting this episode. These allow the use of the tool of modern agricultural economists, stochastic frontier analysis, to estimate production functions for milk and thus find the determinants of these productivity and efficiency advances. We identify the contribution of modernization through specific new technologies and practices.

JEL classification: L2, N5, O3, Q1

Keywords: Dairies, Denmark, development, Stochastic Frontier Analysis

Acknowledgements:
I thank Paul Sharp would like to acknowledge generous support from the Carlsberg Foundation, while Markus Lampe appreciates funding by Spain's Ministerio de Ciencia e Innovación (project ECO2011-25713). We would also like to thank Juan Carmona, Ingrid Henriksen, Silke Hüttel, Alan Olmstead, participants at the Gothenburg FRESH meeting and at the Workshop on 'Quantitative Agricultural and Natural Resources History: Globalization, Agricultural Change and Economic Development', University of Zaragoza, the economic history workshop at Universidad Carlos III Madrid, the economic history seminar at Universitat de Barcelona, the Brown Bag seminar at the Department of Agricultural Economics, Humboldt University, Berlin, and the session on the 'History of the Emergence of the Modern Dairy Industry' at the European Social Science History Conference 2014 for comments and suggestions. Some of this paper was written while Markus Lampe was visiting the Department of Economics, University of Copenhagen funded by a grant from UC3M.

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1. Introduction

The late nineteenth century Danish agricultural revolution saw the modernization and rapid growth of her dairy industry. From the 1890s at the latest, Denmark was at the biological and technological frontier of modern dairy production (Henriksen 1993). This came after a rapid expansion of the industry: the value of dairy products was higher than that of grains in all years after 1859 and rose steadily to 90 per cent of the combined value of grains and dairy products by 1900 (Henriksen et. al. 2012, Figure 2). Table 1 illustrates the rapid expansion of animal production in Denmark compared to other countries. This matters, because as Broadberry (2013) has pointed out, the emergence of a large pastoral sector has important implications for economic growth, since it is a high-value-added form of agriculture, highly capital-intensive, and highly intensive in the use of non-human energy. This then set important precedents as such production forms spread to industry and services.

Table 1: Livestock units per head of agricultural population 1870 and 1910, and annual growth rates

	Livestock units per agricultural population 1870	1910	Livestock units Annual growth rate	Livestock per agricultural population Annual growth rate
Denmark	2.0	2.9	1.4	1.0
Netherlands	1.3	1.4	0.9	0.3
Britain	1.9	2.5	0.4	0.7
France	1.1	1.3	0.2	0.5
Switzerland	0.9	1.4	0.9	1.2
Austria	0.7	0.8	0.6	0.3

Source: Van Zanden (1988), p. 37, T.A.1 (livestock units, agricultural population), own calculations with van Zanden's data.

This expansion of pastoral agriculture was heavily and increasingly export oriented, as illustrated by Table 2, and came itself about as a response to the competition from new grain exporting countries in the context of the first globalization, and was made possible in part by the technological advances stemming from the industrial revolution.

Table 2: Danish milk and butter production and exports

	Total milk produced	Butter equivalent of to milk produced	Butter produced	Butter exported to Britain	Butter exports in per cent of milk production
1880-84	1425	53	47	15	27.4
1885-89	1595	60	53	25	42.6
1890-94	2030	76	68	48	62.8
1895-99	2150	80	74	63	78.2

Source: Jensen (1988), p. 262-264 (production); Christensen (1985), p. 89, Tab. VI1b (export).

Note: All values in 1000 metric tons. 'Butter equivalents of milk produced' calculated with production ratio 26.7:1 (Henriksen/Lampe/Sharp 2011, p. 483, Table 1; sample average for new technology, 1882-1904).

Why this happened so rapidly in Denmark is a matter of much speculation. However, since part of the modernization of Danish dairying entailed the development of modern scientific record-keeping and accounting practices, as well as a sophisticated scientific literature, high quality micro-level data do in fact exist documenting this episode in great detail, and they allow us to investigate the underpinnings of Danish success using the tools of modern productivity analysis, in this case Stochastic Frontier Analysis (SFA)[2]. To our knowledge, these data are unique in two respects. First, no comparable data for dairying exist for other countries for this period. Second, since truly revolutionary changes to an industry are often observed in the early stages of development, which are historically far from today, it is extremely rare to have high quality micro-level data documenting such an episode. So while economists and historians might be able to name a number of examples from history, such as the introduction of the heavy plough in agriculture, or the spinning jenny in the textile industry, it is impossible to perform an equivalent analysis for these to that in this paper.

[2] An alternative approach is to use Data Envelopment Analysis (DEA), see for example Stokes et al (2007).

Previous work has highlighted several factors behind the Danish success.[3] This has mostly focussed on the role of the spread of superior institutions, i.e. the cooperatives, and technology, i.e. the steam-driven cream separator (see Henriksen 1992). Building on this, O'Rourke (2007) argues that the cultural homogeneity of the Danes allowed them to form successful cooperatives, in stark contrast with Ireland, and Henriksen, Hviid and Sharp (2012) demonstrate that the cooperatives also relied on legal institutions which were particularly beneficial in an international context. More recently, the cheap availability of coal has been suggested as another reason why cooperatives formed in Denmark (Henriques and Sharp 2014). Thus, Henriksen et al (2011), using SFA, in common with the present work, examine the productivity of Danish dairying and find evidence for the traditional story. However, all these refer to what might be described as the *second* stage of butter production, i.e. the transformation of milk into butter.

A relatively neglected story, however, at least in quantitative terms, is the *first* stage of production whereby the milk is produced, although one thorough study of one aspect of this is that by Henriksen and O'Rourke (2005), who examine the effect of the introduction of winter dairying to Denmark (which we discuss in more detail below). As they document, and as Table 3 reports in a wider context, Denmark rapidly converged on the leading dairy producers measured in milk yields per cow. As can be seen, milk yields in the highly commercialized and urbanized economies of Britain and the Netherlands were initially higher than in Denmark, but the structural transformations experienced in Denmark were much faster and went beyond what seems to have been achieved in these countries before 1880. In these countries both milk yields and agricultural TFP did not grow very much during our period of study (van Zanden 1991, Smits 2008). Advanced intensive dairy systems using commercial foodstuffs and winter-feeding had been developed in the Netherlands since the seventeenth century, but advanced relatively slowly during the long nineteenth century,[4] so that some of the modern practices adopted in Denmark during this period came to define the best practice frontier at the turn of the century.

[3] See also Henriksen (2008, pp. 123-129), on the wider context of Danish agriculture during this period.

[4] van Zanden (1991), p. 216, 224; Smits (2008), pp. 98-106; Henriksen and O'Rourke (2005), pp. 546-547.

Table 3: Milk yields in tonnes per cow

	1880	1900	Annual growth rate
Denmark	1.6	2.3	1.8
Netherlands	2.5	2.6	0.2
Britain	2.2	2.2	0.1
France	1.6	1.6	0.1
Austria	1.0	1.4	1.5
United States	1.3	1.5	0.9
our sample	2.0	2.5	1.1

Sources: Wade (1981), p. 322, Table D-9 (Denmark), Van Zanden (1985), p. 106, Table 5.14 (Netherlands 1880), Bieleman (2010), p. 291, Table 4.10 (Netherlands 1900), van Zanden (1988), p. 7, Table 2 (Britain 1870, Austria 1870), Federico (2005), p. 71, Table 5.1 (Index numbers to reconstruct Britain and Austria 1880, 1900), Wade (1981), p. 340, Table F-9 (France 1880; 1900 extrapolated with average 1890-1935 growth rate), Olmstead and Rhode (2008), p. 333, table 11.1 (Bateman 1968 estimate for the US).

This development occurred in an environment in which the Danish government played a very limited role, which was by and large confined to support of education, such as the founding of the Royal Agricultural College in Frederiksberg, near Copenhagen, in 1856. Formal agricultural education, as well as the publication of a number of agricultural journals, led to the diffusion of knowledge which was being generated at first by owners of the traditional landed estates, and later also by smaller farmers through the cooperative creameries and academics at the agricultural colleges. These advances largely concerned greater understanding of nutrition, breeding, and veterinary science.

At an early stage, Danish dairymen understood that scientific progress and rational economic decisions could only be taken based on accurate measurement and record keeping, and in fact the data underlying this study are the result of a detailed annual survey of Danish estates published by the *Tidsskrift for Landøkonomi* (Danish Journal of Agricultural Economics) over a number of years from 1880. This allows us to use a popular tool of modern agricultural economists, stochastic frontier analysis (SFA), to estimate production functions for milk and thus identify the determinants of these productivity and efficiency advances. Although there is a large body of literature on the estimation of production functions for milk, particularly using (SFA), none of this has to our knowledge focused on historical time periods. More importantly, none has focused on periods when great changes were being made to the organization of the dairy industry. With our unique data source we can investigate far more radical changes, and we demonstrate the productivity and efficiency implications of a large number of factors, such as feeding, breeding, the modernity of the farm (as a proxy for the farmer's education), scale, and more.

The next section gives a brief history of the Danish agricultural revolution. Section 3 presents our data, Section 4 performs the econometric analysis, and Section 5 concludes.

2. A Brief History of the Danish Agricultural Revolution

The Danish agricultural revolution followed by a century its more famous British counterpart, and built on many of the innovations associated with the latter such as crop rotation and selective breeding, as well as on those from other nations, in particular Germany (Christensen 1996, Overton 1996). As described above, in Denmark the significant innovations came in relation to dairying and the related bacon industry. Thus, around 1860 Denmark had a large concentration of cows, but they were far less productive than just a few decades later. An adult cow in 1860 generally weighed around 300 kg with a milk production of around 1000 kg on average. By 1914 a typical cow weighed between 450-500 kg with a milk production of 2700 kg, that is, production per cow increased by about 1.85 per cent per year. Moreover, the butterfat content of the milk increased from around 3.3 per cent to 3.5 per cent. These advances came through better breeding, feeding, and general care and paralleled the growing importance of dairying for the Danish economy. Danish cows quickly became as productive as Dutch cows, which for a long time had been the leaders (Henriksen and O'Rourke 2005, p. 546).[5]

In relation to feed, advances focused on two areas: on the nutritional value of individual foodstuffs and on the individual animal's requirement for the production of milk or meat. As a basis of this analysis the tenant farmer J. Winkel invented the concept of *kraftfoderenhed* (literally 'unit of concentrate') later shortened to *foderenhed* (literally 'unit of feed') which expressed the

[5] The following discussion draws heavily on Bjørn 1988, pp. 313-350.

nutritional value of any foodstuff in relation to 1 kg of a mixture of 50% barley and 50% oats[6]. A great deal of experimentation, in particular (between 1882 and 1891) centred around N.J. Fjord's Experimental Research Laboratory at the Royal Agricultural College in Frederiksberg, and, supported by generous grants from the Danish government, led to a gradual understanding of the optimum level and mixture of feed to ensure the cows' good health and greatest productive capacity.

Many of Fjord's experimental techniques were completely without precedent and led to great advances in dairy science. Elsewhere, experimentation in Denmark and abroad led to healthier cows, less prone to previously widespread illnesses such as tuberculosis and other infectious diseases, for example those that caused cows to spontaneously abort.

In terms of breeding, one of the great contributions was the new breed of 'Danish Red milk cow', designated for the first time in 1878. Statistics on the proportion of cows of this race for the whole country are not available for the nineteenth century, but the number of red bulls used for mating had increased to 14,281 (53 per cent of the total) by 1893 according to the official statistics[7], and in our sample although no estates had Danish red cows between 1880-86 inclusive, 7 per cent had in 1887, 48 per cent in 1890, and 69 per cent in 1900. These had excellent milk producing qualities, and gradually replaced the more traditional breeds (mostly Jutland and Angler). Shorthorn cattle, introduced from England, were used primarily for meat production[8]. Then, after Fjord's invention of a control centrifuge for determining the butterfat content of milk in 1887 it became clear that it was not feed which, as had previously been assumed, determined the butterfat content of milk, or even so much the breed of cow, but rather the individual cow itself. This led to attempts to find

[6] A similar unit, the *skandinavisk foderenhed* (Scandinavian unit of feed or FE) is still in use today, where 1 kg barley = 1 FE (= 1.1 kg old FE). See Savage (1915) and Van Soest (1994, pp. 404ff). on how it compares with other historical units.

[7] Danmarks Statistik, *Landbrugsforhold i Danmark Siden Midten af Det 19. Aarhundrede.* Statistisk Tabelværk 5,C,4, p. 122.

[8] It should be noted that the shorthorn varieties in Denmark were – contrary to those in the US (see Olmstead and Rhode 2008, pp. 314-315, 339) – multipurpose varieties, which means that they were perceived as 'beef cattle' in comparison with the main varieties used for milk production (Angler, Jutland, Funen, Danish Red).

the good ‘butter cows’ and use them for breeding, and various (part government funded) breeding associations sprang up to support such initiatives.

Finally, perhaps the major advance was the understanding of how to get cows to produce milk in the winter through early calving and stable feeding during the winter. This was proved in 1887 but was understood prior to that date, and greatly increased the productive capacity of a cow and allowed year round butter exports from Denmark. British imports of Danish butter accordingly increased from around 10 per cent of winter imports in 1881 to over 40 per cent in 1900, with much of the rest coming from Australia (Henriksen and O’Rourke 2005, p. 537).

Debate and reports of experiments were widely published and disseminated. Probably the most important publication of the time was the *Tidsskrift for Landøkonomi*, published by the Royal Agricultural Society of Denmark (*Kgl. danske Landhusholdningsselskabet*), which represented the traditional landed estates. It was well understood that progress was based on modern scientific method founded on experimentation and the collection of data. Certain estates thus submitted very detailed accounts to the journal, which were then published on an annual basis. It is these that we use for the econometric analysis below.

3. The data

We make use of the aforementioned annual dairy reports for Danish estates published between 1880 and 1900 in the *Tidsskrift for Landøkonomi*. As Table 4 makes clear, these estates were, on average, at the forefront of productivity in Denmark. However, they were not all at the frontier, and in fact milk yields vary in our sample between 2.1 and 3.0 tonnes per cow in the year of 1900 alone. This variation is what allows us to estimate the model.

Table 4: Evolution of milk production in the estates of our sample

	percentage in summer	milk yield summer	milk yield winter	Annual milk yield
1880	46.1	1.1	1.1	2.0
1885	44.8	1.4	1.3	2.5
1890	44.6	1.7	1.3	2.4
1895	43.2	1.8	1.4	2.4
1900	40.6	1.8	1.4	2.5

Note: All values in tons per cow. Unweighted average of all estates in sample for a given year; 'Percentage produced in summer' and 'annual milk yield' for 365-day production year. Summer and winter yields standardized to sample average of 158 summer and 207 winter days. Since individual units diverge from this summer and winter yield do not add up to annual yields. Summer production includes summer stable feeding if practiced. Source: Own calculation from our sample.

Table 5 presents some summary statistics for the data we use in our analysis. We have an unbalanced panel of 55 estates giving us a total of 377 observations. These returns were anonymized, so we unfortunately do not know the location of the individual estates[9], but we are able to link observations from individual estates over time, since they were given unique identification numbers. All of the estates in our sample are vertically integrated milk and butter producers. We excluded all estates whose main activity was the sale of milk. None of our estates supplied private butter factories (*fællesmejerier*), although four of them switched to outsourcing butter production and supplying their milk for processing in dairy cooperatives, after previously having owned a cream-separator themselves, but only at the very end of our sample (in 1897-1900).[10]

Please note also that the estates were not just vertically integrated milk and butter producers, but also produced many of the inputs (grains and fodder crops) for dairying as well as other agricultural products, and also engaged in the use of dairy byproducts through cheese-making, pig raising, etc. By estimating the technological efficiency of milk production on these estates, we can

[9] But Denmark is a rather small and geographically homogeneous country anyway.

[10] These four estates supplying cooperatives account for just nine observations, less than five per cent of our 178 observations of milk processing with cream separators vs. more traditional methods.

only assume that technological efficiency was also economically efficient – that is, profit-maximizing given output values and input prices, judging from the decisions of their owners and managers. Assessing economic or cost-efficiency would require information on prices of all inputs, including shadow prices/opportunity costs for self-produced inputs, which are not reported in our source. However, we believe this is not a problem as long as we compare production units within Denmark, a rather homogeneous and integrated economy, where prices of inputs would not have varied very much across production units. Nevertheless, if we would compare production efficiency between Danish producers and producers in other countries, input prices certainly did differ (see e.g., van Zanden 1991 and O'Rourke, Taylor and Williamson 1996), and might matter for the cost-efficiency of implementing milk-yield maximizing technologies.[11] But such a comparison would require internationally comparable micro-data of the sort we have uncovered for Denmark that to our knowledge is not available for the same period.[12] Our data and analysis for Danish estates, which we will examine in detail now, will nevertheless provide a useful and necessary starting point.

[11] This has been elaborated on for industrial technologies, especially in cotton spinning, by Allen (2009, pp. 203-216; 2011).

[12] For the second stage of production (milk to butter), we are aware of the extremely detailed compilations of information regarding Swedish cooperative creameries, which, as for Denmark, start around the turn of the nineteenth and twentieth centuries. Similar information is available for Ireland in the *Annual Reports* of the Irish Agricultural Organisation Society from 1896. We are not aware of any comparable information outside of Denmark for the period covered by this paper, let alone information on the first stage of production (cows to milk), although we would be very grateful for any suggestions, also regarding data for other countries such as Germany, the Netherlands, and Sweden.

Table 5: Summary statistics

	Mean	Std.Dev.	Minimum	Maximum
milk	451711	282042	104385	1526440
cows	96.6	58.3	22.5	315
feed	326274	216119	69531	1106930
red	0.379	0.486	0	1
shorthorn	0.024	0.153	0	1
graze	0.942	0.311	0.3	2.8
system	0.501	0.501	0	1
calved	46.8	12.4	11	87

milk is the amount of milk produced per year in Danish *pund* (500g). *cows* is the number of cows on the estate (an average of the number of cows reported for the winter and for the summer seasons, which were reported separately[13]). *feed* is the amount of feed in *pund* given to the cows (expressed in *kraftfoderenheder*). This includes all feedstuffs given to the cows as given in the original records[14] as well as an equivalent for the grass consumed in summer grazing. We joined these two terms into one because the grassland, as much as it is a factor of production, does not necessarily contribute positively to milk production if the cows would have given more milk if fed with concentrates outside or in the stable. We therefore use the grassland, as explained below, as a proxy for traditional dairying, while here we include the grass equivalents, which are a substitute for other feedstuffs, as a part of the feed input. To calculate the equivalent of a *tønde land* (0.55 ha) of grassland in feed units, we follow the calculation of barley equivalents from Buttenschøn (2007, table 6.1, p. 204) who gives the average feed units for different sorts of pasture used in organic dairying today, calculated from average gross yields and utilization levels. These range from 250 SFU/ha for heathlands (*lyng- og græshede*) to 3400 SFU/ha for fertilized and watered meadows (*gødet, vandet græsmark*). We use the average pasture quality, 'nutritious pasture' (*næringsrig tøreng*) which yields 800 to 1000 SFU/ha. Since we have data for *pund* per *tønde land* (0.55 ha) and deal with old Danish feed units (of which 1.1 are one SFU, see footnote 7), we can translate the value of 900 SFU/ha directly to 1089 old FU pund/tønde land[15], and use a rounded value of 1100 *kraftfoderenheder* per *tønde land*. These values have to be considered as averages

[13] Hence the presence of 'half cows' in the data.

[14] Hay, beetroots, carrots, grains, oilseed cakes, etc.

[15] 2*0.55*1.1=1.21.

for the whole of Denmark, not as attributes of particularly rich or poor pastures. Since we lack information on the location of the estate-farms in our source, this exercise should be seen as another rough approximation to the actual amount of feed from grazing. Nevertheless the assumption of 1100 *kraftfoderenheder* per *tønde land* is not particularly critical for our results.[16]

red takes the value 1 if the herd is of 'Danish Red' cows, and 0 otherwise. This measures the use of a more productive, biologically innovated, version of the capital good 'cow'. In contrast, *shorthorn* is a dummy taking the value 1 if the herd is of the shorthorn (Danish: *korthorn*) variety, and thus dual-purpose cattle used at least as much beef as for milk production, hence it was a 'technologically' more vintage and less specialized cow. We assume that 'Danish Red' shift the production frontier upward, while dual-purpose shorthorns shift it downward.

graze is the amount of grassland used per cow in *tønde land*. While above its nutritional value is transformed into *feed*, we also use it independently to explain inefficiency: In traditional pasture farming, the amount of pastureland limits the number of cows and the nutrition for the latter, while stable-feeding and the use of commercial feedstuffs overcomes these limits. We therefore assume that farms that use much grassland per cow are more traditional, using stable feeding potentially more for the survival of summer grazing cows in winter than to actually maximize their production possibilities. Related to it, *calved* gives the percentage of cows that have calved before January 1, and thus are able to produce milk during the winter.

system is a dummy taking the value 1 if the estate is 'modern', i.e. owns and operates an automatic cream separator.[17] We believe this latter to proxy the 'modernity' of the estate, since the cream separator was of no use for the production of milk (only for the extraction of cream from the milk to make butter), so any effect of this variable on the production of milk is not a

[16] The only meaningful alternative source for feed unit equivalents of Danish grassland, Rasmussen (1964, p. 179) quotes that an unwatered pasture yielded about 4800 kg of hay per hectare. In the SFU, 1 kg of hay is equivalent to 0.4 kg of barley (Savage 1915, p. 71). This is equivalent to 2112 *pund* of barley or 2323 old FU *pund/tønde land*. This is in line with the lower part of the second best category in Buttenschøn (2007), 'nutritious, moist pasture' (*næringsrig, fugtig eng*). Making the assumption of 2300 instead of 1100 feed units makes no qualitative and very little quantitative difference to our results reported below.

[17] The nine observations of estates supplying their milk to cooperatives noted above are also coded as 'modern' for *system*.

direct effect of the technology *per se*. It is expected to measure education, professional management and adoption of best practices in a broader sense. Importantly for the analysis, *calved*, *graze* and *system* are not highly correlated, and thus measure different aspects of 'modernity' as Table 6 demonstrates.

Table 6: Correlation Matrix for *calved, graze,* and *system*

	calved	*graze*	*system*
calved	1	-0.010	0.029
graze	-0.010	1	-0.051
system	0.029	-0.051	1

4. Empirical Strategy and Results

We start by estimating a series of baseline models for the production functions using the tools of stochastic frontier analysis (see Kumbhakar and Lovell 2000). These models have the general form for panel data

$$y_{it} = \beta' x_{it} + v_{it} - u_{it} \tag{1}$$

where *y* is the output of firm *i*, and *x* is a vector of inputs. The important contribution of these models is the separation of the error term into a standard stochastic error, v_{it}, and an inefficiency term, u_{it}. The form of the production function – the productivity frontier for our sample – is thus given by the relationship between the inputs and the outputs, while the inefficiency term tells us how far away from that frontier an individual unit is at any point in time.

For our purposes, y_{it} obviously corresponds to the (log) output of milk. x_{it} is defined as follows:

$$x_{it} = \begin{pmatrix} lcows_{it} \\ lfeed_{it} \\ \vdots \end{pmatrix}$$

In x_{it} we also include either a trend, *t*, to capture technological and/or especially breeding progress over time, or direct measures of breed. A trend in the functional form we specify in most of our regressions below, a Cobb-Douglas type production function, can be interpreted as Hicks-neutral, disembodied technical change. This might seem odd at first sight, since breeding progress manifested itself in the bodies of cows. However, it could be argued that what the Danish Red cows achieve is to enable an increase in output from a constant bundle of inputs, in our case, with the same amount of 'cows' and feed. This is the classical definition of the productivity effect of Hicks-neutral technical change (Mundlak 2000, p. 134). However, the case might also be made that the introduction of Danish Red cows was a case of factor-augmenting technological change, since it might have over time (and for different farms at different times) changed the elasticity of substitution between feed and cows. This would be a violation of the assumptions of the Cobb-Douglas production function of constant unity elasticity of substitution. Unfortunately, different specifications of the production function, such as *translog*, turned out to be empirically inferior when used with our data, as explained below, so in practice we interpret the trend as Hicks-neutral technical change, with the above caveat about another possible interpretation.[18]

A potentially more relevant weakness of our data is the lack of any information on labour input. Neither can we control for the size of the estate (i.e. land). While we have no way of accounting for variation in labour between units of production or over time, one might argue that the lack of information about labour input in our historical source, which was designed to give an overview of different practices on dairy estates, indicates that labour input was not a significant source of variation between outcomes and would provide little scope for optimization on individual estates. Nevertheless, this is certainly an issue, but, as noted above, labour is usually found to play an insignificant role in the estimation of the production function. This might be because of a very tight relationship between labour input and the number of cows that we have in fact been able to uncover in the few sources that address this topic. Thus, anecdotal evidence suggests a linear dependence of labour on the size of the herd, as explained in the influential article by Buus (1866) who calculates the total expenses necessary for a well-run dairy, based on figures for Gjedsergaard, the estate he administered for Edward Tesdorpf, the president of the Royal Agricultural Society of Denmark. Here he gives the figure of one milkmaid per 20 cows. In the income and expense records for another estate, Orupgaard, we find that in 1886/87 they had 13

[18] In an additional specification where we use the presence of two varieties of cows, these varieties could in the spirit of a recent paper by Heshmati and Kumbhakar (2011) be interpreted as 'technology shifters', that is, in their words, 'key external (…) factors contributing to shift in production' across units of observation and over time.

milkmaids on their payroll for a herd of 257 cows (19.8 cows per milkmaids) besides some other labourers who were engaged in second-stage (butter- and cheese-making) or by-product and input production (pig-feeders, coopers for butter-barrels).[19]

Information on other capital goods, especially stables, is also missing from our source and scarce in general. In the accounting records we have seen in the archives, we find building and reparation expenses that vary hugely from year to year and include e.g. the purchase and maintenance of cream separators and stables for pigs, which are not used for milk but for butter and pork production.[20] In a follow-up article to Buus (1866), Fenger (1873) looks at the profitability of beef production in Denmark by comparing dairy and beef production farms of similar sizes. He calculates an additional 10 Danish kroner per cow per year of capital-related expenses needed for milk production, of which roughly half were related to milk production. So, it seems not unreasonable to assume that capital costs were proportional to the number of cows in the long-run.[21] However, we are aware that there might be estates using higher or lower labour-cow and capital-cow ratios, and our simplification of assuming some sort of Leontief-deterministic

[19] Landsarkivet for Sjælland, Lolland-Falster og Bornholm (Copenhagen), QA-257 Orupgård, Diverse regnskabsvæsen, 1832-1896. Mejeriregnskaber for Orupgaard, 1886/87 ("Udgift. 1. Lönninger"). We have to admit, however, that this observation might not be completely independent of Buus' articles, since Orupgaard was also owned by Tesdorpf and the 20:1 rule might be his house-rule. But, then, Buus' assumptions were not criticized in later articles on the same subject, probably because they were common-sense. Occasional preserved accounting data from other estates (like those for Basnæs cited below) are not as detailed and in particular do not disentangle work input for milk production from the other dairy activities carried out on the estate.

[20] Archival records for the estate of Basnæs show annual expenses for inventory and buildings between 1884-85 and 1887-88 fluctuating between 1 and 14.5 kroner per cow, with a standard deviation of 6 kroner (Landsarkivet for Sjælland, Lolland-Falster og Bornholm (Copenhagen), QA-010 Basnæs Gods, Mejeriregnskaber 1878-1899. These figures also indicate that at least in the expense records we find, the calculation of return on capital invested or similar ratios was not practiced; this does not necessarily imply that estate-owners did not calculate the profitability of their investments).

[21] His figure is a version of Buus' (1866) earlier figure of 8.4 kroner per cow, of which roughly half are related to butter and pork production (like stables for pigs). Of circulating capital, we cover the most important item, feed, while the other items appearing in Buus (1866), Fenger (1873) and the archival records include all kinds of inputs to run the creamery part of the dairy (firewood, barrels, salt, coal, transport services) and therefore are not relevant for this analysis. We do not include veterinary costs, but these were likely also related to the number of cows.

relationship between both and the number of cows might not be a reflection of reality, although it is a necessary (but justifiable) shortcut.

Also, we are unable to quantify the impact of changes in the butterfat content of the milk over time, since we only have quantities, but as noted in Section 2, the impact of this was far less than the increase in milk per cow, which is the present focus. Finally, and as noted above, note that we here focus on technical efficiency and thus ignore allocative/cost efficiency[22]. However, since the focus of this study is what led Denmark to define the productivity frontier, this can be left as an issue for another paper.

Table 7 reports the estimation results for the baseline models. Models (1a-c) are simple pooled regressions using various formulations of the log likelihood: half normal, exponential, and truncated normal respectively[23] (for more on this see Greene 2009 and Kumbhakar and Lovell 2000, pp. 72-93). For models (2) and (3) we estimate a production function using the stochastic frontier model with a time-varying technical efficiency term formulated by Battese and Coelli (1995). In these models, the inefficiency term, u, is given by $u_{it} = exp[-\eta(t - T)]|U_i|$. In all specifications bar one we assume a Cobb-Douglas production function; although in (3) we experiment with a translog function. This latter leads to insignificance of both factors of production, but clearly this is due to multicolinearity of the *lcows* and *lfeed* variables with their interactions. A joint test of the significance of the three extra variables in the translog specification cannot reject that they should be omitted. All other estimation results are both qualitatively and quantitatively very similar.

[22] But see Battese and Coelli 1992, Kumbhakan et al 1989, Heshmati and Kumhakar 1994, and Tauer 2001.

[23] The Model = (blank), E and T options in Limdep.

Table 7: Estimation results, baseline models, dependent variable *lmilk*

	(1a)	(1b)	(1c)	(2)	(3)
Constant	6.261*** (0.326)	6.239*** (0.331)	6.262*** (0.326)	7.361*** (0.309)	15.165 (12.939)
lcows	0.601*** (0.042)	0.612*** (0.043)	0.602*** (0.043)	0.760*** (0.039)	1.853 (3.125)
lfeed	0.324*** (0.040)	0.316*** (0.041)	0.323*** (0.041)	0.181*** (0.037)	-1.456 (3.132)
lcows^2	N/A	N/A	N/A	N/A	0.061 (0.215)
lfeed^2	N/A	N/A	N/A	N/A	0.088 (0.192)
*lcows*lfeed*	N/A	N/A	N/A	N/A	-0.130 (0.393)
Wald test of constant returns to scale (χ^2)	256.03	247.56	256.80	430.02	0.23[24]
Trend	0.006*** (0.001)	0.007*** (0.001)	0.006*** (0.001)	0.004*** (0.002)	0.005*** (0.001)
μ	N/A	N/A	-0.031 (0.173)	N/A	N/A
λ	3.218*** (0.619)	N/A	3.247*** (0.634)	2.563*** (0.050)	2.472*** (0.055)
σ	0.216*** (0.011)	N/A	0.224*** (0.046)	0.191*** (0.001)	0.184*** (0.001)
$\theta\left(=\frac{1}{\sigma_u}\right)$	N/A	8.871*** (1.019)	N/A	N/A	N/A
σ_v	N/A	0.087*** (0.008)	N/A	N/A	N/A
η	N/A	N/A	N/A	0.019* (0.011)	0.019* (0.011)
Average inefficiency	0.159	0.113	0.155	0.167	0.161
Period covered	1880-1900	1880-1900	1880-1900	1880-1900	1880-1900
No. of cross-sections	N/A	N/A	N/A	55	55
No. of observations	377	377	377	377	377
Log likelihood	224.497	222.808	224.514	371.739	372.649

Notes: */**/*** = significant difference from 0 at 10%/5%/1% level; $\hat{\mu}/\sigma_u = 0$; $\lambda = \sigma_u/\sigma_v$; $\sigma = \sqrt{\sigma_u^2 + \sigma_v^2}$; stochastic frontier, $e = v - u$; for models 2 and 3, $u_{it} = exp[-\eta(t-T)]|U_i|$.

[24] The test for joint significance of the three extra coefficients in the translog specification.

Having determined that the baseline model for the production frontier, and the estimated firm specific inefficiencies, seem relatively robust to the specification of the model, we extend the analysis by modelling the inefficiency terms as $g(z_{it}) = \exp(\eta' z_{it})$, where *z* is a vector of variables which might explain inefficiency[25]. The results are presented in Table 8. In the inefficiency term, z_{it}, we include the variables: *cows* (as a control for the size of the farm)*, graze, system, and calved*. In model (6) we also include a trend.

In model (5) we examine the impact of improved breeding, which we believe largely drove technological progress in milk production, by replacing the trend in the production function with dummies for two types of breed of cow: the Danish Red, and the shorthorn. As explained above, the former is considered instrumental for the productivity gains seen by Danish agriculture over this period. The latter was a dual purpose cow, used both for milk and meat production. The control group of cows is thus all other breeds, who were by and large traditional breeds which the Danish Red was eventually bred from. Our motivation for placing them in the production function is that 'superior' (for milking) breeds of cow would correspond to an outward shift of the production possibility frontier.

[25] Although note that strictly speaking the relationships we uncover are correlations rather than causal, although we interpret them in this way in common with the vast majority of the SFA literature.

Table 8: Estimation results, technical inefficiency effects models, dependent variable *lmilk*

	(4)	(5)	(6)
Constant	7.073*** (0.361)	7.154*** (0.417)	7.136*** (0.369)
Lcows	0.732*** (0.051)	0.717*** (0.054)	0.734*** (0.051)
Lfeed	0.212*** (0.045)	0.216*** (0.050)	0.208*** (0.046)
Wald test of constant returns to scale (χ^2)	280.17	220.32	274.48
Trend	0.007*** (0.001)	N/A	0.005*** (0.001)
Red	N/A	0.040*** (0.012)	N/A
Shorthorn	N/A	-0.150*** (0.050)	N/A
Inefficiency			
Cows	0.001 (0.003)	0.001 (0.003)	0.001 (0.003)
Graze	0.308*** (0.081)	0.395*** (0.129)	0.296*** (0.082)
System	-0.201*** (0.091)	-0.359*** (0.071)	-0.181*** (0.089)
Calved	-0.010*** (0.003)	-0.009*** (0.003)	-0.011*** (0.003)
Trend	N/A	N/A	-0.011 (0.011)
λ	3.215*** (0.102)	2.932*** (0.123)	3.878*** (0.096)
σ	0.230*** (0.005)	0.217*** (0.005)	0.277*** (0.009)
Average inefficiency	0.168	0.167	0.169
Period covered	1880-1900	1880-1900	1880-1900
No. of cross-sections	55	55	55
No. of observations	377	377	377
Log likelihood	388.338	378.893	388.843

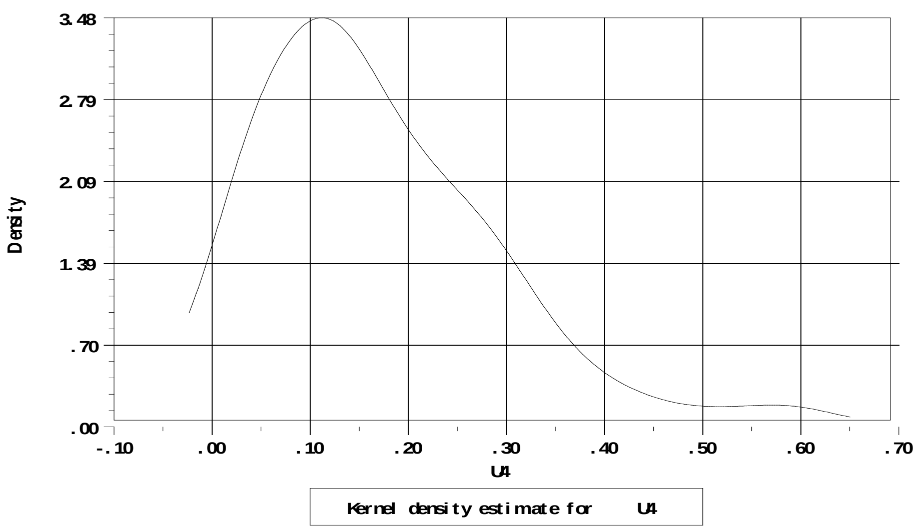
Notes: */**/*** = significant difference from 0 at 10%/5%/1% level; $\lambda = \sigma_u/\sigma_v$; $\sigma = \sqrt{\sigma_u^2 + \sigma_v^2}$; stochastic frontier, $e = v - u$; $u_{it} = exp(\eta' z_{it})|U_i|$.

Note again the robustness of the estimation to the different specifications. Table 9 gives some idea of the similarity of the distribution of the farm-specific inefficiencies for the nine models we estimate. This is especially notable in the light of the fact that these types of model are considered to be very sensitive and prone to give extreme results in the case of misspecification or poor data[26] (Greene 2009, E33-53). Figure 1 gives the kernel density plot for the distribution of inefficiencies in our preferred model (4).

Table 9: The Distribution of the Estimated Farm-Level Inefficiencies for Models (1A) – (6)

	Mean	Std.Dev.	Minimum	Maximum
(1A)	0.159	0.098	0.025	0.360
(1B)	0.113	0.090	0.027	0.582
(1C)	0.155	0.098	0.025	0.371
(2)	0.167	0.119	0.012	0.617
(3)	0.161	0.117	0.013	0.605
(4)	0.168	0.120	0.010	0.619
(5)	0.167	0.113	0.014	0.586
(6)	0.169	0.120	0.010	0.614

Figure 1: Kernel Density Plot of Inefficiencies for Model (4)



Note: The kernel density plot is generated according to a non-parametric logit kernel density function.

[26] Thus paying tribute to the accurate recordkeeping of the farmers.

In all cases the test for constant returns to scale is rejected with a very high test statistic, although in fact the coefficients of the production function in all cases add up to close to 1. As previously explained, we also lack labour as an input, which might be part of the explanation. The sizes of the coefficients in the production function are as expected and within the broad range of estimates for modern dairies (for example, Álvarez and Arías 2004 find an elasticity to the number of cows of 0.686, 0.183 to feedstuffs[27]). The trend implies something approaching 1 per cent 'technological' growth per year[28], but model (5) shows that part of this is actually biological and due to the introduction of the Danish Red breed of cow.[29]

The average inefficiency is between 15 per cent and 17 per cent for almost all model specifications, implying that the same levels of production could have been reached with just 85 per cent of the inputs. In our preferred specification (model 4), the average inefficiency is 16.8%, ranging from 0.9% to 61.9%.[30] It is worth noting that this is relatively efficient compared to findings from modern studies, perhaps reflecting the productivity lead of Danish agriculture at this time. In order to understand better the features of the more and less efficient farms, Table 10 illustrates the mean values of our variables for the first quartile of the distribution of inefficiencies (the least inefficient farms), and for the fourth quartile (the most inefficient farms)[31].

[27] And 0.039 to land, and 0.028 for roughage and 0.045 for labour, but the latter is insignificant.

[28] Formally Hicks-neutral technical change. We return to this below.

[29] Adding both the trend and the breed dummies does not substantially affect the coefficient to the trend, but the dummies are insignificant. This is due to multicolinearity, and to the fact that the trend captures more than just the effect of better breeding.

[30] This implies that the average efficiency is 83.2%, ranging from 38.1 to 99.1% for individual observations.

[31] This way of interpreting the results was inspired by Trestini (2006).

Table 10: Characteristics of farms at different levels of efficiency

	1st quartile (least inefficient)	4th quartile (most inefficient)	Mean
milk	524839	331696	451711
cows	97.5	87.0	96.6
feed	353222	275982	326274
red	0.51	0.14	0.38
shorthorn	0.00	0.06	0.02
inefficiency	0.04	0.33	0.17
cows	97.5	87.0	96.6
graze	0.806	1.191	0.942
system	0.649	0.340	0.501
calved	53.1	43.2	46.8
year	1890.4	1890.3	1890.0

As suggested by the econometrics, the size of the farm and the year do not have a substantial impact on efficiency, although clearly larger farms were generally more efficient – but this was due to the practices they employed rather than their size *per se*. Less efficient farms made more use of summer grazing, less use of stable production in the winter[32], and were less likely to own a cream separator.

In the next step, we try to convert our findings into a common framework by providing estimates of the overall increase in total factor productivity (TFP) in our sample, again focusing on model 4 and the characteristics given in Table 6. Following the literature on productivity and efficiency analysis (Coelli et al 1998, ch. 10, esp. pp. 221-226 and 233-239), TFP growth can be decomposed into the two elements we are estimating here, technical change, i.e., shifting the production possibility frontier, and efficiency change, i.e., getting closer to the frontier at any time. In other words, TFP growth is a combination between more productive available technologies and the

[32] Note in this connection that it was never the case that all cows could produce during the winter (the maximum was 87 per cent), so no farm could in this way be perfectly efficient.

wider and more efficient use of these. In our estimate, the technical change is easy to grasp, since it corresponds to the coefficient for the time trend, which indicates a 0.7 per cent shift per year in the production possibility frontier, leading to a total increase of 15 per cent between 1880 and 1900.

Formally, then, efficiency change is calculated as (Coelhi et al 1998, p. 233)

$$EC = TE_{it}/TE_{it-1}$$

with $TE_{it}=E\left(\exp\left(-u_{it}\right)|e_{it}\right)$

for individual units. For the average in each year we get for our practical purposes

$$EC = \frac{TE_t}{TE_{t-1}} = \frac{\exp(-u_{it})}{\exp(-u_{it-1})}$$

with $-u_{it}$ representing the average inefficiency in the corresponding years.

In our context, it is difficult for us to quantify the contribution of the increase over time of technical efficiency, which is mainly due to the construction of the original data in our sample, which was not supposed to be a representative sample for all farms (or estates) in Denmark, but rather to represent a wide variety of farms even if they were unrepresentative, such as an estate using 1.5 *tønde land* of grass land per cow and running an ice/water dairy in 1900[33]. In fact, average inefficiency does decrease slightly from 20.5 per cent in 1880 to 17.4 per cent in 1890 and 15.9 per cent in 1900, leading to a result of EC = 4.7 per cent between 1880 and 1900 or 0.23 per cent per year. Finally, since TFP growth is obtained by multiplying indices of TC and EC (1880=1), with our dataset we would arrive at total TFP growth of 20.4 per cent in 20 years or 0.93 per cent per year.

However, since the sample average of inefficiencies at no point in time really represents a Denmark-wide average and, as we have shown in Section 2, the different advances became more prevalent over time, although this is not fully reflected in our dataset, we prefer to see the

[33] Note however that the unrepresentativeness of the sample will *not* affect the estimation of the shape of the production function (the frontier), including our estimate of technical change (from *t*), assuming that we have farms in the sample which are at the technological frontier in every period, which we believe to be the case.

differences between the most efficient and the least efficient farms in our dataset as better proxies for this change. In this case, the change in inefficiency between the fourth and the first quartile as depicted in Table 6 corresponds to an EC calculation of 33.7 per cent, which distributed over 20 years would correspond to about 1.46 per cent per year. Combined with the TC estimation of 0.7 per cent per year this would give annual TFP growth of 2.17 per cent (or 54 per cent over 20 years). This is in line with and compares favourably to the TFP calculations by Henriksen (2008, Table 5.3, p. 128) for all of Danish agriculture in the periods 1875-1895 (0.69 per cent annually) and 1895-1910 (1.35 per cent per year). She attributes much of this overall increase to the shift from crop to dairy production and the adoption of modern practices spread to family farms by cooperatives and the tighter relation between agricultural practice and science (ibid., pp. 123-129).

Now, our TFP calculation allows us to give an idea of the relative importance of the different determinants of (in)efficiency in Table 6 to the overall TFP growth as calculated above. We do this by calculating the changes in (in)efficiency resulting from switching from being an average representative of an 'old style' fourth quartile estate to a 'modern' first quartile estate using the coefficients of model (4) and the values in Table 6. Whether or not this is representative of the change that happened on average in Denmark over this period is impossible to know – apart from anything else, our sample only includes estates, while most milk came from small peasant producers. Nevertheless, there are reasons to believe that we are not at least overestimating the change, since one of the big transformations over this period is the rise of the cooperative movement, one of the main contributions of which was the introduction of best practice through the self-enforcement of peasants tied to cooperative creameries (Henriksen et al 2012). The results of our calculations are given in Table 11.

Table 11: Contributions to inefficiency change and annual TFP growth (per cent) by switching from average 4th quartile estate to average 1st quartile estate

	Inefficiency change (%)	per cent	Contribution to annual TFP growth (%)
Total	-86.837	100.0	1.464
cows	0.012	0.0	0.000
graze	-9.956	11.5	0.168
system	-18.216	21.0	0.307
calved	-0.229	0.3	0.004
residual	-58.449	67.3	0.986

Source: Calculations based on Tables 4 and 6. 'Residual' = inefficiency difference not explained by explanatory variables.

We see that among the variables with most importance for explaining the major closeness to the frontier (and hence higher TFP) of 'modern farms' the *system* variable is key, which we consider to be a measure of the modernity and professionalization of the farm, and perhaps also the educational level of the farmer, or at least his openness to new ideas and methods. This is in line with previous work which also finds the education of the farmer to be of prime importance for the efficiency of milk production. Also of importance seems to be the reduction in reliance on traditional summer-grass feeding and grassland per cow – which on the other hand implies more use of stable feeding. These variables also show the largest difference between farms of the 1st and the 4th quartile in Table 6. Although statistically significant in all our estimated models, the difference in the percentage of cows that have calved before January 1st to produce milk through the winter does not seem to have made a substantial difference to total factor productivity. This might be because among the estates covered in our sample this practice seems to have been widely diffused already in 1880, when already on average 48.1 per cent of the cows of each farm had calved. This number was actually lower in 1900 (41.9 per cent), although this is mostly driven by a single outlier (a farm where only 11 per cent of all cows calved before January 1st 1900).

The size of the farm is insignificantly positively correlated with inefficiency in our estimates, and with the estimated coefficient makes virtually no contribution to the overall increase in TFP as presented here. This is in line with the comments of contemporaries who considered it better to work with smaller herds, for example due to it being easier to concentrate feed on the most productive cows and to observe the efficient milking of the cows.[34]

Our findings support to a large extent those from modern studies: for a review of the earlier literature, see the article by Bravo-Ureta and Pinheiro (1993). They describe how production functions are usually specified including land, labour, capital (normally proxied by the number of cows) and feed. Technical efficiency is usually explained by 'farmer education and experience, contacts with extension, access to credit, and farm size' and that all but the latter usually have a positive and significant impact on efficiency. These findings have been largely vindicated in more recent work. Cuesta (2000) estimates a production model for Spanish dairy farms with firm-specific temporal variation in technical inefficiency and compares his results with the more restrictive Battese and Coelli (1992) model. Both show capital (number of cows) and feedstuffs to have the expected sign. Another more recent paper by Álvarez and Arías (2004), again looking at Spanish dairy farms, finds similar results. Common to both these papers is that labour is found to be insignificant, probably because it is linearly related to the size of the herd or inaccurately measured (see also Ahmad and Bravo-Ureta 1996, Brümmer et al 2002, Cuesta 2000, and Hallam and Machado 1995; although see also Bailey et al 1989, Hadri and Whittaker 1999, and Abdulai and Tietje 2007 where the coefficients are significant, but very small). Finally, in a recent study, Atsbeha et al (2012) show the importance of breeding for productivity growth using Icelandic data.

5. Conclusion

The present work presents the first quantitative assessment of the forces behind what stands out as Denmark's lead in agricultural productivity in a period when the basis for modern dairying was developed and diffused rapidly in that country. This should be understood in the context of the nineteenth-century globalization and rapid expansion in demand for dairy products in the industrializing core of the world economy, most importantly Great Britain. We show that several factors had to come together before full advantage could be taken of these opportunities.

[34] This was observed, among others, by the leading dairy consultant in our period, Bernhard Bøggild (1895, pp. 120-2).

Danish farmers were apparently well educated (Henriksen 1999), and our results show that that education and the disposition to use modern methods (like automatic cream separators in the second stage of production) contributed to increasing efficiency of production, as did the adoption of practices leading to more efficient use of the capital good 'cow', here exemplified by calving in the fall and stable-feeding in the winter which allowed for year-round production. Also, biological innovation, although at first on unstable scientific grounds, led to the improvement of the capital good 'cow', and hence to higher milk yields and increasing efficiency. This improvement happened again from a comparatively early stage, since the Danish estates in our dataset had focused on milk instead of beef production from an early date, which can be seen from the few observations on the use of multipurpose beef-milk cows of the shorthorn variety in our sample, and is backed by articles in the leading agricultural journal of that time such as Fenger (1873), who, based on actual accounting data from individual farms, showed that beef production was less lucrative than milk production under the circumstances of the 1870s.

Additionally, by increasing the importance of other, often commercial and imported feedstuffs (grains, oilseed and palm-kernel cakes) relative to pasture area, and using these effectively to increase milk production (e.g., via stable feeding), Danish farmers overcame the constraints of their own lands[35], took advantage of declining prices for grains in Europe during the late nineteenth century and committed to a market-oriented export agriculture.

Clearly, although the factors we describe mattered within Denmark, we cannot assess in an international context that these were the 'fundamentals' of Danish success. We do however believe that they were, inferring this from the fact that Denmark became the world leader and was pushing outward the world production possibility frontier. The Danish dairy industry set an example of organizational, biological and technological innovation that transformed milk production and paved the way to modernity. Dairying outside Denmark was usually more similar

[35] By this, they used the same 'shadow lands' or 'ghost acreage' abroad to feed their cows that figure prominently in accounts of the British industrial revolution and the development of the Northwestern European core of the world economy in the eighteenth and nineteenth centuries, which helped to overcome demographic constraints (see Jones 1987, pp. 83-84; and, more specifically, van Zanden 1991, pp. 216, 224, 232).

to the more traditional and less efficient farms in the present sample (see for example the comparison with Ireland in O'Rourke 2007).

Nevertheless, ultimately the veracity of these statements should be evaluated empirically using comparable data from both traditionally leading dairy regions like the Netherlands, Switzerland, Belgium and Northern Germany as well as more traditional producers in Russia, Finland, modern-day Poland or Southern and Central Europe, if these exist.

Also, at least in Denmark, this was a period when modern dairying spread to the average farmer, who might have benefitted even more than the large traditional estates in our sample, where the minimum herd size is 22.5 cows. By 1900, most of the milk in Denmark was processed by cooperative creameries supplied by small 'peasant' farms, which seem have converged quickly on the larger producers in terms of milk yields per cow.[36]

[36] See the milk yields for Denmark as a whole vs. those for our sample in Table 3.

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