Is it simply getting worse? Agriculture and Swedish greenhouse gas emissions over 200 years

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Is it simply getting worse? Agriculture and Swedish greenhouse gas emissions over 200 years[1]

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This paper challenges the idea that emissions of greenhouse gases simply increase over time with income. It adopts a 200-year perspective and includes the important flows of greenhouse gases related to agriculture, not just the CO_2 from fossil fuels. The result is that the pattern of Swedish total greenhouse gas emissions over time resembles an N. In contrast, when only emissions from fossil fuels are counted, the pattern over time resembles an inverted U. Among the most important factors generating emissions in agriculture, forest management was especially important, but in addition, draining of wetlands for agriculture played a substantial role.

I

It is useful to know the historical development of pollution in order to understand its current and future development. It is important to adopt a sufficiently long-term perspective, one century into the future and two centuries into the past, to understand the interplay between developmental and environmental processes, especially for pollutants like greenhouse gases that have a long lifespan in the atmosphere.[2] Historical emissions of greenhouse gases are also of interest when it comes to the responsibility of individual countries in reducing emissions.[3] If countries' responsibilities for past global warming were to be taken into account in present climate-change negotiations, historical emissions would have political implications. Sources that were more influential in the past may not be so influential today, and vice versa. In addition, it may be the case that we get a biased picture of the historical development if we base our understanding simply on the development of carbon dioxide (CO_2) emissions from fossil fuels. It is widely believed that emissions of CO_2 from fossil fuels always increase with increasing income, although emissions have fallen in Sweden and a few other European countries in the last few decades. This paper shows that, in fact, taking account of the historical development of all relevant greenhouse gases changes this picture profoundly. Agriculture, including forestry, has gone through substantial changes over the last 200 years, and has played an important role in greenhouse gas emissions. These changes are depicted and their effects estimated in this paper. The pattern that emerges is not a simple increase of greenhouse gas emissions over time, but one revealing that emissions have increased in some periods and decreased in others. Maximal emissions occurred not in the twentieth century, but

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[2] Clark and Munn, eds., *Sustainable development*, p. 7.
[3] Neumayer, 'In defence of historical accountability'.

in the nineteenth century. The CO_2 from fossil fuels is relatively easy to account for historically, because the extraction and trade of fossil fuels are well documented,[4] and there are recognized emission factors for each fossil fuel.[5] It is more difficult to estimate flows of CO_2 from forests and agricultural lands, and to identify and quantify historical changes that have caused emissions of nitrous oxide (N_2O) and methane (CH_4). This study does so for Swedish development over the last two centuries. All emissions from agriculture have not previously been estimated for a period extending over 200 years for Sweden, or any other region in the world for that matter. Earlier estimations only dealt with regional emissions from agriculture in Europe since 1975[6] and global emissions from deforestation and land use changes from 1860 to 1980.[7] Fossil fuel emissions are better known historically and will be compared here to emissions from agriculture and forestry.

Sweden is only one tiny region of the world, but its economic development and related greenhouse gas emissions have counterparts in other places. It is reasonable to think that Sweden's economic development will resemble that of regions with similar forest endowments, such as North America, and Northern European countries like Finland and Norway, and will also resemble, to a certain degree, countries like the Netherlands where large areas of peatland have been drained. Many other European countries such as Great Britain, Germany, and France have had similar deforestation and related emissions, but at an earlier date than Sweden. The difference is that those countries did not reforest to the same degree as Sweden during the twentieth century, since they were more densely populated and their land was used for more valuable purposes than timber production.

Sweden is different from most countries in its relatively low dependence on fossil fuels, due to lack of domestic sources. It has developed an energy path relying on its rich hydropower resources, wide use of firewood (and other wood-based energy products, such as spent pulping liquor from the pulp and paper industry), and a nuclear programme which began in the 1970s. Thus in 2000, the Swedish energy system was only 50 per cent reliant on fossil fuels, which is substantially less than in most developed countries.[8] This relatively low dependence on fossil fuels means that the impact from agricultural emissions, as compared to fossil fuel emissions, tends to be greater in Sweden than in other countries that are similar in terms of forestry and agricultural development.

This paper deals primarily with the following five sources of greenhouse gases:

1. methane from domesticated animals
2. N_2O from fertilizers
3. greenhouse gas emissions from agricultural peatlands
4. CO_2 from other agricultural land
5. CO_2 emissions from forestry (including draining of forestland)

Detailed information on these five sources of emissions and the accounting methods adopted are given in the appendix. A few remarks are made here for the benefit of the reader, who may not want to go into these details. First, agricultural

[4] Marland, Boden, and Andres, 'Fossil fuel CO_2 emissions'.
[5] Levander, *Koldioxid*, p. 8.
[6] Freibauer, 'Regionalised inventory'.
[7] Houghton, Hobbie, Melillo, Moore, Peterson, Shaver, and Woodwell, 'Changes in the carbon content'.
[8] Kander, *Economic growth*, p. 126.

land in Sweden is divided into mineral soils and organic soils. Organic soils, which are former peatland that was turned into arable land, contain much more carbon and nitrogen than mineral soils. This is one justification for the separation of sources 3 and 4 in the list above. Another reason for this separation is that greenhouse gas flows from agricultural peatland are more complex than consisting of CO_2 emissions alone. Second, for analytical reasons (enabling comparisons of the benchmarks), the peatland that is considered in this paper is not the total peatland area of Sweden. Since we address emission changes caused by humans, and not natural emissions, only the area of peatland that was drained at some time during the period 1800–2000 is considered in the accounts. This goes for both arable land and forested land.

Section II gives a brief overview of the greenhouse effect, its causes and effects, and how the different greenhouse gases can be aggregated. Section III presents the estimated net-flows of greenhouse gases at some benchmarks (1800, 1870, 1930, and 2000), divided according to the five sources above. Section IV contains a broader discussion of greenhouse gas emissions in Sweden, where these results are related to emissions from fossil fuels, and the total emission pattern is looked at, both in absolute terms and in relation to population and GDP.

II

The so-called greenhouse effect is an unquestioned phenomenon, even though its importance for global warming is still debated. The greenhouse effect arises when short-wave light radiation from the sun reaches through the atmosphere and meets the earth's surface, after which part of this energy rebounds as long-wave heat radiation. When this heat radiation reaches the greenhouse gases in the atmosphere, it does not get through as easily as the short-wave light radiation, but part of it is reflected back to the earth and heats it. The greenhouse gases thus work approximately like the glass in a greenhouse. The natural greenhouse effect is a precondition for life on earth. Without the greenhouse effect generated by water vapour, CO_2, methane, and N_2O, the mean temperature of the earth would be *minus* 18°C instead of the present *plus* 14.3°C. What is normally referred to as the greenhouse effect though, is not this natural and necessary heating effect, but an enhancement of this that makes the climate warmer.

A climate that slowly and steadily gets warmer does not necessarily mean trouble for humans. For the temperate parts of the world, it may even bring about some advantages, with longer growing seasons and higher agricultural productivity, but for tropical areas, the water deficiency that follows the temperature increase will give lower agricultural production. Still other areas of the world will be hit by flooding, because the ice masses at the poles melt and the oceans are expanded at higher temperatures. The energy demand for heating will be reduced, but this saving may perhaps be offset by an increasing energy need for air conditioning. What is especially difficult for mankind and its supportive systems is when rapid climatic changes take place. Then, life conditions may change so drastically within certain areas that some species may not be able to survive there. Without options to move somewhere else (which is often the case with trees, for instance), they die, which means large economic losses. Another likely outcome of a warmer climate is that certain parasites and microbes can spread more and infect humans with diseases. Yet another risk is that climate changes will lead to extreme weather, like storms, hurricanes, drought, and extreme heat occurring more often.[9]

Over the last 120 years, the mean temperature of the earth has increased by 0.7°C, after previously having been rather constant, and the largest increase (0.5°C) took place after the 1970s.[10] The most common explanation for this temperature increase, embraced by the majority of global academia, is that humans have increased the content of greenhouse gases in the atmosphere. Now and then, alternative explanations are put forward, like the natural variation in solar radiation or, more recently, that it is due to heat pollution (waste heat from the use of fossil fuels and uranium).[11] The latter explanation turned out to be easy to dismiss, since it only made up 1 per cent of the human-caused part of the greenhouse gas effect.[12] The idea of natural variation in solar radiation cannot completely be dismissed, but it does not seem sufficient alone. The reinforced greenhouse effect seems to be an indispensable explanation for heating, but even so, there is no simple correlation between emissions of greenhouse gases and heating. The temperature increase took place during two periods: 1910–45 and after 1976. No increase took place between 1945 and 1976, despite the fact that at that time oil had its breakthrough as an energy carrier and that fossil fuel consumption increased markedly in the world. However, emissions of sulphur from industrial activity and volcanoes were greater during this period and may have cooled the climate. Another possible explanation is that emissions related to agriculture have influenced this temperature pattern. Obviously, the picture is complex, and global warming is the result of various interacting factors.

The most important natural greenhouse gas is water vapour. When the reinforced greenhouse effect is considered, only gases that have increased in the atmosphere due to human actions are directly accounted for.[13] The most important of those gases is CO_2, responsible for 60 per cent of global warming; the second most important is methane, responsible for 17 per cent; while other gases (N_2O, freons, halogen gases) are together responsible for the remaining 23 per cent.[14] CO_2 is released when fossil fuels are burnt and when the carbon content of soils and green plants decreases. Soil carbon can either be released as CO_2 or as methane, sometimes called swamp gas, because its bubbling is noticeable in wetlands. Whether the soil carbon becomes CO_2 or methane depends on the oxygen access when the organic material is decomposed. Richness of oxygen gives CO_2 and deficiency of oxygen gives methane. Ruminating animals also form methane, when they digest their fodder without oxygen. A third gas that is relevant in relation to agriculture is N_2O. It is formed by bacteria that transform the nitrogen in the soil to N_2O. It is released increasingly when the soil is fertilized with nitrogen and when nitrogen-rich soils, like wetlands, are drained.

Since this study deals with three greenhouse gases (CO_2, CH_4, and N_2O), with different powers and lifetimes, it is desirable to aggregate them and therefore

[9] Bernes, *Warmer world*, pp. 123–39.
[10] Jones, Parker, Osborn, and Briffa, 'Global and hemispheric temperature anomalies'.
[11] Nordell, 'Thermal pollution'.
[12] Gumbel and Rodhe, 'Comments'.
[13] The degree of global warming generated by a given change in gas concentrates—the climate sensitivity—depends critically on feedbacks such as increased water vapour in the atmosphere.
[14] Sveriges Meterologiska och Hyrologiska Institut, 'Frågor och svar angående klimatet'.

necessary to have a common unit. The method used here for aggregation is the one usually adopted by the UN's International Panel on Climate Change, which is to assess the Global Warming Potential (GWP) of the gases from a hundred-year perspective, and use CO_2 as a reference gas, with GWP = 1.[15]

III

The conditions at the chosen benchmarks 1800, 1870, 1930, and 2000 and the relevant changes between those years are briefly described below. Each description is followed by a table, with the estimated flow of annual greenhouse gases at the time.

Around 1800

The demand for agricultural land increased around 1800 because of a growing population, which rose by 0.5 per cent per year. The overwhelming majority of the population lived in the countryside and were engaged in agriculture with subsidiary activities, handicrafts, and local transport. Industry was still small-scale and mainly located in rural areas. Firewood was the totally dominant source of energy and made up roughly four-fifths of energy consumption in Sweden (the rest was muscle energy), which put pressure on forest resources.[16]

Even though Sweden was less densely populated than many other European countries, there was some local competition for the scarce land resources and the forests. Local wood shortages occurred around the ironworks in the southern and middle parts of the country. The national government promoted industrial timber demands and tried to make the farmers save wood. One step in that direction had already been taken in the 1760s when Cronstedt and Wrede, on a government mission, constructed a highly efficient tiled stove with several vertical smoke channels. These stoves were also spread to the rural areas in the form of a cheaper variant, without the tiles.[17] In this way, firewood was saved because the amount of firewood required to produce the same amount of heat decreased, but still the required heating increased as the population grew. The forest was put under pressure and no real efforts were undertaken to increase its regrowth, so forest resources diminished.

The desire to bring more land under the plough was strong, and interest was directed to dry meadows, peatlands, and forests. This kind of land was much more abundant than the cultivated land, which often stood out like islands in the sea of peatlands. The government tried to interest the farmers in draining the peatlands, but was met with scepticism, since the farmers were not interested in such insecure and labour-intensive projects. What did take place on a large scale was the conversion of dry meadows to cultivated land, which reduced the carbon content of this mineral soil.

[15] *Climate change 1995*.
[16] Kander, *Economic growth*, p. 126.
[17] Cramér, *Den verkliga kakelugnen*, p. 274.

Table 1. *Net flows of greenhouse gases in 1800*

	Number/amount	*Emission factor*	*Emissions*	*Emissions in CO_2 equivalents, thousand tonnes, and percentage*
1. Methane emissions from domestic animals				
a) Cattle	1,468,000	33 kg/animal	48 thousand tonnes	1,000 (7.9%)
b) Horses	397,000	10 kg/animal	4.0 thousand tonnes	84 (0.7%)
c) Reindeer	180,000	15 kg/animal	2.7 thousand tonnes	57 (0.4%)
c) Sheep	1,214,000	6 kg/animal	7.3 thousand tonnes	150 (1.2%)
d) Pigs	450,000	1 kg/animal	0.45 thousand tonnes	9.5 (0.1%)
2. N_2O from fertilizers				
a) Manure	47,000 tonne N	2.5%	1,880 tonnes N_2O	580 (4.6%)
b) Synthetic fertilizers	0	0.8%		0
3. Changed carbon content of the mineral cultivated soil				
a) Cultivation of dry meadows	19,000 ha/ year	12.5 tonne C/ha	240 thousand tonnes C	890 (7.1%)
b) Deeper cultivation of the soil	1.5 million ha	77 kg/ha	116 thousand tonnes C	430 (3.4%)
4. Agricultural-related peatland				
a) Natural	0.7 million ha	0.2 kg CO_2/m^2	1.4 million tonnes CO_2	1,400 (11.1%)
b) Cultivated	0			0
5. Changed carbon storage of the forest				
a) Trees				1,000 (7.9%)
b) Other vegetation				1,000 (7.9%)
c) Dry forestland				1,000 (7.9%)
d) Natural swampland	2 million ha	2.5 tonnes CO_2/ha	5 million tonnes CO_2	5,000 (39.7%)
e) Drained swampland	0			0
1–5 Total emissions expressed in CO_2 equivalents				12,600

Notes and sources: Historisk statistik för Sverige, pt. 2; Hannerberg, *Svenskt agrarsamhälle*. Information on reindeer is missing; I have assumed no change between 1800 and 1870. Emissions of N_2O have been estimated on the basis of the molar weights for nitrogen and oxygen, which are 14 and 16 respectively. This means that one tonne of nitrogen equals 1.6 tonnes of N_2O. One tonne of carbon equals 3.7 tonnes of CO_2, since the relation is (12 + 16 + 16)/12. One hectare = 10,000 m^2. GWP for methane = 21 and GWP for N_2O = 310.

The iron plough became more widespread at this time, due to falling relative prices of iron, but the majority of ploughs were still made of wood.[18] The soil was cultivated more deeply with these new tools, which broke down the soil carbon content and released CO_2 into the atmosphere.

The number of draught animals for agricultural use was relatively large compared to the rest of Europe. One reason for this was that the abundant heavy soils demanded a powerful cultivation. These animals needed large areas of grazing lands and meadows, since fodder was not yet grown in cultivated fields. In summer, manure from the grazing animals simply fell on pasturelands, where it was generally wasted, but in winter the stable manure could be collected more easily and was later spread on the fields. Synthetic fertilizers were not in use at the time.

My estimates of the annual flows of greenhouse gases in 1800 are shown in table 1. The total amount was 12.6 million tonnes of CO_2 equivalents. Forests were

[18] Gadd, *Järn och potatis*, p. 157.

responsible for around two-thirds of these emissions, domesticated animals for 15 per cent, and agricultural land for the remaining 20 per cent.

Around 1870

Industrialization had started to take off in 1870, but the cities were still relatively few and small, and living conditions there were often worse than in the countryside. Much restructuring of the agricultural landscape had taken place since 1800. Enclosures had broken up the villages, changed the field patterns, and increased agricultural productivity. Output from the land had increased, as had milk and meat production. In addition, agriculture had diversified, which meant longer working seasons. Taken together, these changes meant that agricultural labour productivity had increased on an annual basis. The population grew even faster compared to the previous benchmark (1800), and the landless now increased their proportion. Nevertheless, average income was higher at this stage, because the rise in productivity exceeded the population increase.

Soil hunger had resulted in a substantial decline in the share of dry meadows compared to cultivated fields throughout the country, but especially so in the wooded districts. Since most of the newly cultivated land had previously been dry meadows, the amount of hay production was reduced. Introducing grass and leguminous crops in the crop rotation compensated for this. Growing nutritious fodder in the fields had a two-fold positive impact on productivity: a) it became possible to have new species of cattle and horses, which were bigger and demanded more nutritious fodder, and b) leguminous crops (like clover) were able to absorb nitrogen from the air and thus fertilize the soil. This reduced the need for fallow fields and consequently increased the soil available for agricultural production. The grazing areas were reduced and animals were kept in stables to a larger degree, which meant that the effective amount of manure increased.

The number of draught animals per cultivated hectare declined between 1800 and 1870, but at the same time, the amount of manure per animal increased, as did the nutritious content of the manure.

Soil cultivation was deeper in 1870 than in 1800, partly because new tools enabled this and partly because new crops like potatoes and root crops demanded it. This deeper cultivation tended to diminish gradually the carbon content of the soil.

The trees in the forest were reduced in the period 1800 to 1870, and so was the other forest vegetation and carbon in the forest soil. The first accounts of digging ditches in forestland were provided for 1873, and showed that this practice was too insignificant to play a role in emission flows at the time.[19]

The greenhouse gas emissions around 1870 are reported in table 2. Compared to 1800, the total emissions were now four times as high, and amounted to 49 million tonnes of CO_2 equivalents. Forests were responsible for 80 per cent of the emissions and, of the remaining 20 per cent, agricultural land was responsible for a little more than the domesticated animals.

[19] Lindberg, 'Skogsdikning'.

Table 2. *Net flows of greenhouse gases in 1870*

	Number/amounts	*Emission factor*	*Emissions*	*Emissions in CO_2 equivalents, thousand tonnes and percentage*
1. Methane emissions from domestic animals				
a) Cattle	1,501,000	45 kg/animal	68 thousand tonnes	1,400 (2.9%)
b) Horses	428,000	11 kg/animal	4.7 thousand tonnes	99 (0.2%)
c) Reindeer	180,000	15 kg/animal	2.7 thousand tonnes	57 (0.1%)
c) Sheep	1,595,000	7 kg/animal	11 thousand tonnes	230 (0.5%)
d) Pigs	354,000	1.1 kg/animal	0.39 thousand tonnes	8.2 (<0.1%)
2. N_2O from fertilizers				
a) Manure	65,000 tonnes N	2.5%	2,600 tonnes N_2O	800 (1.6%)
b) Synthetic fertilizers	965 tonnes N	0.8%	12.4 tonnes N_2O	4 (<0.1%)
3. Changed carbon content of the mineral cultivated soil				
a) Cultivation of dry meadows	19,000 ha/year	12.5 tonne C/ha	240 thousand tonnes C	890 (1.8%)
b) Deeper cultivation of the soil	2.85 million ha	77 kg/ha/year	219 thousand tonnes C	810 (1.7%)
4. Agricultural-related peatland				
a) Natural	0.55 million ha	0.2 kg CO_2/m^2	1.1 million tonnes CO_2	1,100 (2.3%)
b) Cultivated	0.15 million ha	1.2 kg CO_2	1.8 million tonnes CO_2	1,800 (3.7%)
c) Burning of the peatland	2 million m^3	45 kg C/m^3	0.33 million tonnes CO_2	330 (0.7%)
5. Changed carbon storage of the forest				
a) Trees				12,000 (24.7%)
b) Other vegetation				12,000 (24.7%)
c) Dry forestland				12,000 (24.7%)
d) Natural swampland	2 million ha	2.5 tonnes	5 million tonnes CO_2	5,000 (10.3%)
e) Drained swampland	0			0
Total emissions in CO_2 equivalents				48,500

Notes and sources: synthetic fertilizers: Staffansson, *Svenskt smör*, tab. 35; swamp forests: Berggren, *LUSTRA* under 2001 and 2002; animals: *Historisk statistik för Sverige*, pt. 2. Information on reindeer in 1870 is only available for Norrbotten, and the figures for the counties of Jämtland and Västerbotten have been extrapolated from information for 1885. Emissions of N_2O have been estimated on the basis of the molar weight for nitrogen and oxygen, which are 14 and 16 respectively. This means that 1 tonne of nitrogen equals 1.6 tonnes of N_2O. For peat-burning for cultivation, I have assumed that half of the land was burnt to a depth of 20 cm. This means that 0.07 million hectares were burnt between 1800 and 1870, containing in total 140 million m^3 peat, which is equal to 2 million m^3 burnt peat per year. The bulk density for coal is around 4.5% (out of 1 m^3 of fresh peat, 45 kg is carbon) (Bergner, Bohlin, and Albano, *Vad innehåller torv?*). Sveriges Lantbruksuniversitet and 1 kg of carbon = 3.7 kg of CO_2. GWP for methane = 21 and GWP for N_2O = 310. One hectare = 10,000 m^2.

Around 1930

By 1930, the land under cultivation was at its historic peak, but the countryside had been depopulated partly, and people had moved into the industrial cities. Around 200,000 left the countryside between 1890 and 1930. The traditional countryside-based industries like ironworks and sawmills had reduced their share of industrial production, and new branches like the paper industry, chemical industry, and manufacturing, situated in cities, had expanded. The population increase continued at the rate of 0.6 per cent per year between 1870 and 1930. The drive for new land to cultivate continued, but was now more stimulated by positive incentives. Progress in natural sciences and technology both reduced the relative labour needs in agriculture, releasing these people for other work, and enabled a more successful reclamation of new land through innovations of tools and methods.

Large areas of peatland had been drained and cultivated since 1870, stimulated by institutional changes in the form of new laws, funding options, and organizations. The total land under cultivation was 3.7 million hectares in 1930, which meant a total increase of 0.7 million hectares since 1870, and most of this new land consisted of previous peatland.

One reason for higher agricultural productivity in 1930 than in 1870 was the use of synthetic fertilizers. From the 1870s, the production and use of these fertilizers grew steadily, but the really impressive breakthrough for synthetic fertilizers did not take place until after the Second World War. Positive experiences from using synthetic fertilizers initially led to some neglect of manure care, but when the consequential large losses of nitrogen from manure became obvious, more interest was paid to its maintenance, and practices were developed whereby the nitrogen was preserved. One method for preserving the nutrient content of the manure was to mix it with peat, and another was to pack it more densely.[20] The available manure was more evenly spread on the crops in the rotation system than it was in 1870, when most of it was put on fallow land. Human excrement was to some extent also taken better care of by mixing it with peat and lime, but at the same time, cities gradually adopted water closets and sewage systems, which meant that nutrients were lost to the nearest watercourse.

Initially, grain was grown on the reclaimed peatland, but there was a switchover to more grass, and, to a lesser extent, potatoes, during the first decades of the twentieth century. This should, in principle, have reduced the emissions of greenhouse gases from the reclaimed peatland.

The number of trees in the forest, which had been reduced during the nineteenth century, was now increasing. The forest law of 1903, which required measures to be undertaken to make the forest grow again after cutting, contributed to this, but in addition there were outright economic reasons for silvicultural improvements, because the higher demand for thin wood dimensions made a rational forestry with district cutting and replantation profitable.[21] This turned the forest into an important sink for atmospheric CO_2. At the turn of the century, however, the draining of forestland took off, and this increased emissions. This process reached its absolute peak around 1930–1, with 2,300 kilometres of ditches dug on state-owned land alone.[22]

Table 3 shows the emissions of greenhouse gases in 1930. The most drastic change since 1870 was that the forest had changed its role from being a large source to being a sink. This meant that the other emissions from agriculture were outbalanced and the net result was negative emissions, i.e. agriculture with subsidiary activities absorbed more greenhouse gases from the atmosphere than it released.

Around 2000

In 2000, agriculture looked profoundly different from the way it appeared in 1930. The change may be categorized in terms of the industrialization of agriculture. The

[20] Juhlin Dannfelt, *Lantbruket i Norden*, p. 43.
[21] Kander, *Economic growth*, pp. 167–75.
[22] Lindberg, 'Skogsdikning', pp. 486–90.

Table 3. *Net flows of greenhouse gases in 1930*

	Number/amounts	*Emission factor*	*Emissions*	*Emissions in CO_2 equivalents (thousand tonnes)*
1. Methane emissions from domestic animals				
a) Cattle	2,632,000	50 kg/animal	130 thousand tonnes	2,700
b) Horses	571,000	16 kg/animal	9.1 thousand tonnes	190
c) Reindeer	279,000	15 kg/animal	4.2 thousand tonnes	88
c) Sheep	448,500	8 kg/animal	3.6 thousand tonnes	76
d) Pigs	1,445,000	1.3 kg/animal	1.9 thousand tonnes	40
2. N_2O from fertilizers				
a) Manure	106 thousand tonnes	2.5%	4.2 thousand tonnes N_2O	1,310
b) Synthetic fertilizers	18.5 thousand tonnes	0.8%	0.24 thousand tonnes N_2O	73
3. Changed carbon content of the mineral cultivated soil				
a) Cultivation of dry meadows	2.1 thousand ha/year	12.5 tonnes/ha	26 thousand tonnes C	97
b) Deeper cultivation of the soil	3.0 million ha	77 kg/ha	231 thousand tonnes C	850
4. Agricultural-related peatland				
a) Natural	0			0
b) Cultivated	0.7 million hectares	1.1 kg CO_2/m^2	7.7 million tonnes CO_2	7,700
5. Changed carbon storage of the forest				
a) Trees				–10,000
b) Other vegetation				–10,000
c) Dry forestland				–10,000
d) Natural swampland	0.9 million ha	2.5 tonnes CO_2/ha	2.2 million tonnes CO_2	2,200
e) Drained swampland	1.1 million ha	7.5 tonnes CO_2/ha	8.2 million tonnes CO_2	8,200
Total emissions in CO_2 equivalents				–6,500

Notes and sources: SOS, *Jordbruk*. For the amount of nitrogen from synthetic fertilizers: Jansson, *Handelsgödseln*. I use Staffansson's estimate that 20% of the nitrogen comes from synthetic fertilizers at this time to estimate the manure (Staffansson, *Svenskt smör*). 1 kg of nitrogen = 1.6 kg of N_2O. GWP for methane = 21 and GWP for N_2O = 310.

technical transformation of this sector, based on the diffusion of electricity and combustion engines, and a wide use of synthetic fertilizers and pesticides, contributed to the closing down of three-quarters of the agricultural enterprises of 1930 and to only 5 per cent of the population being occupied in the sector. However, agricultural production was somewhat greater than it had been 70 years earlier.

The land under cultivation was 800,000 hectares less in the year 2000 than it was in 1930, and the meadow area was now only 350,000 hectares. The amount of synthetic fertilizers increased substantially, especially the amount of nitrogen, from approximately 5 kilograms to 80 kilograms per hectare.[23] The use of synthetic fertilizers contributed to increasing land productivity, which in turn meant that the mineral soil in general had worked as a small sink for CO_2. However, this had not taken place in all areas, because some regions specialized either in livestock (with grass growing), which increased the carbon content of the soil, or in grain, which reduced it.[24]

[23] Morell, *Jordbruket*, p. 222.
[24] Persson, Otabbong, Olsson, Johansson, and Lundin, *Vad är bördighet?*, pp. 28–31.

Table 4. *Net flows of greenhouse gases in 2000*

	Number/amounts	*Emission factor*	*Emissions*	*Emissions in CO_2 equivalents (thousand tonnes)*
1. Methane emissions from domestic animals				
a) Cattle	1,684,000	55 kg/animal	93 thousand tonnes	1,900
b) Horses	89,000	18 kg/animal	1.6 thousand tonnes	34
c) Reindeer	221,000	15 kg/animal	3.3 thousand tonnes	69
c) Sheep	432,000	8 kg/animal	3.5 thousand tonnes	74
d) Pigs	1,918,000	1.5 kg/animal	2.9 thousand tonnes	61
2. N_2O from fertilizers				
a) Manure	31 thousand tonnes	2.5%	1.2 thousand tonnes N_2O	380
b) Synthetic fertilizers	175 thousand tonnes	0.8%	2.2 thousand tonnes N_2O	690
3. Changed carbon content of the mineral cultivated soil			–0.25 million tonnes C	–925
4. Agricultural-related peatland				
a) Natural	0.4 million ha	0.2 kg CO_2/m^2	0.8 million tonnes CO_2	800
b) Cultivated	0.3 million ha	1.0 kg CO_2/m^2	3 million tonnes CO_2	3,000
5. Changed carbon storage of the forest				
a) Trees				–7,000
b) Other vegetation				–7,000
c) Dry forestland				–7,000
d) Natural swampland	0 million ha			
e) Drained swampland	2.0 million ha	7.5 tonne/ha	15 million tonnes CO_2	15,000
Total emissions in CO_2 equivalents				83

Notes and sources: Jordbruksstatistisk årsbok. GWP for methane = 21 and GWP for N_2O = 310; –7,000 for the forest emissions in CO_2 equivalents is the average for the period 1986–95. If, instead, the average for the period 1930–95 is chosen, it is –14,600.

The cultivation depth was greater than it had been in 1930 and was now around 20 centimetres, but on the other hand, methods used for cultivation did not turn the soil as much as previous methods, which partly offset the carbon releases.

Some of the reclaimed peatland had been restored to wetlands again. At the same time, some new peatland had been brought into use for energy production since the 1980s: around 300 hectares per year.[25]

The trees in the forest had increased since 1930, mostly as a consequence of conscious silviculture, but also as an effect of involuntary fertilization of the forests with nitrogen, a consequence of the use of fossil fuels in society. Draining of forestland continued, but declined during the 1990s, and ceased completely in 1997, when it was prohibited by law.[26]

Table 4 shows the flows of greenhouse gases from agriculture and forestry in 2000. The net emissions were positive, but still low compared to the nineteenth

[25] Statistics Sweden, *Naturmiljön i siffror*, fig. 3.105, p. 182.
[26] Gustafsson, *Jordhunger*, p. 47.

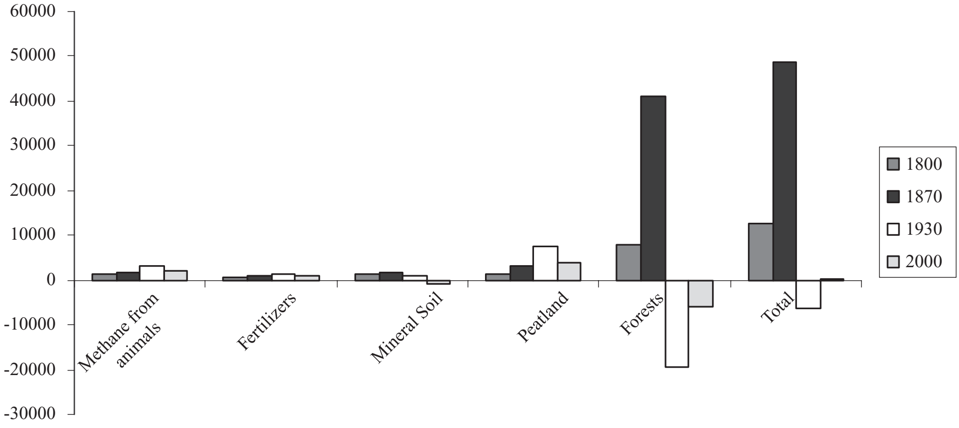

Figure 1. *Net emissions of non-energy-related greenhouse gases in agriculture with subsidiary activities, 1800, 1870, 1930, and 2000, thousands of tonnes of CO_2 equivalents*

Note: In 2000, the net total emission flow was only 83,000 tonnes, and therefore not visible in the graph.
Source: Tabs. 1–4 in this article.

century. Drained swamp forest was the single largest source of greenhouse gas emissions at this time, and it released 15 million tonnes per year.

IV

One purpose of this study is to illuminate how different greenhouse gas emissions in agriculture and forestry have developed over the last 200 years in order to determine their relative importance. Figure 1 compares five sources of emissions, and it is obvious from this that the forest has played a major role in emissions in this sector throughout the period. During the nineteenth century, forest management caused large emissions of CO_2, but improvements in silviculture turned the forest into a sink for CO_2 during the nineteenth century. In 1800 and 1870, positive CO_2 emissions from forestry were overwhelming compared to the other four sources in agriculture. In 2000, the negative CO_2 emissions from forestry balanced all other non-energy-related emissions from agriculture. In 1930, this relative forest effect was even stronger, so the sector in total acted as a net-sink, despite the fact that emissions from peatland and methane from animals reached a peak at this time. The second most important factor was the draining of peatland. This effect is directly demonstrated in figure 1 under the label ‘agricultural peatland’, but it also makes up part of the forest impact, since this includes the draining of swamp forests. The third most important source is methane from domesticated animals, while N_2O from fertilizers and changed carbon content of mineral soil are the two least important sources.

Another equally important purpose of this study is to illuminate the role of these agricultural emissions in relation to the emissions normally focused on: those from fossil fuels. Here the study presents really startling results, showing that agricultural emissions are more than comparable with fossil fuel emissions historically, and thus deserve attention in studies of greenhouse gas emissions. This is impor-

Table 5. *Greenhouse gases intensities in agriculture with subsidiary activities*

	Value added, constant prices, million SEK, 1910/12 years' price level	*Non-energy related emissions, thousand tonnes of CO_2 equivalents*	*Energy emissions, thousand tonnes of CO_2 equivalents*	*Total emissions in agriculture with subsidiary activities, thousand tonnes of CO_2 equivalents*	*CO_2 intensity (tonnes per 1,000 SEK)*	*Index of intensity 1,800 = 100*
1800	205	12,800	0	12,800	62.4	100
1870	543	48,500	0	48,500	89.3	143
1930	970	−6,100	0	−6,100	−6.3	−10
2000	1,047	83	2,000	2,100	2.0	3

Sources: value added: Schön, *Historiska nationalräkenskaper*; non-energy related emissions: see tabs. 1–4 in this article; energy-related emissions for 2000: Statistics Sweden [URL: www.scb.se].

tant if we think that countries should be held responsible not only for present emissions, but also for past emissions that continue to affect the climate and have paved the way for their economic prosperity.

Intensity indicators are now frequently used to understand the interplay between economic development and pollutants. These relate the pollutant to the country's economic performance; for instance, GDP or the value added of a sector. Pollutant/GDP indicators enable assessments of whether more or less economic value is achieved from a certain level of pollution and what direction the economy is moving in: towards more or less pollution. Greenhouse gas intensities in the agricultural sector declined in the long run in Sweden, but not in a straightforward manner. Table 5 shows value added, emissions, and intensities in the agricultural sector (including forestry) over this period. Between 1800 and 1870, the annual increase in real economic output of the agricultural sector was lower than the increase in greenhouse gases. This means that the greenhouse gas intensity of production increased in this period. In the next period, 1870 to 1930, output continued to grow, but now emissions became negative. In the period 1930–2000, output increased modestly, and greenhouse gas emissions grew substantially, especially when the sector's fossil fuel use is included. Despite the large increase in emission intensity from 1930 to 2000, the intensity level in 2000 was below that of 1800, and the absolute emissions in 2000 were far below the level of emissions in the nineteenth century.

So, if we only focus on the greenhouse gas emissions from the agricultural and forestry sector, we get quite a positive view of the effects of economic development: things are getting better, both in relative and absolute terms. However, this naturally is a limited picture of greenhouse gas development. We need to account for all fossil fuel emissions, not only agricultural fossil fuels, to get an accurate picture of long-term changes. Figure 2 depicts two sources of greenhouse gases: a) non-energy-related emissions in agriculture and forestry, and b) all fossil fuel emissions. From this figure, it is evident that non-fossil fuel emissions matter considerably for the entire picture. The surprising result is that Swedish total emissions of greenhouse gases were approximately of the same size in 1800 as they were in 1930. Over a period of 130 years, with substantial increases in income levels and a transformation of the economy, environmental loading in the form of greenhouse gas emissions did not monotonically increase. Emissions increased between 1800 and 1870, but then declined again, and in 1930 were back at 1800 levels. Similarly, for the two years 1870 and 2000, levels were almost the same,

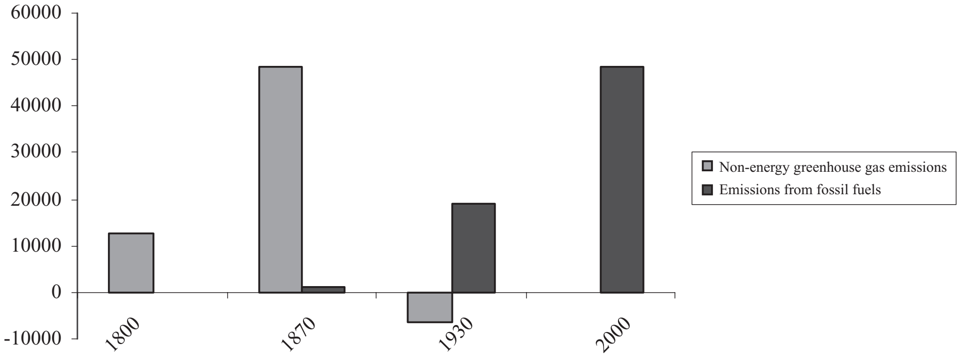

Figure 2. *Non-energy-related greenhouse gas emissions versus emissions from fossil fuels in the Swedish economy, thousands of tonnes of CO_2 equivalents*
Source: Tabs. 1–4 in this article; Kander, *Economic growth*.

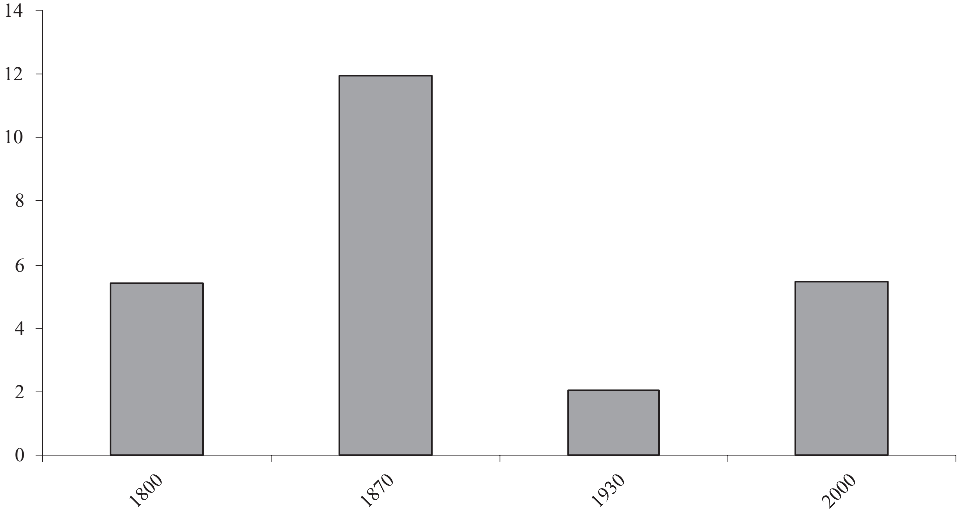

Figure 3. *Total greenhouse gases per capita, tonnes of CO_2 equivalents*
Source: Tabs. 1–4 in this article.

which again means that 130 years of economic growth took place without any simple increase in emission levels. It should also be noted that in 1870 and 2000, total emission levels were much higher than in 1800 and 1930.

The population of Sweden increased from 2.3 to 8.9 million between 1800 and 2000, so although absolute emission levels were the same in 1800 and 1930, and in 1870 and 2000, the per capita emission levels certainly were not. Figure 3 shows the aggregate greenhouse gases per capita. Per capita emissions were 5.4 tonnes of CO_2 in 1800, 11.9 tonnes in 1870, 2.0 tonnes in 1930, and 5.5 tonnes in 2000. Thus, considering emissions in relation to population, we are back at the same level in 2000 as in 1800, which is another surprising result.

The careful reader may ask why greenhouse gas emissions from firewood are not accounted for here. Certainly, firewood causes CO_2 emissions when it is burnt.

However, when the forest is allowed to re-grow so that timber volumes stay constant, this does not imply any net emissions of CO_2, because the growing forest will absorb as much CO_2 as is emitted from the firewood combustion. In other cases, when timber volume resources are actually declining, as was the case during the nineteenth century in Sweden, all of the CO_2 emitted from firewood combustion is already included in the deforestation effect, so it would be inappropriate to include it again.

Still, one may argue that knowing the amount of firewood burning compared to other reasons for forest decline would be of interest. Such a comparison is, however, hard to make, not only because it is difficult to determine the consumption of firewood, but also because of the dynamics involved in establishing forest management that enabled the timber volumes to re-grow in twentieth-century Sweden. The two driving forces behind this successful silviculture were legislation and demand for thin timber dimensions. Demand for firewood and thin timber for pulp and paper made it economically rational to clear-cut large areas and then replant them again, rather than relying on selection systems, where one cuts what one wants and leaves the rest. The selection system has advocates today, for reasons of biodiversity and for creating forests that are less vulnerable to shocks than even-aged forests, but this was done in the past without scientific skill, and hence left forests which were in such poor condition that they were useless. In view of its positive effects on silviculture, it is hard to argue that firewood burning had any detrimental effects on forestry and timber volumes, even in times when the number of trees was decreasing.[27]

How can we then categorize the Swedish long-term pattern of greenhouse gases? There are some stylized descriptions used for long-term developments of pollutants in relation to time or economic growth, the simplest cases being, of course, that pollutants either increase or decrease over time. Access to clean drinking water is something which is normally attained with higher income, while CO_2 and refuse heaps normally just increase with higher income. Another very popular idea is that of the Environmental Kuznets Curve (EKC). The idea that some pollutants show a slope-like pattern, with an initial increase, a peak, and an eventual decline, has been popular ever since the *World development report* in 1992.[28] Panayotou labelled this inverted U-curve the Environmental Kuznets Curve, after Simon Kuznets, who proposed a similar pattern for economic inequality over time.[29] This hypothesis has stimulated hundreds of reports and analyses, and cannot be treated in any depth here.[30] One reason for thinking that growth will cause an inverted U-curve for emissions is that people with low incomes will prefer to increase their level of consumption, regardless of environmental effects, while richer people can afford to care about the environment. Another reason is that economic growth entails structural change. This could mean a movement from less harmful sectors to more pollutant sectors and then over to less pollutant sectors again, which could create an inverted U-shape curve. This idea has been related to agrarian societies becom-

[27] Kander, *Economic growth*, pp. 166–85.

[28] World Bank, *World development report*.

[29] Kuznets, 'Economic growth'; T. Panayotou, 'Empirical tests and policy analysis of environmental degradation at different stages of economic development', working paper WP238, Technology and Employment Programme, International Labour Office, Geneva.

[30] A good overview is provided by Stern, 'Rise and fall'.

ing industrial and then becoming service economies. However, the positive environmental effects of the service transition can be questioned, and decreasing emissions from the 1970s onwards, at least in Sweden, have more to do with the third industrial revolution and microelectronics.[31] A third reason, very much related to the structural outcome, is that technical change can have two opposing effects when it comes to the environment. It can open up new possibilities of using energy and material (which in many cases will increase growth and emissions), and it can improve efficiency, which will decrease emissions.

The empirical EKC reports typically test the correlation between pollutants per capita and income per capita. Since income per capita normally grows over time, it is also justified to think of the inverted U-pattern as something occuring over time. This was actually Kuznets's original idea regarding the growth-income distribution relation. Furthermore, the main conclusion of the empirical EKC studies is that the inverted U-curve is not only related to income levels, but also to levels of technology and efficiency improvements that are spread among countries over time.[32] Thus it is warranted to investigate time aspects of emission levels.

Most studies of greenhouse gases only account for CO_2 from fossil fuels, and they tend to find that these emissions increase more or less monotonically with income, with possible indications of turning points at extremely high income levels (outside of the sample).[33] Sweden is an exception in this regard, with relatively large reductions in CO_2 since the 1970s, mainly due to changes in the sources used to supply energy and a stabilization of energy consumption. The Swedish pattern, with CO_2 from fossil fuels alone, in fact resembles an EKC.[34]

The results of this study, including emissions from agriculture and forestry, modify this picture fundamentally, and suggest that Swedish emissions of total greenhouse gases roughly take the form of an N-shaped curve in the long run, with bottom values in 1800 and 1930 and top values in 1870 and 2000. An N-shaped curve for certain pollutants has already been suggested by de Bruyn et al. and Focacci.[35] This N-curve for Sweden seems very much related to the fact that they have three different EKCs; one for forest emissions, a second for the draining of peatland, and a third for fossil fuel emissions, with different timings of their peaks. The forest curve reached its turning point shortly after the turn of the century, and the draining of agricultural peatland reached its peak around 1930, but the fossil fuel emissions did not reach a peak until the 1970s. If we take snapshots of the combination of these curves in our benchmarks, the pattern that emerges is an N-shaped curve. An EKC for forest emissions seems to be a general feature of economic development in contrast to fossil fuel emissions, so in that respect Sweden is not exceptional.[36]

The result here, that Swedish long-term emissions of greenhouse gases roughly resemble an N-shaped curve, provides a less optimistic message than the EKC, but still shows that greenhouse gas emissions do not always, or simply, increase with economic development. The interplay between economies and their environment

[31] Kander, 'Baumol's Disease'.
[32] Stern, 'Rise and fall'.
[33] Holtz-Eakin and Selden, 'Stoking the fires?'.
[34] Kander and Lindmark, 'Energy consumption'.
[35] De Bruyn, van den Bergh, and Opschoor, 'Economic growth'; Focacci, 'Empirical evidence'.
[36] Bhattarail and Hammig, 'Institutions'.

is more complex and varies in different periods. So far, Sweden has managed to address some of its major agriculture-related emissions. The practice of draining wetlands has ceased and timber production is presently sustainable. In contrast, methane from domesticated animals and nitrogen from fertilizers continue to affect the atmosphere, but these sources are of less importance than forestry and wetlands. Those agricultural practices that changed in an environmentally-friendly direction did so because of economic incentives, and not primarily out of an idealistic concern for the environment. Despite the benign development of non-energy emissions in the agricultural sector, Sweden is still a large emitter of CO_2 from fossil fuels, although some improvements have also been carried out in that field since the 1970s. Sweden still has a long way to go before it is near to having a sustainable energy system, and economic incentives need to be strengthened, especially given the risks of the large costs involved in climate changes.

The conclusion here, that total emissions of greenhouse gases follow a very different pattern from that of emissions from fossil fuels alone, warrants further inquiries into non-fossil fuel emissions for more countries and regions. This may be of importance for solving some of the puzzles when it comes to global warming mentioned earlier in this paper; for instance, why some periods show more modest increases of temperature than expected. Having access to entire greenhouse gas accounts of the past is likely to modify our understanding of the interaction between emissions and global warming.

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APPENDIX

The bases for the estimates of annual emissions for the benchmark years 1800, 1870, 1930, and 2000 are accounted for in this appendix. The estimates of historical emissions from sources other than fossil fuels are by necessity somewhat rough, and should be taken for what they are: figures that give information of magnitude and development trends, rather than exact information, because they rely on a combination of data and assumptions. It is important to inform the reader about a general feature of these flows of gases. In some cases, it is possible to make punctiform estimates; for instance, to determine how many animals there were in 1800 and what emissions they caused, or how much fertilizer was put in the soil and the related emissions. In other cases, the emissions we deal with here are the result of long-term changes, such as changing timber volumes, changing carbon content of the mineral soils, and draining of peatland. For such long-term changes, the emissions for a specific benchmark year are the annual average over a certain period, described in this appendix.

a) Methane from domesticated animals

Animals partly digest their fodder through the action of anaerobic micro-organisms, and this gives rise to methane emissions. The bulk of this methane is emitted through breathing, and only 3 per cent comes from manure, which makes manure irrelevant for the estimate of the contribution from this source.[37]

Different species of animals typically emit varying amounts of methane; cattle are the worst emitters of methane, followed by horses, reindeer, sheep, and pigs, but even within one species, the amounts of methane vary according to the amount and composition of fodder. Since the composition of fodder is difficult to model in a historical study, this aspect is omitted here. An aspect that this study does take into account is that the size of animals has increased over time through breeding and better fodder. This means that, in general, the fodder intake has increased. The emission factors used here are thus average

[37] Murphy, *Växthusgasutsläpp från husdjur*, p. 25.

Appendix table 1. *Methane emissions from domesticated animals, kg per year and individual*

A	*B*	*C*	*D*	*E*
Year	*1800*	*1870*	*1930*	*2000*
Cow	33	45	50	55
Horse	10	11	16	18
Reindeer	15	15	15	15
Sheep	6	7	8	8
Pig	1.0	1.1	1.3	1.5

Source: E: Lantsheer, Svensson, and Rodhe, 'Sources and sinks'.

emission factors for different species to date as shown in appendix table 1, column E. The assumed values for the years 1800, 1870, and 1930 are found in columns B to D. These assumptions are based on the development of breeding that is accounted for by Kander.[38]

b) Nitrous oxide (N_2O) from fertilizers

Excessive use of nitrogen-rich fertilizers causes two kinds of environmental problems: nitrification of watercourses with resulting death of fish and transformation of nitrogen into nitrous oxide (N_2O), which acts as a greenhouse gas. Even though only a fraction of the nitrogen turns into N_2O, this may be of some importance, since this gas is very powerful as a greenhouse gas (and in addition destroys stratospheric ozone). Based on a study by Bouwman,[39] the IPCC makes the assumption that 1.25 per cent of all the nitrogen that is applied to land is transformed into N_2O. This figure does not take into account the large regional variations due to climate, irrigation, soil, and crops. For instance, a study of grasslands in Scotland during the 1990s showed that a specific amount of nitrogen could result in 20-fold variations of N_2O.[40] Kasimir-Klemedtsson concentrates on contemporary Swedish conditions and estimates that 0.8 per cent of the nitrogen in manure and 2.5 per cent of the nitrogen in synthetic fertilizers turn into N_2O.[41] These figures are used here.

The use of artificial fertilizers is better accounted for than the use of manure, which must be estimated for the first three benchmarks. Figures on the average manure production of different kinds of animals at the time of the First World War are given in appendix table 2. This table also provides information on the available nitrogen content of the manure. These figures are taken to be valid for the benchmark year 1930. For the benchmark years 1800 and 1870, some downward revision of these figures is carried out, to take account of the fact that animals grew bigger and worked harder during the nineteenth century, and hence ate more and produced more manure over time. These revisions are described in Kander,[42] and the results for manure are given in tables 5 and 6. For the year 2000, total amounts of nitrogen from fertilizers are provided in the statistics.

[38] Kander, *Economic growth*, pp. 42–6.
[39] Bouwman, 'Direct emissions'.
[40] Conen, Dobbie, and Smith, 'Predicting N_2O emissions'.
[41] Kasimir-Klemedtsson, *Metodik för skattning*, pp. 11–12.
[42] Kander, *Economic growth*, pp. 43–6.

Appendix table 2. *Manure from domestic animals in 1914*

Type of animal	*Number of animals*	*Manure per animal and year, tonnes*	*Share of nitrogen (%)*	*Annual production of nitrogen, tonnes*
Horses, more than 3 years old	524,895	4	0.6	12,600
Horses, less than 3 years old	118,287	2	0.6	1,400
Oxen	98,974	4	0.4	1,600
Bulls	48,270	8	0.4	1,500
Cows	1,871,939	8	0.4	60,000
Young cattle and calves	952,265	2.8	0.4	11,000
Pigs	1,233,660	1.2	0.65	10,000
Sheep and goats	1,251,654	0.25	0.8	2,500
Birds	5,873,500	0.01	1.7	1,000
Total				101,000

Source: Statens krigsberedskapskommission, *Betänkande*, tab. 22, p. 66.

Human excrement was taken care of in two ways: partly through industrial refinement where it was mixed with peat, and partly through direct collections and transportation out to agricultural fields. For the industrial refinement (poudrette), there is quite good information for 1914, but for the direct applications (latrine), only very rough estimates are available. The total amount of nitrogen from human excrement in 1914 was estimated to be 4,200 tons. In the absence of better information, these figures will be used here for the benchmarks 1800, 1870, and 1930, with the changes in population and food consumption per capita being taken into account.

c) Transformation of natural peatland into agricultural organic soils

In contrast to methane from animals and N_2O from fertilizers, peatland usage gives rise to complex changes in the flows of greenhouse gases. When peatland is drained, through the construction of ditches, to get more fields under cultivation, the flows of CO_2, CH_4, and N_2O change. Normally, under these circumstances, CH_4 emissions that naturally flow from peatland cease, while CO_2 and N_2O emissions increase. Consequently, it is the net effect of these changes that is crucial for assessing the importance of peatland transformation over time. Significant research on these effects has taken place lately, but some uncertainties still remain, typically on the long-term storage of carbon in natural peatland.

In order to calculate the effects of the draining of peatland, the emissions from natural peatland must be known. The natural emissions of methane differ for various kinds of peatland. There are large differences between nutrient-rich marshlands and bogs, and there are even some mires that do not emit any methane at all. Nutrient-rich marshlands are the largest emitters of methane and can release up to 30 grams of CH_4 per square metre per year.[43] Whether natural peatland to date sequesters or emits CO_2 is not a settled question. Historically, peatlands must have sequestered more carbon than they emitted, otherwise there would have been no peat formation. The figures normally used for carbon storage in natural peatland rely on average build-up over thousands of years. For Sweden, the estimates for average sequestration over 1,000 years is 60 grams of CO_2 per square metre, but according to recent measurements of sequestration to date, it may only be six grams per square metre.[44] The figure used in this study is 60 grams, since this study deals with past emissions.

The emissions from peatland drained for agriculture consist of both CO_2 and N_2O. There is a clear, positive correlation between the two kinds of emissions: when there are

[43] Granberg, *Environmental control*.
[44] Kasimir-Klemedtsson, Nilsson, Sundh, and Svensson, *Växthusgasflöden från myrar*, pp. 18–26.

high emissions of CO_2, there are also high emissions of N_2O. The total amounts of greenhouse gases differ with crops. Black, bare fields release more CO_2 and N_2O than green, covered land. Kasimir-Klemedtsson has provided information on emissions from former peatlands with specific crops, which forms the basis for the estimates here.[45]

For historical modelling of this source, it is necessary to make some simplifying assumptions about the kind of peatland that was drained and what was grown there. Bogs, as the intermediate stage between mires and marshland, are taken to be the kind of peatland that was drained. We know that initially the drained peatlands were used for grain, but later these fields were used for fodder grass instead, and this change is included in the modelling.

It is also necessary to define the boundaries of our system, since peatlands make up a large share of total Swedish land. The choice made here is to limit the examination of changes in emissions to the peatland that was actually drained at some time during our 200-year period of investigation; in other words, peatland of around 700,000 hectares.

According to agricultural statistics, the area under cultivation was 0.85 million hectares in 1800 and 2.4 million hectares in 1870. Hannerberg found these figures unrealistic, and estimated that the total cultivated area was 1.5 million hectares in 1800 and 3.0 million hectares in 1865.[46] Holgersson reached a similar figure for 1865.[47] This study assumes that 1.5 million hectares were put under cultivation between 1800 and 1870. There is no direct information on how much of this newly cultivated land consisted of peatland, but we know that draining-out projects had started in various places at this time. Many new projects were initiated, especially after 1840, when governmental subsidies were provided. Up until 1859, there were 237 subsidized projects, and thereafter the frenzy continued. The area drained in 1859 amounted to 90,000 hectares.[48] In this study, it is assumed that 150,000 hectares of peatland were drained between 1800 and 1870, which in turn means that 1.35 million hectares of dry meadows were cultivated. At this time, it was rather common to burn the peatlands before cultivation, which led to even higher emissions of CO_2.[49]

The size of the peatland area that was drained and cultivated between 1870 and 1930 should have been around 550,000 hectares (from 150,000 to 700,000), since investigations have shown that in 1920 the total area was around 650,000, and we know that feverish activities continued throughout the 1920s and subsided after 1930.[50] The total land under cultivation was 3.7 million hectares in 1930, which means a total increase of 0.7 million hectares since 1870, and we can conclude that this new land consisted mainly of previous peatland. Initially, grain was grown on the reclaimed peatland, but there was a switch to more grass, and to a lesser extent, potatoes, during the first decades of the twentieth century. This should, in principle, have reduced the emissions of greenhouse gases from the reclaimed peatland.

Emissions of CO_2 equivalents per cubic metre from natural peatlands, such as natural mires, bogs, and marshland, and from cultivated peatlands covered with grain and grass, are found in appendix table 3.

[45] Ibid., p. 41.
[46] Hannerberg, *Svenskt agrarsamhälle*, pp. 27–31.
[47] Holgersson, 'Cultivated land'.
[48] Gadd, 'Den agrara revolutionen', pp. 312–13.
[49] Juhlin Dannfelt, *Handbok*, pp. 121–2.
[50] Runefelt, 'Svensk mossodling'.

Appendix table 3. *Emissions from natural peatlands and cultivated peatlands, in CO_2 equivalents, kg per m² and year*

	Peatland cultivated with grain	*Peatland cultivated with grass fodder*	*Natural mires*	*Natural marshlands*	*Natural bogs*
N_2O	0.3	0.1	0	0	0
CO_2	0.9	0.8	–0.06	–0.05	–0.08
CH_4	0	0	0	0.3–0.8	0–0.2
Total	1.2	0.8	–0.06	0.25–0.75	–0.08–0.1

Sources: Kasimir-Klemedtsson et al., *Växthusgasflöden från myrar*, fig. 18b and tab. on p. 7.

d) Changed carbon content of the mineral agricultural soil

Besides the draining and cultivation of peatland, which has caused net emissions of greenhouse gases, other changes in agriculture have affected the carbon content of the soil. Not just organic soils (previous peatlands), but also mineral soils have changed their carbon content.

We know that a small net increase of carbon has taken place in these soils during the last couple of decades, roughly 0.25 million tons per year, as a consequence of large-scale agricultural production. What took place earlier is uncertain, but there are two changes in agricultural practices that indicate a former reduction.

Firstly, large areas of grassland were being put under the plough and cultivated during the nineteenth and early-twentieth centuries. This meant that the carbon content of these soils was reduced. Studies have shown a drastic reduction of carbon in grasslands when they were cultivated, often by as much as 20–5 per cent, which implies that the carbon content can be reduced by 10–15 tonnes per hectare a year until a new balance is reached.[51] This figure is used in this study to capture the effect of the cultivation of grasslands.

Secondly, the technique for soil cultivation changed over time. The transition from wooden tools to more advanced iron ones enabled a deeper cultivation of the soil. Deeper cultivation meant more access to oxygen, and thus a faster breaking down of the organic material in the soil. Kritz estimates that the cultivation depth has doubled from 10 centimetres in early agricultural times to 20 centimetres today.[52] From the 1950s onwards, the excessive use of synthetic fertilizers and pesticides meant that the soil was no longer cultivated as deeply as it used to be. This factor has contributed to the increase of carbon in these soils during recent decades. The assumption made in this study for quantifying the impact of changed cultivation is that the reduction was in total 10 tonnes of carbon per cultivated hectare between 1800 and 1930. This figure is chosen since studies show that it is possible to increase the soil content of 5–15 tonnes per hectare by reducing the cultivation of land and increasing the amount of grass crops.[53] No change is assumed for the period between 1930 and 2000.

e) Forest-related emissions

Forests can either act as a sink for, or as a source of CO_2. There is a complex process of concomitant release and absorption of CO_2 in a forest. What needs to be accounted for in the context of global warming is only the net-exchange with the atmosphere, which is

[51] Paustian, Collins, and Paul, 'Management controls'.
[52] Kritz, 'Jordbearbetning', p. 139.
[53] Lilliesköld and Nilsson, *Kol i marken*, p. 44.

dependent on whether the timber stock decreases or increases. When the quantity of trees and other vegetation increase, normally the soil carbon increases too, and then the forest works as a net-sink for atmospheric CO_2. When the number of trees decreases, the forest instead works as a source of CO_2.

The present Swedish forest area is around 23 million hectares, which sequesters 5 million tonnes of carbon per year (counted as an average over the last 30–50 years), despite the fact that cultivation of forest soil releases 1–2 million tonnes of carbon annually.[54]

The amount of carbon sequestered or released from forest soil depends on the growth of trees and other vegetation. It therefore seems reasonable to model the development backwards in relation to how the standing timber volumes have changed. During the period 1950–95, trees increased by 4.4 million tonnes of carbon per year, according to the National Forest Inventory. This is roughly the same amount that was sequestered in the soil during the same period. Lilliesköld and Nilsson estimate that the total vegetation in the forest (trees and other material) has sequestered around 8 million tonnes annually during the last 30–50 years.[55] These figures underpin the modelling here, so that every change in timber volume is followed by an equally large change in other vegetation (including root systems) and an equally large change in the carbon content of forest soil.

The changes in timber volumes since the first Swedish Forest Inventory in the 1920s are well known; however, estimates are necessary for earlier years.[56] The estimates used here are from Kander,[57] and the results are fairly similar to those of Lindmark.[58] Both estimates rely to a large extent on Linder and Östlund for Norrland from 1870–1990.[59] The basic feature of this estimated timber development is that it resembles a U-curve, with approximately the same amount of standing timber today as in 1800. One solid cubic metre of timber is equivalent to 1.036 tonnes of CO_2.[60] The turning point, when deforestation turned into reforestation, occurred in the early-twentieth century.

Not just agricultural land, but also the forest, contains large areas of peatland that have been drained partly. Presently, around 10 per cent (or 2 million hectares) of the forestland is drained. This land emits 15 million tonnes of CO_2 per year, but would only have emitted 5 million tonnes if it had not been drained.[61] Consequently, it seems justifiable to assume that draining increases the emissions from such land three-fold. In line with the treatment of peatland that was transformed into agricultural land in this analysis, only the changes for the area that was drained at some time within the period 1800–2000 are assessed here: 2 million hectares.

No draining of forestland took place before 1870. At the turn of the century, the draining of forestland took off, and reached its absolute peak around 1930–1, with 2,300 kilometres of ditches dug on state-owned land alone.[62]

[54] Ibid., p. 7. To some degree the present absorption of CO_2 in forests is actually due to the large combustion of fossil fuels. When these fuels are burnt, they fertilize the ground with nitrogen, and this improves forest growth. We thus find here an example of interesting dynamics from a greenhouse gas perspective: on the one hand, fossil fuels increase the emissions of CO_2 into the atmosphere, but on the other hand, they fertilize the forest, which grows faster and partly offsets these emissions. However, in the long run this dampening effect will not continue, since the forest soil will become too acidic and release aluminium, which leads to tree damage and eventually tree death. However, this complex interaction between fossil fuels and forest growth is not taken into account in the accounting exercise of this paper.

[55] Lilliesköld and Nilsson, *Kol i marken*, p. 7.

[56] Swedish Forest Statistics, *National forest inventories*.

[57] Kander, *Economic growth*, pp. 161–5.

[58] Lindmark, *National accounts*, pp. 102–16.

[59] Linder and Östlund, *Förändringar*.

[60] Hultkranz, 'National account'.

[61] von Arnold, Weslien, and Klemedtsson, *Vad betyder sumpskogar?*

[62] Lindberg, 'Skogsdikning', p. 487.

The amount of forestland that was drained between 1870 and 1930 has been assessed here by using available statistics on the annual increase of ditches on the state-owned land. For private land, there are no similar statistics, so its draining has been assumed to follow the draining of state land proportionally. Lindberg states that at least 120,000 kilometres of ditches were dug on private land between 1905 and 1958.[63] In the same period, 38,000 kilometres of ditches were dug on state land, which means that the ration of state land to private land was 1 : 3. Consequently, the total number of kilometres of ditches on state land has been multiplied by a factor of four to estimate the total length of new ditches. Using that method, we find that 133,000 kilometres of ditches were dug in total between 1870 and 1930. In order to transform this length of ditches into drained hectares, the figure of eight hectares per kilometre has been used, based on some scattered information in the state statistics (ranging between eight and 11) and Lindberg's estimate of four hectares per kilometre in 1950. This means that 1.1 million forest hectares were drained between 1870 and 1930, which corresponds to an increase of 5.5 million tonnes of CO_2 from this land. Between 1930 and 2000, the draining of forestland continued, but declined during the 1990s, and ceased completely in 1997, when it was prohibited by law.[64]

[63] Ibid., p. 488.
[64] Gustafsson, *Jordhunger*, pp. 47–8.

