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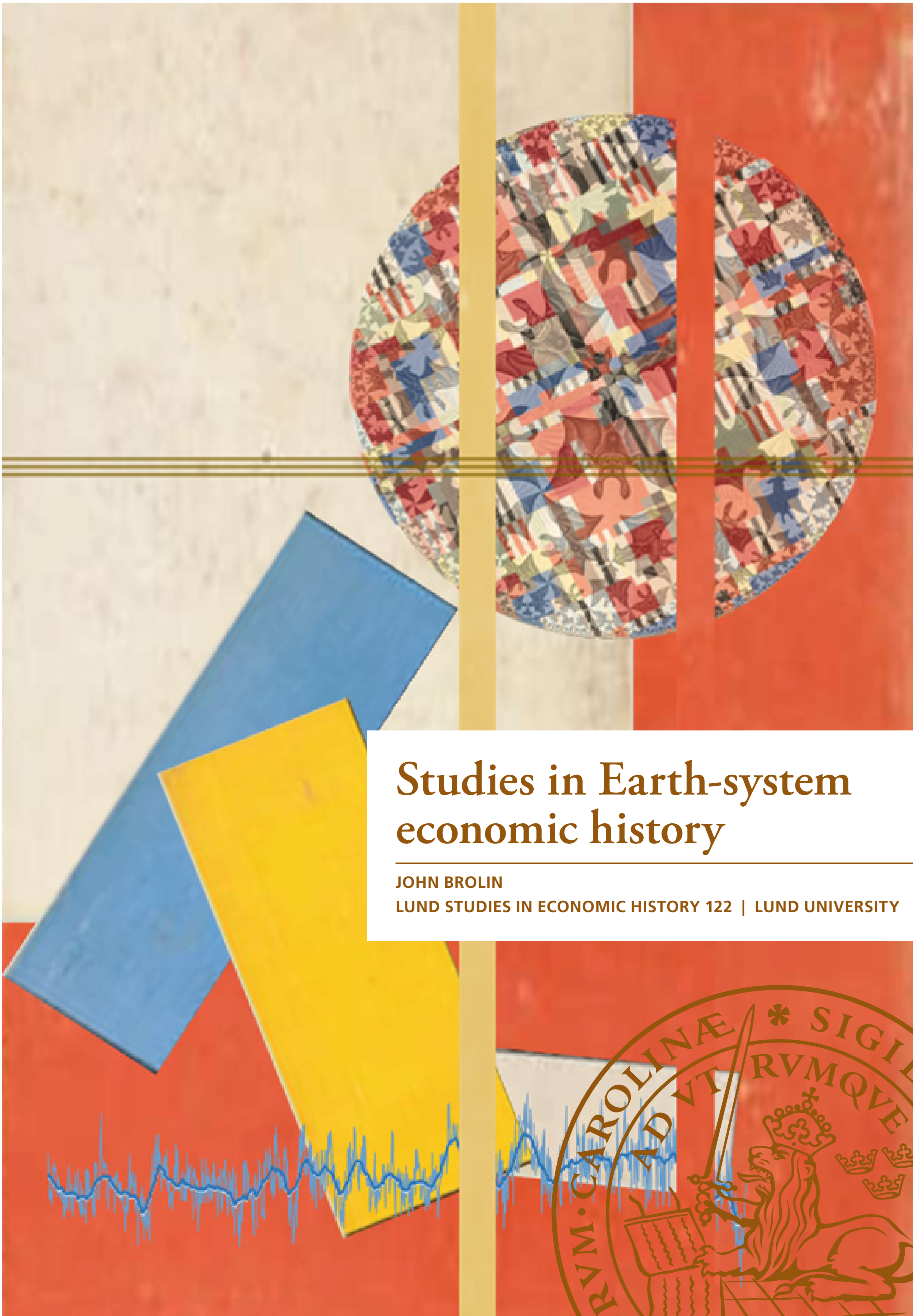

Studies in Earth-system economic history

JOHN BROLIN

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Studies in Earth-system economic history

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John Brolin

LUND UNIVERSITY

DOCTORAL DISSERTATION

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Abstract:

The urgency of global climate change and other geological-scale anthropogenic impacts also suggests new perspectives on economic history. This thesis argues for the inclusion into economic history of more Earth-system centred feedbacks, both in terms of environmental and climatic consequences and environmental and climatic causes, where consequences in one realm may again become causal in the other. More specifically this cause-consequence interplay between the Earth-system and the economic system is traced through the transition from an organic to a mineral energy economy, first in the original domestic energy transition in London and England, then for Western Europe and the world in the market-expanding globalisation phases of the first and second industrial revolutions. Since the original driver for adopting coal was domestic heating, which would have been profoundly impacted by the cooling climate of the Little Ice Age, the thesis develops methods to quantify both climate (temperature, precipitation) effects on potential wood supply and of changing temperatures on fuel requirements in England and the London region over the 1200–1800 period. The results reveal not only this climate effect, but also the shortcomings of fuel supply even when including coal, suggesting potential links between climate and both the coal and textile industries. The early-modern shortcomings of an organic economy were tentatively solved by geographical expansion, including into oceanic fisheries. The thesis also creates methods to estimate the land alleviation and ocean appropriation of seafood consumption in Europe, 1500–1800. The alleviation is compared favourably against coal for Europe as a whole until the mid-18th century, but unfavourably with the alleviation from either coal of yield increases in Western England over the same period. Finally, having identified decades of empirical study into trade-embodied environmental inputs and impacts over the past two centuries, the thesis finds converging patterns between those linked to the organic energy economy, best explained by comparative advantage according to resource endowments, and those linked to the mineral energy economy best explained by unequal exchange according to wealth and/or environmental efficiency. The Kappa and a postscript place the individual papers within both Earth-system and economic historical context, and proposes new avenues for research.

Key words: energy transition, Little Ice Age, early modern, England, climate history, fisheries, ghost acreage, global trade, environmental footprint, Anthropocene, Great Divergence, Great Transformation, Great Acceleration

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To Ulf Brolin, 1937–2022,
for whom the grave was always half full

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Malmö, 20 October 2025

1 Introduction

1.1 Aim and motivation

1.1.1 Aim

Quantification has been a crucial tool for economic history since the cliometric revolution. This is true also for energy and environmental economic history as conducted in Sweden, and for environmental accounting in general at many other places in the world. The aim of this thesis is to broaden the tradition of quantitative environmental economic history by introducing new methods and kinds of quantification for the preindustrial period, for example, for ocean resources and climate-societal interaction, but also widening the spectrum of environmental indicators studied overall, making it more systematic and comprehensive enough to qualify as 'Earth-system economic history'. Although relying on plenty of quantitative materials and methods, it is to be hoped that this thesis will nevertheless be found readable in parts.

1.1.2 Societal relevance

Every age needs to interpret its past in ways that put their ultimate concerns into relevant perspective. Concerns over human impact on Earth system processes and global climate have recently climaxed in the proposition that the fossil fuelled industrial revolution inaugurated a new, human-dominated geological epoch, the Anthropocene (Crutzen and Stoermer 2000). Anthropogenic climate change, a looming sixth mass extinction following a 100–1,000-fold speedup of extinction rates (Cowie et al 2022), the recent finding that a rising share of 5% by weight of the middle-aged human brain now consists of nanoplastics (Nihart et al 2025), and a host of other disruptions of fundamental global ecological and geological processes suggesting a transgression of all but a few of the proposed planetary boundaries (Richardson et al 2023), all indicate that something is amiss. In mythological language, these changes would qualify as potential end-of-the-world crises or catastrophes, which may explain the popular success of the 'Anthropocene' and the proliferation of offspring denominations.[1] Despite the rejection of an Anthropocene epoch by the Subcommission on Quaternary Stratigraphy (SQS) of the International Union of Geological Sciences (IUGS) in March 2024, the geological scale of the ongoing transformation was never in doubt and can easily be demonstrated (e.g., Figure P1 in the Postscript).

While there is much desperation and talk about these crises, climate in particular, synthesising interpretations that can put them in long-term perspective and give them meaning are lagging. Lacking long-term, and preferably global, perspectives—a chronological provincialism or presentism complementing the geographical one—tends to make the present unnavigable, responses reactive, possibility horizons narrow, and futures bleak. Scholars have a duty to contribute to such syntheses but also to abide by the Humpty-Dumptian analytical practice of science where large problems are solved by breaking them down into smaller pieces before putting them back together again. This thesis is motivated by the urgency of the problem, curiosity about their causes, and a wish to bring economic history to bear on—and vice versa, to promote the engagement of economic history with—a fuller spectrum of natural or earth-system processes.

1.1.3 Scientific relevance

The present thesis argues for the inclusion into economic history of more Earth-system centred feedbacks, both in terms of environmental and climatic consequences and environmental and climatic causes, where consequences in one realm may again become causal in the other. More specifically this cause-consequence interplay between the Earth-system and the economic system is traced through the transition from an organic to a mineral energy economy.

In the context of the industrial revolution or modern/sustained economic growth, Wrigley (2010: 55) has argued that 'attempts to establish a hierarchy of causation are less fruitful than examination of the nature of the feedback between the components of change.' For Wrigley, economic growth in organic economies is held in check primarily by the negative feedback of a fixed supply of land, the solar energy falling on that land, and the portion captured through photosynthesis, whereas the rising mineral energy economy transforms the growth process to one in which positive feedback prevails.

Current debates on the anthropocene and planetary boundaries indicate that negative feedbacks are again coming into play through the human appropriation of net primary productivity, infiltration of biomes, speedup of biogeochemichal cycles, and climate change. As indicated by the shift from the energy crisis of the 1970s to the climate crisis of the present, problems spring not from the limited supply of

[1] As of 2020 there were at least 91 alternative terms—the one uglier than the other (Chwałczyk 2020). The recent rejection of an 'Anthropocene' epoch notwithstanding, even among geologists it still survives as an 'anthropocene' event.

fossil energy but rather from it being not limited enough. Negative feedbacks instead return via the fossil economy's expansion of the organic economy to the ends of the earth, its new products and chemical entities, and the effluents from land use and fossil fuel combustion, and then only after passing via extra-economic Earth-system processes.

However, the argument for widening the sphere of feedbacks to include Earth-system processes applies not only for such environmental consequences but also to the origins of the industrial revolution, or rather, and more specifically, the preindustrial transition to coal. The fossil energy economy will thus be embedded at both the beginning and the end within long-term climate trends. In this sense, the original working title of the thesis is still apt: 'The causes and consequences of the Little Ice Age energy transition.' A concluding postscript will present a vision of what this widening of feedbacks to include Earth-system processes could mean over the very long run, and for the evolution of both fossil and organic economies.

This thesis focuses on environmental limits and potential climatic causes of the original English transition from an organic to a mineral energy economy, and how, as the world followed this transition, a broad spectrum of environmental inputs and consequences that can be traced to either the organic or mineral energy economy, have been redistributed and appropriated through trade.

The transition from an organic to a mineral economy has been widely explored before in economic history, the focus usually being on economic, technological, institutional, or social drivers of the (British, capital-letter) Industrial Revolution. However, the transition in England preceded the industrial revolutions. Since it ultimately draws all its resources from photosynthetic inputs, a preindustrial organic energy economy would be much more exposed to environmental limits, and to both long- and short-term variations in climate. This potential climate driver has not been much explored and never quantified. Filling this a research gap is a major scientific motivation for the present thesis.

The role of coal in alleviating the land and environmental limits of an organic economy, and of trade in appropriating resources from elsewhere have also been much debated, notably in the Great Divergence debate between E.A. Wrigley, Kenneth Pomeranz, and others. However, ambitious quantification (in terms of 'ghost acres') is only available for the nineteenth century. For the period before 1800, estimates are fragmental even for trade, while potential land alleviation from seafood are wholly absent. To start filling this gap is another motivation of this thesis.

The European and world transition to a mineral energy economy can be dated to about 1850 and 1900 respectively, but its character was very different from the original English. This transition was industrial and still dominated by UK production and exports of coal. Thus, trade and globalisation were both consequences of, and main vehicles for, the world transition to coal in the nineteenth century, the Great Transformation, and to oil in the twentieth, the Great Acceleration. Exploring these transitions from the perspective of conflicting trade theories: were trade flows determined by comparative advantage according to resource endowments, or by unequal exchange according to wealth and power? Were traded goods and environmental inputs and impacts originating in the organic energy economy of continued or perhaps even greater importance, even as the mineral energy transition transformed the world? Even if trade flows could be explained by endowments, who in the end consumed the final goods, thereby appropriating the natural resources and environmental services that they embodied? Does trade aggravate or help to alleviate environmental problems, or does it merely shuffle them around. These are scientific questions also motivating this thesis, as is the wish to expand the surface areas of contact between the economic and Earth systems.

1.2 Research question

The overarching research question of this thesis is: What was the role of natural resource appropriation, especially in relation to Earth-system processes, in the transition from an organic to a mineral energy economy? In the individual papers this question is specified into the following: Paper 4, looks at the original transition in England and London, asking, 'How was potential supply of wood fuels and latent demand for fuel affected by climate cooling, and how much did coal contribute to filling potential shortages?' Paper 3, looks at the limits of an organic energy economy and asks, 'How much did West European seafood consumption contribute to the alleviation of land-based resource limits, how much did this alleviation correspond to in appropriated ocean resources, and how much was it compared to other means of alleviation such as coal or agricultural yield increases?' Paper 2 looks at the European or world transition to coal—the Great Transformation—and Paper 1 at the world transition to oil—the Great Acceleration—asking, 'What role did trade play in redistribution and appropriation of natural resources and environmental services?'

This thesis is thus organised around questions relating to the transition from an organic to a mineral energy economy, first in the preindustrial transition in London and England, then in comparison with the role of fisheries in alleviating land constraints in organic-economy Atlantic Europe, and finally in two waves of globalisation accompanying market-widening phases of the first and second industrial revolutions. The organisation of the papers follows the advice never to try beginning at the beginning but instead to progress backward, letting the problems lead you back (Fairbank 1969: ix), or in other words to proceed from the known (the present and its problems) to the unknown (their root causes in the past). Thus, the papers will appear in reverse chronological order in terms of their subject matter, starting with the most topical and familiar relating to the ongoing environmental crises in Paper 1, and working its way back in time with each paper to the early modern and medieval period in Paper 4. The concluding Postscript goes even further, placing the papers within the timeframe and context of Earth-system history.

Papers 1 and 2 are both concerned with how environmental inputs and impacts have been redistributed by trade during globalising phases of industrial revolutions (the 2nd and the 1st respectively), particularly if there are differences between the flows depending on whether they originate in the organic or the mineral energy economy, if they can be related to the environmental endowments of countries, their level of income, or technological development. Since the papers are attempts at synthesis, they accordingly first pose the general research question: What is known from quantitative estimates about environmental inputs and impacts (=environmental factors) embodied in trade during these phases, either globally (Paper 1) or nationally (Paper 2) over the long run? In summarising and organising the empirical estimates (rather than the interpretations possibly given by the original authors), they move on to the questions: 'Do differences between flows depend on whether they originate in the organic or the mineral energy economy?' and 'Do they depend on the environmental endowments of countries, their level of income, or technological development?'

The answers to these questions are used to illuminate questions on comparative advantage or ecologically unequal exchange often posed by the original authors, e.g.: 'To what extent have the rich and developed, or perhaps simply populous, countries protected themselves from the environmental consequences of their actions through environmental load displacement, i.e., by externalising/outsourcing environmental impacts to poor, less developed, or simply peripheral?' Another question raised by the papers are: 'Do the answers differ between the first and second industrial revolutions or waves of globalisation?'

Paper 1 approaches these questions for global studies covering the period after 1950 in the following terms: Are trade flows primarily *equalising* – unburdening environmental impacts from densely populated regions to land- and resource-rich regions in line with conventional economic theories of comparative advantage? Are they *unequalising*—siphoning resources and unburdening affluent/developed countries of their impact to poor and less developed countries through mechanisms of unequal exchange? Or yet again, are flows rather the result of some countries being more environmentally efficient than others in producing their exports, thereby only superficially unburdening their impact? Do conclusions differ between methods? Do they differ between environmental factors, and depending on whether they originate in the organic or the mineral economy?

Paper 2 poses these questions for long-term national studies covering the period *c.*1800–1950 in the following terms: Do net transfers of environmental factors represent an unequal exchange following a logic of divergence between rich and poor countries; do they reflect comparative advantage (or rather environmental factor endowments) following a logic of specialisation—not only between food and raw materials vs. manufactures but even more between some kinds of food and raw materials vs other kinds of food and raw materials—or, finally, are net flows simply not quantitatively important enough either way? Do conclusions differ depending on whether environmental factors relate to the organic or the mineral energy economy?

Papers 3 and 4 move on to the early modern period and beyond, and deal specifically with problems concerning the limitations of an organic energy economy facing resurging populations and a cooling climate. Paper 3 deals with how these limitations relate to the expansion of the resource base in Atlantic Europe through ocean fisheries, and Paper 4 explicitly with how they relate to the adoption of coal in early modern England and London, i.e., the mineral energy transition.

The principal research question of Paper 3 is: 'What contribution did the ocean fisheries make to the alleviation of Atlantic Europe's land constraints in 1500–1800?' Given that alleviation refers to the land of the fish consumers, an analogue but subsidiary question is also posed: 'What does this alleviation represent in terms of ocean appropriation?'(If alleviation refers to the importance of the fisheries for the consuming economies, appropriation instead refers to what this consumption means in areal terms of actual ocean net primary production). A final research question is: 'How does the land alleviation from fisheries compare with other kinds of land alleviation, such as that from coal or from higher agricultural yields?' It suggests answers these questions by various quantitative estimates of 'ghost acreage'.

Paper 4 focuses on climate (temperature, precipitation) as a potential cause of the mineral energy transition from wood fuels to coal, more specifically how climate affects potential wood fuel supply (=availability) and latent demand (=requirements). It examines the preindustrial transition to coal, driven by domestic heating, in the London region and England over the medieval and early modern period in order to answer the question: 'How much did climate change (precipitation and temperature) between the (high-)Medieval Warm Period and the early-modern Little Ice Age—more specifically from 1300 or 1500 to 1600–1700—contribute to the fossil energy transition in London and England?' It answers by developing methods to estimate potential wood fuel supply and latent fuel demand in England and the London region in 1200–1800 CE.

1.3 Limitations in time period, geographical scope, variables, and analytical agenda

The period covered in this thesis extends over some 800 years, relatively evenly distributed over time. However, the geographical coverage decreases back in time from the global to the local. In Paper 1, the geographical and chronological scope is global after 1950, although with some excursions further back in time to 1910, 1800, and beyond. Paper 2 is temporally limited to c. 1800–1950, although, again, with some excursions into earlier and later periods; the geographical scope is mostly on European and a few other developed countries, although with some global ambitions. Paper 3 covers 1500–1800 and is West (or rather 'Atlantic') European and North Atlantic (ocean) in scope. Paper 4 covers the period from 1200–1800, focusing attention on England and the London region in 1300 and 1600.

The environmental indicators or factors studied also become fewer with distance from the present. Thus, Paper 1 tries to encompass any possible environmental indicator, classified under eight headings. In Paper 2 only four remain (land, virtual water, materials and energy). Paper 3 could be said to focus solely on 'land' equivalents, although also introducing oceanic acreage. In Paper 4, the main variable is wood fuels (or wood-fuel equivalents), complemented with coal, although deriving much information also from climate reconstructions.

While an underlying frame of reference, the focus of the present thesis is not so much on the technological dimensions of industrial revolutions as is common within the Schumpeterian tradition, although something is said especially on heating technologies underpinning the domestic energy revolution. Instead, I have has tried to extend this tradition towards a more comprehensive Earth-system perspective.

The scant attention devoted to political, military, or ideological factors is clearly a limitation of the present thesis, shared by the Schumpeterian tradition of interpreting energy transitions. Economic historians may disagree with ranking politics and ideology higher than economics and technology (Fressoz 2024), but the political economic dimensions of energy transitions are clearly important (Bergquist and Lindmark 2023). This is only partly excused by the economic historical assumption, or historical materialist prejudice, that the economic foundations are ultimately what matters also for politics—the relation should nevertheless be expressed. Future work should try to incorporate more political economy or geopolitical perspectives. The Marxist tradition probably has more to offer here, or the 'realist' tradition on great powers in international relations. The overlap between revolutionary shifts in energy, industry, and globalisation on the one hand, and shifts in Great Power status on the other—the UK with coal, the US (and USSR) with oil, and China's growing prominence in electrification—clearly suggests important linkages (also for understanding environmental issues) that have been more emphasised in other research traditions and should be further explored in the future. The US and China Great Power struggle is already portrayed as a battle between a fossilising petrostate and an emerging electrostate, based on China's dominance in solar technology, lithium and sodium batteries, electric vehicles, but also rising leadership in artificial intelligence, rare-earth metal processing, etc.

1.4 Mindmap of Papers within the overall conceptual framework

The present thesis is the fruit of my engagement with environmental accounting and with energy history as practiced at the Lund Department of Economic History. The conceptual framework is one of multiple industrial revolutions each consisting of one or more development blocks of complementary technologies or energy sources. These in turn develop through phases of market suction and market widening—where the latter is linked in Figure 1 below to the respective wave of globalisation and environmental impact.

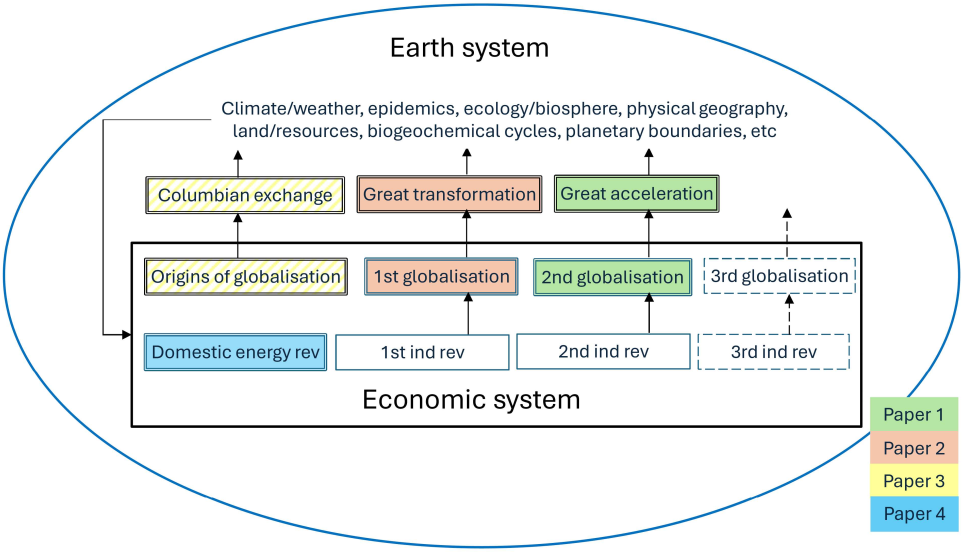

Figure 1. Mind map of thesis
This mind map places the economic system within the Earth-system, and articles in relation to industrial revolutions respective market widening phase of globalisation, and phase of environmental impact. Arrows indicate causal relation. Note the absence of causal link from the domestic energy revolution to the origins of globalisation; here, causality comes rather from the common limits of an organic energy economy (but possibly also from the Columbian Exchange to the domestic energy revolution via its effects on CO_2 uptake and climate cooling). Colour coding indicates which paper treats which topic or phase.

Here, as in much of environmental or ecological economics, the economic system (marked by a rectangle) is placed within an ecological or Earth system (marked by an oval). Each industrial revolution, especially in the globalising or market widening phase, has extensive environmental consequences (indicated by arrows pointing out of the economic system). Earth-system scholars, including historians such as John McNeill, refer to those accompanying the (first) Industrial Revolution as the Great Transformation (Kates et al 1990; without reference to Polanyi 1944, with 'transformed' instead presented as an escalation from 'modified' in Marsh 1965

[1864] and ‘changed’ in Thomas 1956). The rapid rise in environmental impacts after World War II accompanying the market-widening of the second industrial revolution are called the Great Acceleration (Hibbard et al 2007, describing findings in Steffen et al 2004; also, McNeill and Engelke 2014: 213f, and Steffen et al 2015b; for the ‘50s syndrome’, cf. Pfister 1995). These globalising environmental phases have been afforded one article each (Papers 2 and 1 respectively).

Preceding the industrial revolutions and globalisations, Figure 1 also includes the origins of globalisation (de Zwart and van Zanden 2018; cf. Kuznets 1966, on the ‘epochal innovation’ of early-modern growth) and a ‘domestic energy revolution’, examined in papers 3 and 4 respectively. The links between the parts and the details are more obscure for the early modern period, leaving them open for elaboration. Overall drivers would be rising populations in organic economies facing limited land availability, but also climate cooling affecting yields. The most evident environmental consequence of the origins of globalisation concerned the ‘Columbian Exchange’ (Crosby 1972) which began a global homogenisation of ecologies, diseases, and agricultural systems, in addition to expanding the resource base. Here, Paper 3 concerns the contribution of ocean fisheries in alleviating European land constraints. If the domestic energy revolution could be affected by deteriorating climate, which is the topic of Paper 4, it can hardly be linked causally to the Columbian exchange (thus, no arrow). However, there is a possible feedback link from the Columbian Exchange to the domestic energy transition. Thus, the depopulation of the Americas, following the transfer of infectious diseases, also entailed reforestation and therefore contributed to the fall in CO_2 and temperatures over the late 16th and 17th centuries. Both the energy transition to coal and the overseas expansion of fisheries and the Columbian Exchange could be considered ways of coping with declining land availability (which can of course be affected by socio-economic, distributional conflicts) and deteriorating climate (which can of course affect the economy even without anthropogenic influences).

1.5 List of papers

Paper 1 (with Astrid Kander). ‘Global trade in the Anthropocene: A review of trends and direction of environmental factor flows during the Great Acceleration’, *The Anthropocene Review* (2022), Vol. 9(1): 71–110.

Paper 2 (with Astrid Kander). ‘Environmental factors in trade during the great transformation: advancing the geographical coverage before 1950’, *Journal of Global History* (2020), 15: 2, pp. 245–267.

Paper 3. ‘Plenty more fish in the sea? Alleviating European land constraints though ocean fisheries, 1500–1800’; unpublished manuscript.

Paper 4. ‘The Little Ice Age energy transition, or: “Did climate cause fossil fuels?”’; unpublished manuscript.

1.6 Contribution to (environmental) economic history

With respect to the energy and environmental economic history of the transition from an organic to a mineral economy, the main contribution of the articles in this thesis is the attempted integration of humans and their economies as integral parts of earth-system processes. These can be divided into a modern/recent part emphasising human transformation of Earth-system processes and links to globalising trade, and a medieval/early-modern part emphasising the Earth-system transformation of socio-economic processes, such as societal consequences of climate cooling on limited organic energy resources. Thus, the emphasis of Papers 1 and 2, covering recent periods, is more on the consequences of human actions, Paper 3 and 4 more on limits and non-human agency.

One kind of contribution consists in synthesising a large amount of information. One of the key contributions to understanding recent and modern economic history concerns linking industrial revolutions to the human transformation of Earth-system processes, specifically how environmental inputs and impacts are redistributed though globalising trade. This has revealed parallels between different kinds of inputs and impacts, depending on whether they can be attributed to the organic or the mineral energy economies. It also showed similarities and some shortcomings of interpretation due to biased or too narrow focus. This concerns also various interpretations relating the Great Divergence to the overcoming of resource constraints through land-intensive imports ('ghost acres') in the nineteenth century while failing to look at exports. Papers 1 and 2 contribute a fuller and more consistent Earth-system framework for environmental indicators as applied to trade. They systematise contributions examining the role of trade in redistributing (global) inputs from and impacts on earth-system processes. In identifying temporal limits of global studies and geographical limits of long-term national studies, they also help to prepare the way for longer-term global studies.

For the medieval/early modern periods, a greater focus has been on developing new methods or tools of interpretation. Thus, Paper 3 addresses the question of overcoming land constraints by expanding the resource base by constructing novel ways to estimate, for the first time in historical studies, the ghost-acre contribution (and ocean appropriation) of seafood consumption, i.e., the fish acreage. This is related quantitatively to the alleviation from coal (coal acreage) or higher yields (yield acreage) in England. (The yield acreage for England may be another first, although Wrigley has one for London). In addition, the difference between estimates using alleviation or appropriation is drawn on to clarify different approaches to estimating trade acreage in the Great Divergence debate, using yield factors from either the importing (alleviation) or the exporting (appropriation) countries, and suggesting that the difference can be used to gauge overall gains or losses from trade.

Paper 4 is the most novel, retrieving the preindustrial coal transition in England and London as a topic worthy of study in its own right, identifying the main contenders of interpretation and the main problems within each, proposing how they can be climatically extended and how the climate argument can be tested, constructing methods to quantify potential wood supply and fuel requirements, including the share dependent on climate (both precipitation and temperature), identifying the best climate data and translating it into the right format (including perhaps the first historical estimate of heating degree days), making the quantitative estimate, and integrating the results into a more coherent story of the fossil energy transition from the fourteenth to the eighteenth century. (The many steps in this argument also help explain the great number of Appendices). Paper 4 is also where Earth-system processes, in the form of climate change, most clearly emerge as a 'protagonist' (Campbell 2010), a causal agent affecting human societies rather than the reverse.

2 Economic historical context

This section will place the articles both in the context of the main narrative of economic historiography and in the context of the drawn-out transition from an organic to a mineral energy economy, and what this could mean in terms of energy and material throughput. Section 2.1 will first outline a genealogy of the mainstream 'Growth & Development' paradigm of economic historiography and of its main ecologist, degrowth, and other critics. In section 2.2, the economic historical context of the transition from an organic to a mineral energy economy will be briefly summarised and related to the Papers of the thesis. This starts with the transition's English origins in domestic heating, where climate is proposed as causal agent, and moves on to the two globalisation waves of its fulfilment. The Great Transition in Western Europe and the world coincided with vastly expanded UK coal consumption and exports during the first industrial revolution's expansionary globalising phase in the nineteenth and early twentieth century. It culminates with the Great Acceleration of the mineral energy economy after 1950, and the simultaneous impacts related to the organic economy. The final section 2.3 then explains how the organic and mineral energy framework can be expanded into a systematic Earth-system framework.

2.1 The Growth & Development paradigm and its limits

The main research program (Chalmers 2013: 122; Kuhn 1962, Lakatos 1970) of economic history has long concerned explaining the origins and spread (or not) of—and distribution of the spoils from—the industrial revolution or modern economic growth. Social consequences of industrialisation have been part of the story from the start (Toynbee 1884), and Malthusian fears of resource scarcity have been a dark accompanying shadow. However, global climate change and the anthropocene puts the whole rationale of the research program in a new and different light, where 'the long arc of development is now bending toward recognition of both cultural and biological diversity' (McMichael 2016). This does not imply a departure from economic history per se but in a sense a return to its original emphasis on the material foundations of history—a deeper historical materialism.

One of the most engaging aspects of early economic history was that it proposed underlying economic causes for political and ideological surface events. However, if the originality of economic history once sprang from its reversal of 19th-century idealism, it has now largely become subsumed under a 19th-century belief in growth and development (G&D)—i.e., growth in rich and development in poor countries (Arndt 1978, 1987), where the former, 'more developed industrially only shows, to the less developed, the image of its own future' (Marx, *Capital*, 1867, quoted in Arndt 1981). Where once material and worldly realities took precedence over ideas and personalities in guiding the course of history, economic historians have again reverted to idealism where G&D is concerned. G&D are central features of world-wide governmental policy, discourse, institutional and legitimation structures sometimes referred to as a 'growth paradigm' (Schmelzer 2016) or 'development discourse' (Ziai 2016, Macekura 2017), although given its extra-scientific reach it could perhaps better be referred to as a socially constructed reality (Berger and Luckmann 1966).

According to McNeill (2000: 336; cf. Cullather 2000), 'the overarching priority of economic growth was easily the most important idea of the twentieth century.' However, its lineages reach back to mercantilists and the early modern 'invention of improvement' (Slack 2015), via the expansion of colonial empires and the US in the 19th century and the European civilising mission using 'machines as the measure of men' (Adas 1990, 2003). In the UK, Joseph Chamberlain advanced a program of 'constructive imperialism' in the 'underdeveloped estates' (Hodge 2016: 130), while in the US post-civil war Reconstruction reforms were internationalized after the Mexican and Russian revolutions to stave off further socialist unrest, supposedly originating in population-resource crises (Adas 2006; Ekbladh 2010; Leffler 1994; Perkins 1997). A new international order of G&D became institutionalised after two world wars and the Great Depression, with incipient decolonisation and nation building (cf. Ikenberry 2001). Economic growth was deemed essential to avoid another Great Depression, believed to have precipitated the Nazi seizure of power in Germany, and in the ideological struggle with the Soviet Union (Ziai 2016; Macekura 2017: 115). Economic development played a similar role in trying to avoid communist takeovers in 'backward' countries, as happened in China in 1949. G&D thus rose to discursive and institutional prominence with postwar reconstruction in the decolonising cold-war context of Harry S. Truman's Point Four Program (Leffler 1992; cf. Rostow 1960), but was soon endorsed also by former colonies.[2] Since the demise of counter-cyclical, state-investment Keynesianism and the rise of neoliberal austerity, critics on the left argue that G&D

[2] Colonial governments in the 1940s had thought of development as something that would reinvigorate an imperial system under pressure from colonial 'disturbances', but it soon became central for how local elites formulated independence. Development thus started as a reformist project with hordes of experts sent to teach farmers how to farm, with the aim to make colonies more productive and ideologically stable. However, after a decade it came instead to be conceived 'as a natural unfolding of a universal social process, which human agents could facilitate but which was driven by history', and as such had 'as strong an appeal to nationalist elites as to colonizers' (Cooper 1998: 64).

has been abandoned in favour of capital accumulation. Whatever the reality, this only underlines the function of G&D as unifying ideals.

G&D have been repeatedly questioned, criticized, and supplemented, either as a goal or as a possibility. Indeed, Kuznets (1934; quoted in Costanza 2023: 3) himself could not see the point of growth, by and for itself, of the GDP indicator he had helped to create: 'The welfare of a nation can scarcely be inferred from a measurement of national income as defined by GDP. […] Goals for "more" growth should specify of what and for what.' After WWII, neomalthusians criticised population growth, overconsumption and resource depletion (Osborn 1948; Vogt 1948; Borgström 1962, 1965; cf. Linnér 2003; Robertson 2012). Agricultural gains made on the back of organic chemistry spread reasonable fears about pesticides in food, water, and air (Carson 1962, Lytle 2007), leaving global PCB traces that could serve as geochemical markers of the Anthropocene (Dong et al 2021).

From the late 1960s, two lasting forms of criticism were formulated, concerning the social and environmental costs of, or limits to G&D. The criticism was in turn met by individual scientists—often mockingly, as when Solow referred to Meadows et al (1972) as the Doomsday model and Carl Kaysen (*Foreign Affairs*, July 1, 1972) as 'The computer that printed out W*O*L*F'. More persistent was the response at the highest organisational level by OECD in the case of growth and the United Nations in the case of development, 'framing environmental problems in such a way as to make them seemingly compatible with continued growth and with the international free market regime, thus paving the ground for what has been characterized as "liberal environmentalism."' (Schmelzer 2016: 289f.; cf. Bernstein 2001). On a UN and discursive level, the response to accusations of neglecting environmental and social limits to growth was to incorporate them into sustainable development, comprising economic, social, and environmental spheres (Macekura 2020, 2016; Ziai 2016, Ch. 14; Selcer 2018; Borowy 2014; Anker 2020: 229). These must be sustainable either individually (strong sustainability) or together (weak sustainability). Since economic sustainability was equated with economic growth (Brundtland Commission 1987: 14, 18, 24), the only course open even for strong sustainability becomes improving environmental efficiency (lowering impact per GDP through better technology). This has been the mainstream political position ever since, with various theoretical motivations over time, and in its most recent avatar as 'green growth' assuming purely market-based solutions, with a carbon tax to offset negative externalities but no harsh legal framework or state-organised investments.[3]

[3] Nordhaus (2021: 108) makes good use of economic sustainability in criticising Martian colonisation, pointing out that 'Biosphere 2' experiments have a GDP/capita of minus $190,095, and an NNP/capita of minus $3,443,064 (in 2015$). It is possible that this cost of sustaining Musk on Mars would still have been cheaper for the US than the opportunity cost of keeping him on Earth.

In the 1970s, general interest was spurred by the energy crisis (the 'oil shock') and a fear of running out of natural resources but then waned as prices of energy and natural resources stabilised or fell. Ecologists who had placed all their bets of natural resource scarcity, clearly underestimating the power of modern economies to (indefinitely) overcome them, suddenly appeared to be standing there—falsified—with no clothing (Sabin 2013).

Following this debacle of falling resource prices, an alternative interpretation was revived, based on the old idea that rich countries profiteered from the natural resources of the poor, notably through falling terms of trade for such resources. Relying on the authority of Singer's and Prebisch's theorem rather than any specific theory or study of prices, this was an ecologised version of dependency or world-systems theory—often referred to as ecologically unequal exchange (Brolin 2006). Alternative ecologisations of old concepts are Jason Moore's 'commodity frontier' or 'world-ecology' (from Wallerstein's 'world-system'). Similarly to Rosa Luxemburg's interpretation of capitalism where profits can only be maintained through geographically expanding markets, the argument here is that constantly expanding resource frontiers entail lower prices—not higher as could be assumed from Ricardian land—whether because resources are more abundant or the (often forced) labour is cheaper. The popularity of this tradition stems from its attempt to unify the environmental and social critiques of growth in an international context: growth in rich countries depends on displacing its disrupting social and ecological effects to the poor.

The waning of the energy crisis and waxing of the climate crisis signalled a shifting emphasis from a natural resource floor to its ceiling. Thus, the original limits-to-growth debate concerned primarily the material and energy inputs, whereas over the past decades focus has shifted increasingly to impacts from effluents and land use. The limits-to-growth narrative has been revived in this new context in the form of planetary boundaries (Rockström et al. 2009a, 2009b; Steffen et al. 2015). These include such things as climate change, ocean acidification, increased rates of circulation of nutrients (nitrogen and phosphorous), loss of biodiversity, new chemical entities (e.g., DDT, plastics), etc, none of which can be reduced to the other, although the main economic drivers causing the impact in many cases may be the same. While many of these concern resources such as land, freshwater, nitrogen, or phosphorous, the problems highlighted commonly refer not to their limits as inputs but rather to the environmental consequences of their not sufficiently limited use—thus providing a new ceiling for the economy.

In line with the social limits to growth of the 1970s and the social dimension of sustainability, this environmental ceiling in turn inspired the addition of a social floor, turning it into a 'safe and just operating space' for humanity in the form of a 'doughnut' or 'care' economy (Raworth 2012, 2017a, 2017b; Jackson 2025). If social wellbeing can be achieved within planetary environmental boundaries, this reinforces degrowth-arguments that economic growth becomes irrelevant and should be replaced—economic growth as a source of geopolitical power is another matter. Studies quantifying how nations manage to keep within a safe and just operating space have found only a few encouraging historical examples—e.g., Cuba and Vietnam (O'Neill et al 2018; Hickel 2019; Infante-Amate et al 2024). In the political arena, 'degrowth' has re-emerged in recent decades (from its 1970s predecessors) as the main alternative narrative to 'green growth', with a 'green new deal' as a Keynesian state-investment based compromise (Warlenius 2022: 15–118).

What this historical overview purports to show is not that G&D is necessarily an untenable ideal permeated by increasingly outmoded political motivations—the ideological and geopolitical context for the emerging environmental sciences is virtually identical—but simply that it *is* an ideal, not a material foundation or something that can be taken for granted as unproblematic. G&D might re-enter through a 'realist' (à la Hans Morgenthau or John Mearsheimer) geopolitical backdoor, but then that assumption should be made explicit and openly discussed. The economic sphere can still be regarded as a material basis of society, but judging from the critics above so must the actual material and energy processes of the world. When introducing the concepts of organic and mineral energy economies below, it will indeed be suggested that the mineral energy economy provided the material underpinnings of the G&D ideal.

Section 2.2 spells out the main phases of the transition from an organic to a mineral energy economy, and how the individual Papers fit into this story, while section 2.3 then shows how the organic and mineral energy framework can be augmented into an Earth-system accounting framework.

2.2 The transition from organic to mineral energy economies

The 'organic energy economy' and 'mineral energy economy' will appear throughout this thesis. An organic energy economy as used by E. A. Wrigley refers to an economy that relies exclusively on energy derived from sources that are ultimately based on the annual flow of solar energy, including human and animal muscle power (fed by food crops and fodder), biomass fuels such as wood, charcoal, straw, turf, (possibly) peat, and wind and water power (used in mills or ships). Organic or traditional economies are constrained by competing uses of limited land and its yields. By contrast, a mineral energy economy is based on fossil fuels such as coal, oil and natural gas that are the result of millions of years of stored solar energy. Being sourced from a point rather than a land surface, it is not constrained by land availability or yields, therefore allowing sustained or modern economic growth. For Wrigley, the classical economists all moved within the confines of an organic economy. The difference between organic and mineral economies is paraphrased in the difference between classical political economy and neoclassical growth economics.

Inherent not only to Malthus's particular version but to all classical political economy was the belief that a limited factor of production or one with decreasing returns—land—would eventually permeate the whole economic system and produce a 'stationary state'. Trade could postpone the inevitable by connecting regions that were outgrowing their scarce or decreasingly productive land with those where it was still plentiful or more productive, but ultimately these too would face decreasing returns, prices of agricultural goods and raw materials would rise compared with industrial goods, cost of living rise, profits fall, and growth/accumulation grind to a halt (Smith 1776, Vol. 1, Bk. 1, Ch. 9; Ricardo 1816, 1817, Ch. 5–6; Mill 1848, Vol. 2: 306). Marx (1973: 748, cf. *Capital*, Vol 3, Pt 3) considered the falling tendency of the rate of profit to be 'the most important law of modern political economy'. They all made some allowance for improvements in arts and machinery.

If the neoclassical theory of economic growth appears more in line with actual developments, this stems not least from dispelling 'nonaugmentable' factors such as land, as explained in the founding article by Solow (1956: 66f): 'Output is produced with the help of two factors of production, capital and labor […] This amounts to assuming that there is no scarce nonaugmentable resource like land. Constant returns to scale seems the natural assumption to make in a theory of growth. The scarce-land case would lead to decreasing returns to scale in capital and labor and the model would become more Ricardian.' The neoclassical growth paradigm was reinforced by the emergent resource economics, for which any problems created by growth would be resolved, via shifts in relative costs and demand, and the drive to expand markets, through substitution and technical progress. Thus, the 'notion of an absolute limit to natural resource availability is untenable when the definition of resources changes drastically and unpredictably over time', and that a 'limit may exist, but it can neither be defined nor specified in economic terms' (Barnett and Morse 1963: 7, 11; cf. Boserup 1965). Defined and specified in Wrigley's terms, modern growth theory requires indefinitely augmentable mineral energy inputs.

For present and future purposes, it might be useful (or at least hopeful) to divide mineral energy economies into 'fossil' and, say, 'electric' (modern non-fossil: hydro, nuclear, geothermal, wind, and solar)—a tripartite division like Lewis Mumford's (1934) eotechnic, paleotechnic, and neotechnic eras.[4] This gives us one historic energy transition from the organic to the fossil energy economy, and one present/future, from the fossil to the electric. Historically, the electric energy

[4] Mumford used the terms more as 'the long road to', the first, and the second industrial revolution, whereas for Patrick Geddes the neotechnic was a future age characterised by 'better use of resources and population towards the bettering of man and his environment together' (quoted from Palmblad 2023: 209; for context and the related term 'biotechnic', cf. pp. 208–214).

economy has been regionally important (especially hydro and nuclear) but globally marginal. Just as the organic energy economy coexists with the fossil, so the electric coexists with the fossil. Thus, most electricity has been generated from coal and gas, and is thus not truly 'electric' by the definition used here—similar to fuelling your steam locomotives with wood as in the early US or India. Currently the electric energy economy is undergoing rapid, rear-wind changes based on wind and solar, and starts penetrating the old fossil economy through lithium and sodium ion batteries, EVs, etc, that might possibly result in a true transition (in the sense of substitution). Thus, a rising electric energy economy can avoid at least some of those social costs, negative environmental externalities and earth-system feedbacks arising from fossil energy effluents.

However, the interest of this thesis is with the past rather than the present or future, and it can be structured around the transition from an organic to a mineral energy economy, through a domestic and multiple industrial revolutions. Section 3.1 will explain further how each industrial revolution can be seen as having its own market 'suction' and market widening (globalisation) phases. Figure 2A shows the beginning of the organic to mineral energy transition in England & Wales sometime in the first half of the eighteenth century. Warde has estimated energy consumption for England and Wales in 1560–2008, divided into the primary energy sources, food, feed, fuel, coal, wind, water etc. By grouping these into traditional or organic energy sources versus coal or mineral energy sources, his estimate suggests that coal overtook other sources already by 1620 individually and together by 1710, thereby dating the energy transition well before the classical industrial revolution. Paper 4 is devoted specifically to the transition in England, and the higher wood yields there suggest that these transitions occurred rather in the 1670s and 1740s. However, the main point still stands that the energy transition preceded large-scale industrial use of coal and was driven by domestic consumption directly and indirectly. Compared to the innumerable theories about the causes of the Industrial Revolution, those on this early energy transition are remarkably few, focusing on a 'wood famine' caused primarily by resurging population growth, especially around London and consequent to its commercial development, which also led to the invention and spread of the 'coal-burning house' (Nef, 1932, Malanima 2003, Allen 2009). The fact that this coal transition, driven by domestic heating, coincided with the coldest decades and centuries of the past millennium has also suggested that climate may have played a role (e.g., Rackham 2003, Spufford 2006, Fouquet 2008, Malanima 2010-11; Kander et al 2013), but this idea has never been put to the test—nor has anyone suggested how it could be tested. This is what Paper 4 tries to do.

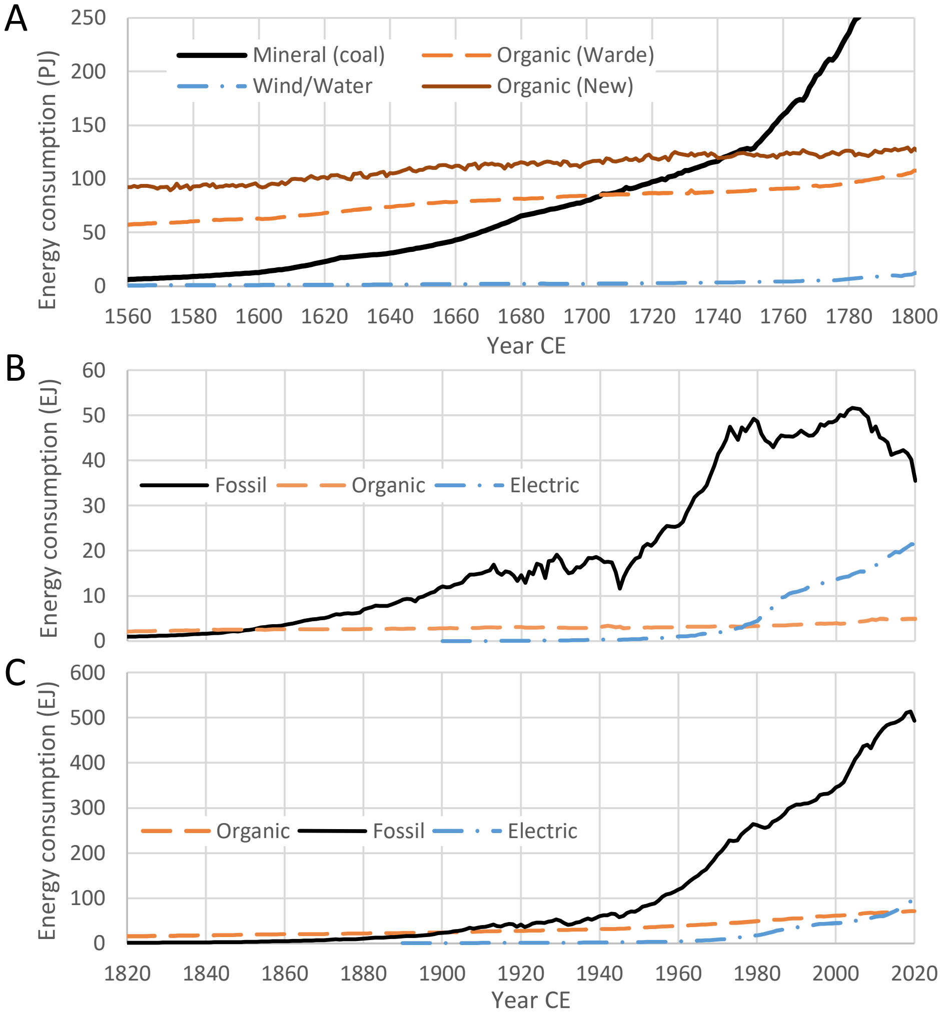

Figure 2. Energy consumption and energy transitions
A. Total England& Wales energy consumption by source, 1560–1800. B. Total West European energy consumption by source, 1820–2020. C. Total world energy consumption by source, 1820–2020. Organic: food, feed, fuelwood, bioenergy; Fossil: coal, oil, natural gas; Electric: hydro, wind, solar, nuclear). Source: Malanima 2022, Warde 2007, Paper 4.

Using Malanima's data, Figure 2B shows the same organic to mineral energy transition occurring in Western Europe around 1850, and Figure 2C the world around 1900. However, here the driver was different, namely industrial use of coal, still mostly in, or exported from, the UK. As depicted in Kander et al (2013) the centuries leading up to that in Figure 2B was instead a period with declining (organic) energy consumption from 1500 to 1600 followed by a drawn-out stagnation until 1800, consequent upon a cooling climate and the limited organic energy that could be supplied from the land. Paper 3 discusses alternative ways that people managed to expand the organic economy in Western Europe in 1500–1800. The environmental constraints of Europe's early-modern organic economy have been the subject of considerable debate among economic historians. In one formulation, introduced to economic history in Eric L. Jones's *The European Miracle* (1981), Europe responded to its land constraints by geographically expanding its 'Great Frontier' and importing 'ghost acreage'. He listed both temperate areas in the Baltic and North America, and tropical areas in the Caribbean and elsewhere, but also the Newfoundland cod fisheries. Wrigley (1988) may have been the first to quantify a woodland area corresponding to British coal consumption, a 'coal acreage'. Inspired by these authors (and Sidney Minz), Kenneth Pomeranz's *The Great Divergence* (2000) estimated that the British 'trade acreage' embedded in timber, cotton, and sugar imports from the Baltic, North America, and the Caribbean around 1800 made an even greater contribution to alleviating British land constraints than coal. The combined ghost acreage from coal and trade was what ultimately explained Euro-Chinese divergence over the subsequent century. The most important follow-up studies are those by Dimitris Theodoridis (2018; Theodoridis et al 2018), which were unique in their comprehensiveness but also in looking at British exports, including that embedded in British direct and indirect coal exports. Estimates have concentrated on the nineteenth or last decades of the eighteenth century, but ironically the origins of divergence have again been pushed back towards the early eighteenth century. This has created a gap between estimates and what they were supposed to explain, which still remains to be bridged as far as trade is concerned. In addition, no one has even attempted to estimate the contribution from fisheries in Jones's original proposal. Thus, Paper 3 looks specifically at land alleviation through fisheries, the 'fish acreage', for Western (or 'Atlantic') Europe in 1500–1800. It shows that seafood was more important than coal for Western Europe, taken as a whole, at least until the mid-eighteenth century. However, for England & Wales specifically, coal was much more important than fisheries, as was the ghost or 'yield acreage' from higher agricultural yields between 1500 and 1800. The study also shows that the *appropriation* of resources does not necessarily equal the *alleviation* it offers—it may be greater or lesser, a difference paralleled in trade-studies by accounting in yields of the exporting or importing country respectively.

After the Napoleonic Wars, the first, or British, industrial revolution entered a market expanding, globalising phase that lasted until World War I. Paper 2 is about trade-embodied flows of resources and environmental factors accompanying the nineteenth- and early twentieth-century mineral energy transition in Western Europe and world over this period. As noted, the driver here was no longer domestic but industrial use of coal, mostly in, or exported from, the UK. Drawing on Theodoridis et al (2018), Paper 2 shows that while the UK was a net-importer of land, the exports of coal (in organic-energy woodland equivalents) was even greater, so that, overall, the UK contributed to the European or world alleviation of land. 'Alleviation' may be a poor word to use. The mineral energy transition on the one hand added a new kind of resource to the old and on the other served to connect a wider sphere of organic (and mineral) energy economies. What happened was that the world consumption of both organic and mineral energy resources increased, expanding the world's actual land acreage by a virtual ghost acreage—exactly as in those estimates of ecological footprints showing how we are now consuming 1.5 or so 'Earths'. The main topic of Paper 2 is whether these and other environmental factor flows are best explained by the environmental endowments of countries or by net imports to rich powerful countries. Adding that the US was also a net exporter in material, land, and energy terms until the 1920s, while simultaneously surpassing the UK as the world's richest country, there is no avoiding the conclusion that, during the first globalisation wave, net flows were determined primarily by endowments, not diverging incomes or power relations. However, as shall be elaborated further in section 3.2, income or power relations may still have distorted or biased flows. Thus, Paper 2 does not imply that the world necessarily gained from the division of labour or that the appropriation of environmental services was in any sense equal.

Paper 1, finally, concerns the trade-embodied environmental factor flows accompanying both the organic and mineral energy economies during the market widening, globalisation phase of the *second* industrial revolution—based on oil, combustion and diesel engines—which began around 1950 and came to a world-wide halt only in 2007 with the global financial crisis. It moves in a world where the mineral energy economy has environmental consequences of its own but also accelerates the global integration of the still largely organic-energy resource base. Like Paper 2, Paper 1 concerns how international trade redistributes the environmental consequences of the mineral energy transition according to different logics depending on whether these environmental consequences can be traced to the organic or the mineral economy. It also reflects on how the different material characteristics of coal and oil economies may have impacted developments. The relative cumbersomeness of coal and steam engines created linkages to the local economy—including strong unions in the UK whose influence was destroyed only with Margeret Thatcher in the 1980s. By contrast, oil can be pumped into diesel fuelled oil tankers and trucks, or pipelines at great distances between producers and consumers, which together with the flexibility of combustion engines and electric motors did not stimulate local community organisation. Instead, it greatly strengthened the power of large, mainly US, oil companies, whose vested interests are still impacting the geography, speed, and geopolitics of the clean ('electric') energy transition.

A third industrial revolution has already been proclaimed multiple times, as has a fourth and a fifth, although many of these claims have likely been nearsighted and premature. Similarly, a third globalisation wave has been pronounced for the 1990s onwards, based on how the Information and Communications Technologies (ICTs) allowed more complex chains of production and outsourcing to low-wage countries, mainly China. There are indeed signs of another and ongoing industrial revolution and energy transition having to do with ICTs, artificial intelligence, lithium (and sodium) ion batteries, electrification of energy production (hydro, wind, solar, and nuclear), and transportation (rail, electric vehicles). However defined, a third globalisation wave of similar duration and status as the previous two is likely to involve Chinese trade with the global south and confrontation with the old US-dominated system. However, instead of integrating energy transitions with geopolitics or communications, the focus here has been to broaden the surface interaction between the economic and the Earth-system. [5]

2.3 Environmental factors and the Earth-system

Neoclassical economists may believe that the economy can get along without resources (*vide* Solow), but even classical political economy, up to and including the energy version sketched by Wrigley, tend to include only resource inputs rather than outflows. From that perspective it is not clear why fossil energy effluents would become a hindrance to profits or economic growth—indeed, one problem is that they don't. Theoretically effluents are included as negative externalities and considered market failures, but from the perspective of private business, externalisation is not a market failure but a success—a way of shifting costs from the firm to the public—while proper internalisation of social and environmental costs through taxation would likely force many enterprises out of business (Warlenius 2022: 30; for an overview of business history from a sustainability or Anthropocene perspective, cf. Bergquist 2019, 2020). Even non-market systems can of course externalise social costs to other classes, regions, and future generations—the will-bes or 'may-bes'—or to other components of the Earth-system. In this context, the Earth-system is the ultimate *social* system, incorporating not only human societies, but the biosphere in all its diversity, the Earth's energy balance, global biogeochemical cycling of materials, and all their interconnected feedbacks and feedforwards, including the climate system.

[5] Previous industrial revolutions have also had their communications dimension, e.g., the mechanisation of the printing press to make newspapers accompanying the first industrial revolution in the early 19th century, the electrification of communication with telegraphy and telephony, radio and television, computers and satellites, accompanying the second industrial revolution. It would be a worthy topic to study the interconnections between these industrial and communications revolutions, including consequences in the political and geopolitical sphere (cf. Innis 1950).

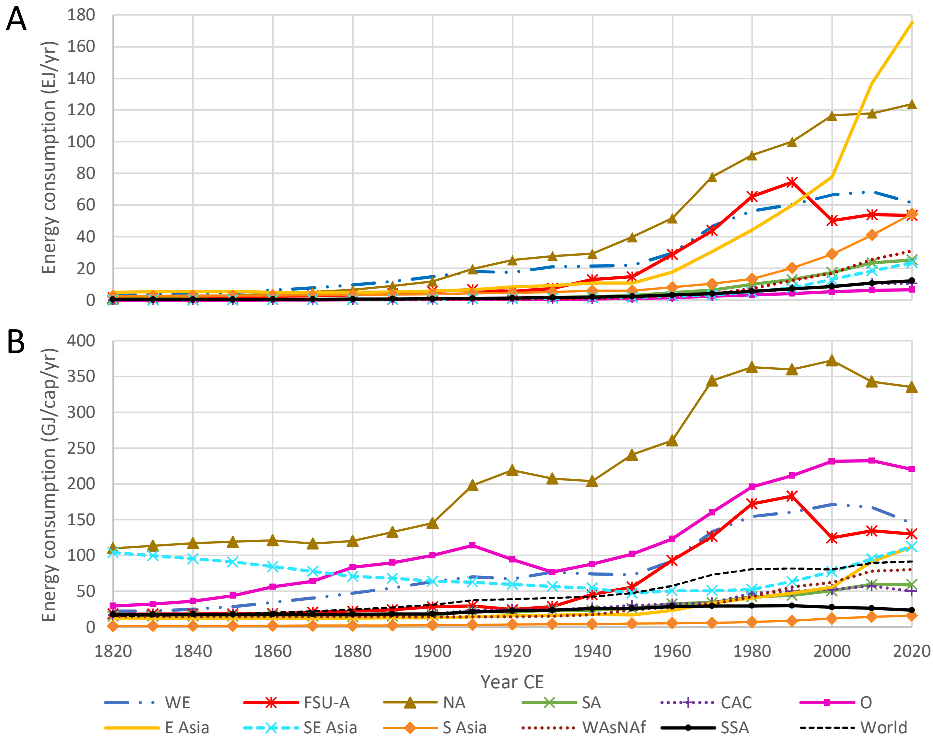

Figure 3. World energy energy consumption by region, 1820–2020
A. Total energy consumption by world region. B. Per capita energy consumption by world region. WE: Western Europe; FSU-A: Former Soviet Union and Allies (=Eastern Europe); NA: Northern America; SA: South America; CAC: Central America and the Caribbean; O: Oceania; WasNAf: Western Asia and Northern Africa; SubSaharan Africa. Source: own elaboration based on Malanima 2022.

Up to and including the 1970s energy crises, economic historians have taken an interest in energy mainly from the input side. As the climate crisis started looming larger in public debate from the 1990s onwards, energy effluents have risen on the agenda. An example of this is Malanima's recent world energy dataset from 1820–2020, which also includes estimates of greenhouse-gas emissions (GHGs). Dividing these into the same geographical groups as in Paper 1, Figures 3 and 4 allow one to see their many similarities with one another (but also with other environmental input and impacts originating in the mineral energy economy). Looking at the per capita levels, North America and Oceania stand out, followed by Western Europe and the Former Soviet Union and Allies (here, Eastern Europe including Russia), i.e., those traditionally classified as 'developed'. However, a surprising feature is the very high per capita energy consumption in Southeast Asia in 1820, which (if correct) was on the same level as North America, twice that of the UK or Sweden, and four times or more that in other regions. From the low GHG- emissions, we may conclude that it

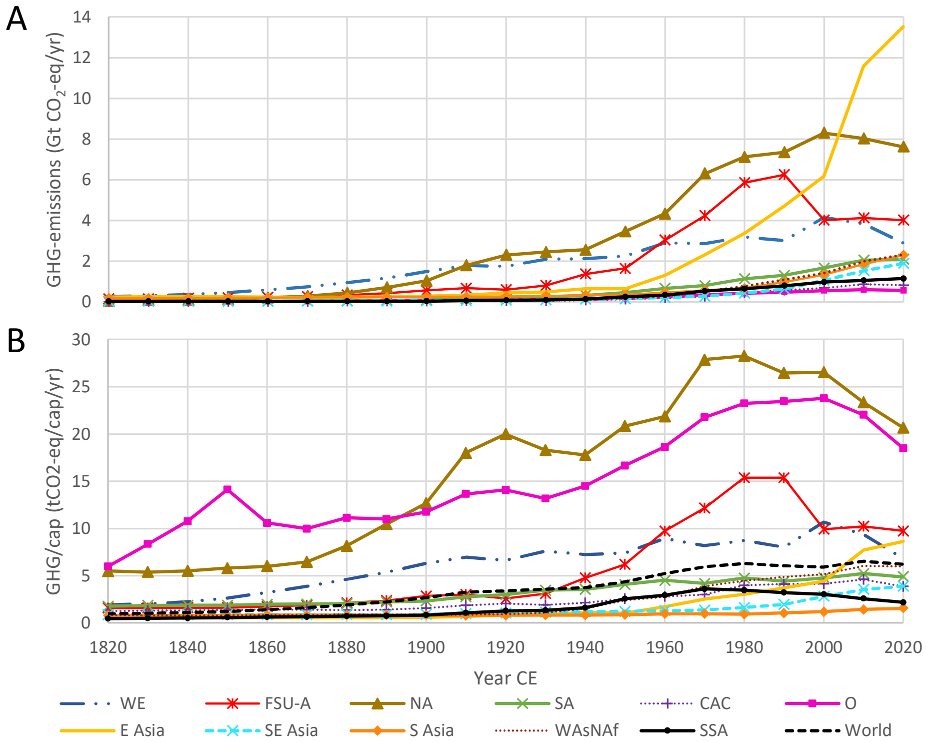

Figure 4. World GHG-emissions by region, 1820–2020
A. Total GHG-emissions by world region. B. Per capita GHG-emissions by world region. WE: Western Europe; FSU-A: Former Soviet Union and Allies (=Eastern Europe); NA: Northern America; SA: South America; CAC: Central America and the Caribbean; O: Oceania; WasNAf: Western Asia and Northern Africa; SubSaharan Africa. Source: own elaboration based on Malanima 2022

must be linked to a high involvement of organic, not mineral, energy consumption, and among these likely not feed for animals.

In the case of energy consumption and GHGs there are evident similarities in scale and trends, as they reflect two sides—input and effluent—of the same mostly mineral energy economy. Yet, as noted with respect to Southeast Asia, they are not identical. To start with, the units are different, being measured in Joules and tonnes respectively. Thus, while energy is fundamental it is certainly not all—at the very least, matter matters too (or so said Nicholas Georgescu-Roegen). Material-flow through societies, with an emphasis on mass balance, is the main topic of the prolific social ecology, or social metabolism, approach (Fischer-Kowalski 1998; Fischer-Kowalski and Hüttler 1998; Haberl et al 2019). Matter is much more heterogeneous than energy, and a certain division of labour has emerged with other approaches specialising in certain of its forms, on the input side notably water. In addition, certain environmental impacts are not well captured solely by inputs and outflows but reflect system changes such as land-use scale and intensity or biodiversity. For the purposes of this thesis, I have coined the term 'environmental factors' to encompass all these various inputs, outflows, and impacts, by analogy with the standard 'productive factors' of economics, or as an environmental extension of the 'land' factor, which has commonly been used for all resource inputs but not outflows. Alternative expressions would be environmental indicators, services, or 'inputs and impacts', which is perhaps more descriptive and less at risk of causing confusion.

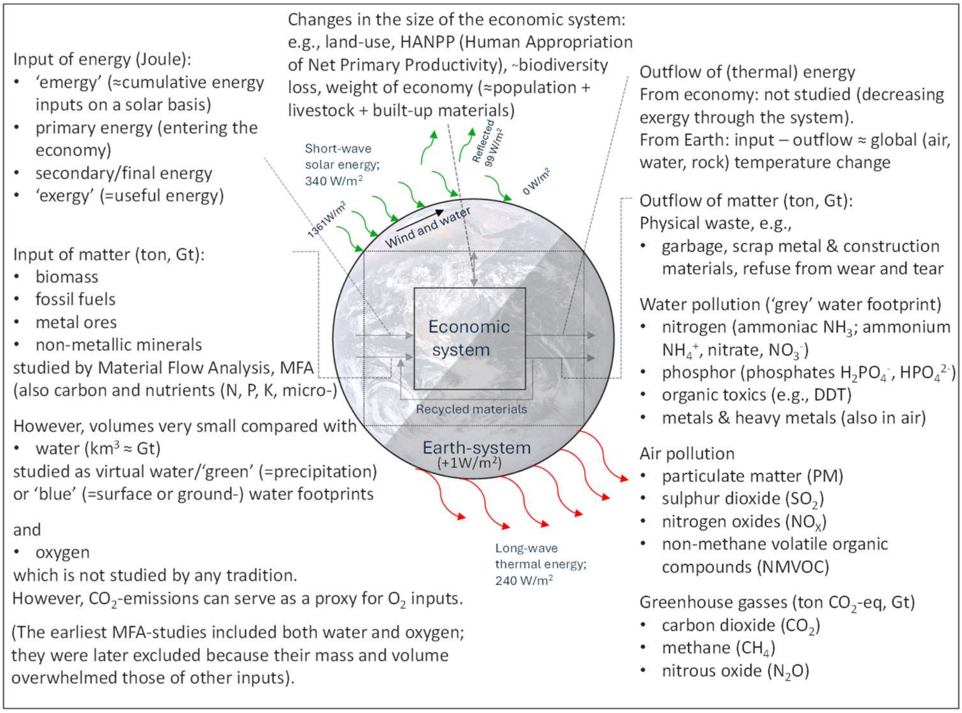

Figure 5. Overview of environmental factors
Environmental factors linked to energy and material inputs and outputs, or changing system characteristics (e.g. economy size, biodiversity), assuming energy and mass balance.

Figure 5 presents an attempt to systematise these factors, with inputs on the left, system changes in the middle, and outflows on the right. This systematisation is partly based on the inventory of existing studies in Paper 1 but (as explained there) also has parallels in studies of biogeochemical cycles and earth-system approaches to planetary boundaries. The central image of the Earth is modified from Herman Daly's (1996: 49) ecological economic illustration of an economy embedded within the Earth's biosphere. The small, full-line square indicates Daly's concept of an 'empty' world, and the large, dotted square his concept of a 'full world' (perhaps reaching Rockström's et al 2009 'planetary boundaries'), while the arrow between them illustrated the changing size of the economic system. The circle representing the Earth-system contains also the climate system, biosphere, all biogeochemical cycles, and an intricate web of positive and negative feedback processes that could also affect the economic system (independently of whether ultimate causes are anthropogenic or natural). The shorter-wave, green arrows represent the inflow of solar energy (part of which is reflected), declining from the equator to the poles, thereby causing a corresponding equalising energy flow internally through air and ocean currents. The longer-wave, red arrows represent the outflow of thermal energy, and the difference between the two corresponds to global warming of the air, land, and (predominantly) oceans.

Economic historians have previously studied several factors partially or in isolation, such as land, organic and fossil energies, food, raw-material, or nitrogen inputs, or even sulphur and greenhouse gas-emissions. However, a systematic approach would integrate these into a consistent whole. The 'land' category is augmented by estimates of human appropriation of net primary productivity, involving both extent and intensity of land use, as well as biodiversity. Several material flows are added (divided into biomass, fossil fuels, metals, and non-metallic minerals), freshwater (relating to the global water cycle and divided into blue [reservoir], green [precipitation], and grey [polluted] water), and pollutants. Pollutants mean either completely new chemical entities (such as DDT or plastics) or established substances in the wrong amounts or place, divided mainly into macronutrients (nitrogen- and phosphorous), sulphur, and a disparate and expandable 'rest' category. Four of the nine planetary boundaries relate to such pollutants (Rockström et al 2009). 'Mass balance' means that whatever element (of the periodic table) you put in at one end of a system either contributes to expanding the system or comes out again at the other end, usually in some new, less useful, or dangerous constellation as emissions, waste or pollutant. Energy always comes out in a less useful form, ultimately as long-wave radiation (=heat).

Apart from their direct relevance and transparency, what is appealing with using environmental indicators that are biophysical in nature, rather than some index of sustainability (of which there are several), is that this allows keeping much of the ideology and politics out of the units of measurement. Starting well over a century ago, global environmental assessments also illustrate the increasing depth of human impacts. Thus, an early perception of the Earth's *surface* as *modified* by human action (Marsh 1965 [1864]; Thomas 1956), has changed to one of an ever-deepening human *transformation* of *Earth-system processes* (Turner II et al 1990; Steffen et al 2004). Quantitative estimates have become increasingly available, often extending several hundred years back. Paper 1 contains an overview as of 2020, but there is an increasing number of studies and reports, and from 2024 an annual overview (Planetary Boundaries Science 2025) with updated data references. Taken together, the framework shifts from an environmentally extended energy history to encompassing the total appropriation of, and impact on, the Earth's main energy flows, biogeochemical cycles, and ecosystems.

What ultimately transforms this into an Earth-system economic history is when the economy is integrated into these Earth-system processes, and where both economic and Earth system processes, with all their feedbacks and feedforwards, can be considered causal agents and where consequences in one realm may ultimately transform into causes in the other. Current environmental fears for the future are mostly about such consequences transgressing tipping points and becoming societally causal, but the interplay goes both ways with autonomic environmental causes potentially transgressing societal tipping points (as suggested by the argument in Paper 4).

In Section 3, more will be said on the drivers and economic historiography of energy transitions, on trade theories of factor endowments and unequal exchange, and on climate as an agent of societal change.

3 Theory and previous research

An economic historical tradition connecting energy transitions, industrial revolutions, and globalisation provides an important background for understanding this thesis (cf. Figure 1). The role of this tradition is more of a stepping-stone of 'normal science', from which this thesis takes a further step, than theoretical foundation. More 'what we teach in class', than the theories themselves having necessarily been used in the thesis. This refers to the idea of several industrial revolutions, each linked to a particular primary energy source which is complementary to a set of industrial technologies that, as they mature, enter an expansive, globalising phase. Standing on this foundation, the thesis seeks to expand perspectives in two major ways: first, to understanding the globalisation phases by including a broader set of environmental indicators (representing both organic and mineral economies), and alternative theories on the role of trade; second, to understanding the preindustrial drivers of the original transition from an organic to a fossil energy economy, which was domestic, not industrial, and shaped much more by environmental limits and, it is proposed, non-human agency in the form of climate cooling.

This section shall describe, first, the 'shoulders' on which the thesis stands (Section 3.1); then the alternative trade theories brought in to help understand the globalisation phase (Section 3.2); and, finally, some of the available models of climate-societal interactions and the modifications introduced by this thesis (Section 3.3).

3.1 Energy transitions, industrial revolutions, and globalisation

The tradition of structural analysis, with a strong presence also at the department of economic history in Lund, can be traced back to Joseph Aloïs Schumpeter. Trying to understand increasingly longer-term business cycles, Schumpeter argued that they were linked to transformations brought by clusters of technological innovations. A Schumpeterian analysis was further developed by Erik Dahmén and applied to interwar Sweden in his 1942 licentiate's and 1950 doctoral theses. There he introduced the idea that economic development is shaped by structural tensions, complementarities, and development blocks. Economic success at certain stages may require the realisation of several complementary stages. Certain developments may be premature and not realise their potential as long as the complementary developments are missing, leading to structural tension. Such tension could act as a stimulant to entrepreneurial initiatives but may also be retarded by lack of knowledge on how to solve the problems involved, whether related to technology, organisation, marketing, etc, or by institutional factors such as resistance from vested interests, monopolies, government regulations, etc. In Dahmén's (1988: 5) words a development block refers to 'a sequence of complementarities which by way of a series of structural tensions, i.e., disequilibria, may result in a balanced situation.'

Dahmén insisted on a close analysis of enterprises and the transformation brought by even minor technological innovations, and was critical of interpretations in terms of macroeconomic aggregates. The idea that major new technologies formed the core of development blocks was used in a wider macroeconomic context by Lennart Schön to analyse technology shifts in economic growth, emphasising dynamic and reinforcing synergy- and development-promoting effects of major technologies. These were poorly captured, e.g., in Robert Fogel's counterfactual social savings approach and therefore contributed to the small impact detected by him even from the railway. Other related concepts were integrated such as general-purpose technologies (Bresnahan and Trajtenberg 1995) and of three industrial revolutions stretching out over two centuries rather than one big Industrial Revolution that started in Britain in the 18th century. These industrial revolutions could in turn be characterised as consisting of one or more development blocks. Thus, the main development block of the first industrial revolution, starting in the 18th century, consisted of complementary coal, iron, and steam technologies, but came into full bloom over the 19th century with the spread of steam locomotives and ships. The second industrial revolution, starting in the 1870s but with greatest impact only after WWII, consisted of two development blocks: first, oil, the combustion and diesel engines; second, electricity, with the generator, electric motor, and transformer (allowing high-voltage transmission with small losses). The third industrial revolution was related to Information and Communications Technologies (ICT) and the tensions and complementarities surrounding the microprocessor, computer, and telecommunications.

Interest in energy transitions began in earnest with the energy crises of the 1970s, mostly from the perspective of limited resources, but has been revived in recent decades with greater awareness of the climate crisis. The hope now is that studying past energy transitions could provide clues and guidance on how to achieve the transition to a sustainable, non-fossil energy transition (Bergquist and Lindmark 2023; Fressoz 2024).

This has stimulated more detailed energy and environmental economic analyses by Astrid Kander, Magnus Lindmark, and similarly minded scholars elsewhere (e.g., Kander 2002; Rubio 2005, Malanima 2006; Warde 2007; Henriques 2011; Kander et al 2013; Nielsen 2017). Here, the multiple industrial revolutions or development blocks are linked explicitly to energy transitions, and the relative environmental performance of economies, e.g., the absolute or relative versions of the so-called Environmental Kuznets Curve (energy efficiency or CO_2 emissions per GDP). In line with the Dahmén-Schön tradition, energy transitions are seen as initially driven by a market suction phase and later a market widening phase: 'The market-widening phase occurs when the new energy carrier (first coal and later oil) is used to transport itself out to the customers, via railways, steamships and oil tankers, so the price of it falls so drastically it stimulates the transition' (Kander 2016: 183). In this thesis, these market-widening phases are referred to as waves of globalisation, and by this definition, it would as yet be premature to talk of a third globalisation wave. Another theme concerns whether development blocks tend to expand or save on energy. The general image that energy and economic growth are inherently intertwined is based on the coal and oil development blocks which had both been energy expanding. However, the electricity and ICT blocks have instead been energy saving, and the 'third', ICT, industrial revolution largely coincided with a halt in energy expansion. This appeared to signal that the downswing of the Environmental Kuznets Curve (so named by analogy to the inverted-U shape of Kuznets' GDP-inequality curve) had finally arrived. This was linked by some to the transition from an industrial to a service economy, and by others merely to an outsourcing of energy intensive and pollutant industries—instead importing such goods and hiding the true appropriation of energy and consequent CO_2 emissions—but could instead be explained by the energy saving character of the ICT development block.

The argument on appropriation of environmental services and outsourcing of environmental pressures through trade is evaluated in Papers 2 and especially 1, where it is found to differ depending on the environmental factor—less true for those pertaining to the organic energy economy, more true for those relating to the mineral energy economy. Distinguishing between the population, income, and technology effects, Paper 1 finds the population effect—relating to the relative per capita environmental endowments, i.e., availability of land, water, etc per capita—are more important in the environmental factor flows of the organic than the mineral economy, and that the income and technology effects—referring to the relative income/consumption level and technological efficiency, both of which affect net flows of environmental factors in the same direction—are more important to flows of mineral economy environmental factors. The next section will elaborate on different perspectives on trade that are contrasted in the Papers.

The above Schumpeterian paradigm has recently been subjected to criticism by Jean-Baptiste Fressoz (2024; citing Smil 2010; Wilson and Grubler 2011; Grubler 2012; Kander et al 2013, and others). [6] He makes two points, that are conflated in

[6] Fressoz is a student of David Edgerton, author of an iconoclastic history of technology emphasising the persistence of old and slow penetration of new technologies—'the shock of the old' (Edgerton 2007). Already in *The Shock of the Anthropocene*, Bonneuil and Fressoz (2016: 91, 96) pointed out that the history of energy 'is not one of transitions, but rather of successive additions of new

his criticism: (1) transitions are presented as substitutions of one kind of primary energy by another, when in fact they have merely added new kinds of energy to the old (Figure 6); (2) transitions are presented as following technological innovations by an internal deterministic economic logic, when instead they are determined by political, military, and ideological choices. The second characterisation is mostly correct, and while economic historians may dispute Fressoz's preferred hierarchy of causality, it does suggest that the tradition could be politically and geopolitically extended in interesting ways. The first point is mostly correct as a description of what energy transitions have entailed, but not as a characterisation of energy historians, nor would it be as a critique of the present thesis.

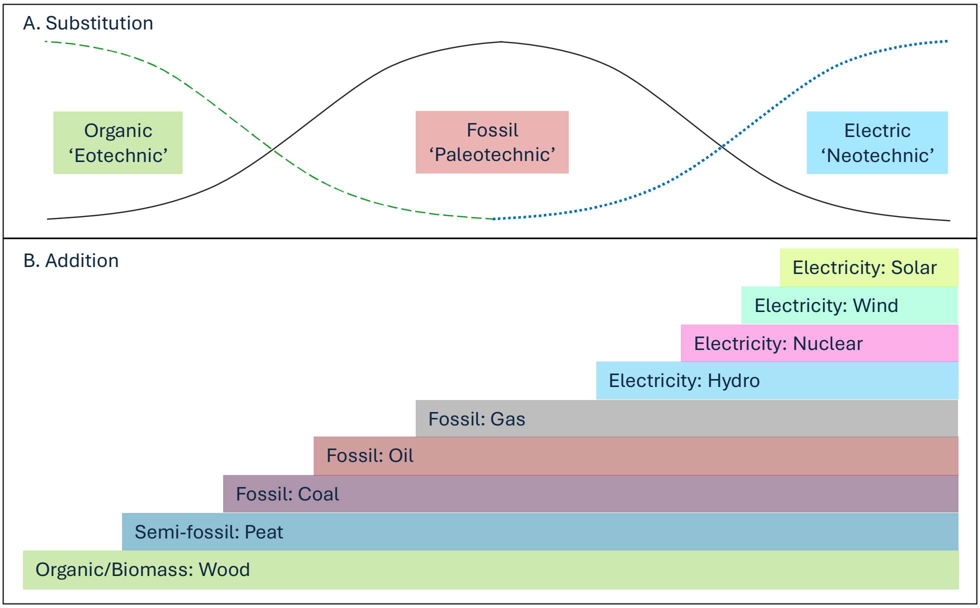

Figure 6. Energy transitions as substitution or addition
Two perspectives on energy transitions: A. Substitution; B. Addition. Organic: food, feed, fuelwood, bioenergy; Fossil: coal, oil, natural gas; Electric: hydro, wind, solar, nuclear). Source: own elaboration, inspired by discussion in Fressoz 2024; in A. the terms in quotation marks are from Mumford 1934.

In common parlance, an energy transition can imply a shift from one system to another. However, in historical studies it is commonly defined as the period between the introduction of a primary energy source, and it rise to a substantial share. Smil (2017) sets this share at 25 percent, which is reasonable given that the modern world has a wide variety of sources. However, if we compare only two categories of

sources of primary energy' and does not follow 'an internal logic of technical progress, […] nor a logic of scarcity and substitution […], nor even a logic that was simply economic.' This argument was expanded into a book format by Fressoz (2024; the original title was *Sans transition*, i.e., 'without transition').

energy, such as the transition from organic to fossil, it seems more coherent to use 50 percent, as has been done in this thesis. This difference between common and technical usage can invite confusion.[7]

Fressoz (2024) clearly spells out the two main alternative perspectives on what a transition can entail: either a substitution or an addition of energy sources. Figure 6A is an idealised rendering of how one kind of energy is substituted for another. This is commonly shown using relative shares of the total (Marchetti 1975), perhaps suggesting a transition from an agricultural, to an industrial, and then service economy, but here presented as transitions from organic to fossil to 'electric' energy sources, adding Mumford's (1934) precursor denominations. Figure 6B instead shows how new energy sources are merely added to the old and no kind of energy ever disappears or decreases in use. This is instead shown in absolute terms (Gaucher 1972). What is needed to solve the climate and many other environmental problems is for absolute consumption to follow something like the trajectories in Figure 6A. Fressoz charges that energy historians present transitions as substitutions when in fact they have been additions.

While useful in clarifying the difference, this criticism is clearly overblown.[8] Indeed, a slightly earlier review summarised the general take-home lessons from the energy historical literature:

> it is never about the complete discontinuation of one energy source in favor of another. Instead, new energy sources find their own space within the prevailing energy framework, complementing rather than replacing the existing sources. At the same time, with the current urgency driven by climate change considerations, the nature and pace of these transitions will need to differ from those of the past (Bergquist and Lindmark 2023: 2).

Thus, it is well recognised among energy historians both that existing, e.g., organic, energy sources rarely decrease in absolute terms as new kinds appear, and that, unlike previous transitions, the sustainability, clean-energy, or 'electric' (Figure 6A) transition will have to imply a substitution rather than addition.

A major point of Paper 1 is how the organic economy lives on and even expands along with the environmental pressures deriving from it, even as the mineral economy and its related environmental impacts grow exponentially. Since the organic economy consists largely of the classical four F's—food, feed, fibres, and

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[7] E.g., Fouquet and Pearson (2012: 1) define an energy transition as 'the switch from an economic system dependent on one or a series of energy sources and technologies to another'. While thus implying a comprehensive shift from one group of sources to another, this image is immediately negated by that of new sources being added on top of the old (Fouquet and Pearson 2012: 2).

[8] E.g., Kander et al 2013: 281: 'The decline of traditional fuels did not normally mean that the consumption of these energy carriers went down in absolute amounts. Rather, there was a slower growth in the use of traditional fuels and an enormous expansion of fossil fuels and primary electricity in total energy consumption.'

(wood) fuel—it is hardly surprising if it should grow roughly in pace with population, even if an increasing share of this population also consumes increasing amounts of fossil fuels and minerals. Recent reminders of the organic economy's continued importance after the mineral energy transition is the realisation that agriculture could be responsible for 60% of effective radiative forcing change since 1750 (Wedderburn-Bishop 2025)[9] and a major driver in transgressing many planetary boundaries (Campbell et al 2017). It is also clearly visible in the estimates of greenhouse-gas emissions other than CO_2 in Malanima's (2022, 2024) recent world and world-regional energy estimates. This of course has important implications for a future sustainability transition, which must not only substitute the fossil economy with an 'electric' economy, but also a large part of the traditional organic (i.e., photosynthetic, plant/animal) economy with, say, a fungal economy.

3.2 Resource endowments vs unequal exchange

The role of trade in classical political economic theory was briefly explained in section 2.2 above. The existence of a limited factor of production such as land would cause prices of food and raw materials to go up domestically relative to manufactures. Trade could temporarily postpone this development by giving access to the products of countries where land was relatively more available—in less industrially developed countries the products of the land would be relatively cheaper, as was shown by the theory of comparative advantage. In the long run, however, this land would also reach its limits compared with industry, and the relative price of food and raw materials (the terms of trade) start going up compared with those of manufactures. The rate of profit would decline and eventually the economy grind to a halt in a 'stationary state'.

Two points can be made here. First, classical political economy unanimously predicted falling terms of trade for manufactures, based on a limited factor of production and what Wrigley called the organic energy economy. Second, Ricardo's theory of comparative advantage, while formulated in terms of relative differences in labour productivity, suggests that trade ensures a more efficient use of environmental inputs, either by lowering factor inputs for the same total world output, or by raising total world output based on the same factor input. The Heckscher-Ohlin version of the theory brings comparative advantage up to date with the marginalist revolution. Here, trade ensures global savings or gains by allowing specialisation where productive factors (e.g., natural resources) are most abundant

[9] Effective radiative forcing refers to the 'running account' of warming rather than the 100-year warming potential used to assess climate change. The 100-year accounts may and have misjudged how much woodland would regrow and therefore underestimates the climate impact of the organic economy compared with the running account.

and, therefore, cheapest. This link between price and abundance—in some physical, objective way, existing before trade—is essential for the theory to hold.

How would the transition to a mineral energy economy affect these predictions? Fossil energy could be interpreted as an additional 'virtual land', a 'subterranean forest', a coal or 'ghost acreage', allowing industrial growth to proceed without running into some 'nonaugmentable' factor. (If we add the ability of 'mining the sky' for nitrogen, even actual agricultural land can be made 'augmentable'). Seemingly, this need not alter the way trade specialisation serves to save on resources or raise the floor for everybody as they specialise in their relatively most productive branches or abundant factors. Countries with abundant coal would simply specialise in branches utilising coal and export their products. The abundant and cheap coal and its virtual acreage would then spill over to other countries through trade, while other countries would produce and export the produce of their relatively most productive branch or abundant factor. This means that overall savings or raised efficiency from trade are not incommensurable with unbalanced net flows of trade-embodied factors, but on the contrary require them (as should be clear from Vanek (1968) and pointed out in Papers 1 and 2). Similarly, trade can ease pressures on the environment by redistributing environmental services from where they are abundant to where they are scarce. These transfers of productive or environmental factors should follow the patterns expected from the factor endowments of countries, e.g., from land- or water-, or coal-abundant to land-, water-, or coal-scarce countries.

Comparative advantage describes a logic for a specific technological or endowments situation, valid under certain assumptions at a given moment in time. One criticism of this perspective has been that some branches are more dynamic than others, for example those belonging or complementary to an ongoing industrial revolution. Thus, specialising in agriculture and importing your manufactures may seem like a good idea but could imply losing manufacturing capabilities that could become even more useful in the future. A related criticism of Heckscher-Ohlin is that factor 'endowments' are not nature-given by but created—Germany does not have a lot of chemical industries because it has a lot of chemists; instead, people study to become chemists because there are a lot of jobs in chemical industries. Even natural resources are not simply found but must be produced along with the capacities to produce them. According to a longstanding tradition—including mercantilists, protectionists, import-substitutionists, *dependendistas*, ecologists, and others—the production and exchange of food and raw materials for manufactures is unequal and detrimental to a country's relative prosperity. The proposed reasons have varied over time. One recent avatar is an alleged 'resource curse', another 'ecological unequal exchange' (EUE).

According to EUE, trade involves a geographical displacement of environmental burdens from economically developed centres to their less developed peripheries, or an exploitative transfer from poor countries to rich and powerful ones. This exploitation is reflected in unbalanced net flows of trade-embodied (environmental or productive) factors. This is archetypally seen in the exchange of food and raw materials, which are consistently or even inherently underpaid, for manufactured goods. Thus, transfers of productive or environmental factors flow from peripheries/poor countries to centres/rich countries. Early attempts to theorise this inequality were phrased in energy or quasi-thermodynamic terms. Thus, the useful energy of raw materials must be higher than that of the manufactures produced from them, which follows from the laws of thermodynamics. At the same time, the price of manufactures must be higher than that of the raw materials from which they were produced, which follows from the value chain of production. EUE links this to the traditional worldview where poor peripheries have always supplied the raw materials to rich centres producing manufactures. Finally, this was thought to entail a self-reinforcing spiral where centre development (low entropy) emerged by appropriating useful energy from peripheries who thereby suffered immiseration (high entropy) in a zero-sum game. Versions of this argument can be found in the works of Howard Odum (1971, 1996), Stephen Bunker (1985), and Alf Hornborg (1998).

There are many problems with this interpretation, both theoretical and empirical. Theoretically, it has not been shown that *appropriation* will be higher in manufacturing than in raw-materials production, or that raw-materials-exporting countries will be economically disadvantaged over time.[10] One empirical problem has long been known to economic historians such as Sidney Pollard (1981: 174f):

> These trading relationships between the more and less industrialized nations have for well over a century been consistently misinterpreted as an ‘exchange of food and raw

[10] For example, imagine a stone-age economy (in tribute to Marshall Sahlins) consisting of two countries trading exclusively blocks of stone or stone tools. Country A extracts a raw-material stone block, which is sold to country B for $100 (as debt in the minds of both sellers and buyers). Country B chips away (nail and tooth) at the stone block, manufacturing 101 stone tools, of which 100 stone tools are sold to country A for $100 (thereby repaying the debt). The total value of the manufactures thus becomes $101, which is higher than the value of raw materials, $100, as it should be, and trade is balanced in monetary terms. In material terms there has been a net transfer from country A to country B, consisting of 1 stone tool (perhaps plus a heap of toxic waste/rubble used as landfill). Thus, the balanced monetary transfer has hidden an ecological unequal exchange in material terms, which is the definition of EUE. This process is repeated for 10 cycles of production (or until country A runs out of stone blocks). The example conforms to all the criteria set up by EUE. Thus, according to EUE, because there has been a net transfer of matter from country A to country B, we should expect B to become developed and A underdeveloped, just as we would expect from country A being an extractive economy and country B a manufacturing economy. However, if we use accumulated means of production—stone tools were made primarily to produce wooden tools, not to hit people on the head—as a measure of development (as Paul Bairoch famously did with steam engines) then at the end of the 10 cycles, country B will be left with 10 stone tools and country A with 1000, i.e., the extractive, raw-materials-exporting country A will have become 100 times more developed than industrial, manufactures-exporting country B. Therefore, EUE-theory is incomplete or simply wrong. This is independent of the fact that the above exchange relations could easily be manipulated to yield the opposite result, i.e., by the block of stone exchanging for only 1 stone tool valued at $100.

> materials' against 'manufactured goods'. As it happens, the coverage is not dissimilar, but it is false. […] Thus coal, which is plainly a primary or raw material, has always belonged to the export list of the most advanced European economies, and thus has upset innumerable statistical tables.

This is why an energy trade-imbalance between more and less developed nations cannot explain this gap for the nineteenth century. It didn't exist because developed countries exported the most energy intensive good: coal. Even more, most food products were exchanged between developed countries, as in the famous European grain invasion from North America and Russia (and Ukraine). As pointed out in Paper 1, most trade during the first wave of globalisation was not an exchange of food and raw materials for manufactures, but for other food and raw materials.

This has not hindered many other economic historians (and economists) from basing their explanations of the Great Divergence between developed and developing countries on the same dichotomy. One tradition claims that the falling, another the rising, terms of trade for food and raw materials against manufactures explains the development-underdevelopment gap. The prediction by classical political economy of falling terms of trade for manufactures was mentioned above. However, by the late 1930s and 1940s, economists such as Paul Samuelson, Charles Kindleberger, Hans Singer, and others, began observing that since the 1870s the terms of trade for manufactures had improved. Alternative explanations sparked wide-ranging debate within the emerging field of development economics. The Singer-Prebish theorem proposed, on the one hand, inspired by Engel's law, that demand for manufactures would rise faster than that of food and raw materials, and, on the other, that wages in industrial nations were kept high (or raised) through political and union struggles, and that these higher labour costs were then shifted onto the consumer (also in developing countries) through higher prices. However, the empirical foundation for a general fall in the terms of trade for food and raw materials has always been shaky. Others have tried using the opposite trend of falling terms of trade for manufactures to explain underdevelopment. In this scenario, ever cheaper manufactures deindustrialised less developed countries such as India or the Ottoman Empire by underselling and outcompeting domestic producers (e.g., Williamson 2011). Both these approaches fail to appreciate all the countries that grew rich while exporting food and raw materials, or the observation by Kindleberger (1956) that it was not the terms of trade for food and raw materials per se that were falling, but the prices of goods from less developed countries per se, whatever they were producing. Singer (1958) accepted this conclusion and referred to it as the 'Kindleberger effect', complementary to the 'Prebisch-Singer effect' of falling terms of trade for food and raw materials. Theories attempting to explain the Kindleberger effect have been less common, but include those of Arthur Lewis (1954, 1969, 1978) and the theory of unequal exchange by Arghiri Emmanuel (1962, 1972). They involve three main theoretical points:

First, on overall gains or losses from trade. Both Lewis and Emmanuel start with the proposal that prices are not determined by the abundance or scarcity of productive factors but by wages, and wages, in turn, either by the output per worker in subsistence agriculture (Lewis) or institutionally, by political struggles, tradition, etc (Emmanuel). If factor prices (wages) are determined exogenously so that the cheapest factor is not necessarily the most abundant, then specialisation according to comparative costs at market prices does not necessarily result in overall gains from trade, either socially or environmentally. (This conclusion has also been reached many times over by Sraffian economists).

Second, on the terms of trade and the allocation of goods and services. Lewis only reasons in terms of labour costs, while Emmanuel also introduces an internationally equalised rate of profit. For both, it is the price of factors that determine the price of goods, not the other way around. In terms of the latter model, it can be shown, that a rise in nominal wages in one country will cause a proportionally smaller fall in the international rate of profit, and therefore a rise in the price of the goods produced in that country. However, to the extent that workers consume other goods than their own, real wages will thereby also rise while the real wages of all other countries will fall to the extent that they consume the more expensive good. Thus, this offers not only an explanation of the terms of trade but also shows how workers of one country can appropriate part of total societal output at the expense of other classes, both the international capitalist class and the working classes of all other countries.[11] Instead of higher prices leading to a balance of payments crisis, unemployment, or instant devaluation of the currency, high-wage countries simply consumed more of their own goods, trading amongst themselves (cf. Maizels 1963). This is one mechanism by which the appropriation of environmental services takes place. Since this theoretical framework refers to appropriation via the price mechanism, the claims to a share of in societal output are accounted for in term of worker wages, capitalist profits, and government (indirect) taxes. In the environmental accounting framework of Paper 1, appropriation (consumption-based accounts, environmental footprints, etc.) refers instead to the final consumption of countries, divided into household consumption, business investments, and government expenditure.

Third, on biased technologies and the development gap. An exogenous wage gap will set in train the process of divergent development: higher wages favour specialisation and investments in more productive, capital-intensive technologies that may not be profitable at lower wages. The argument is now familiar to economic historians from Robert Allen's work on the industrial revolution and its spread (Allen 2009, 2014) but is here placed explicitly in the context of international specialisation. The same argument can be made with respect to qualified labour: a

[11] While productivity in poor country primary production increased, 'a large part of the benefit was transferred to the industrialized nations via the relative decline in the prices of primary products. Increased primary production, combined with favourable terms of trade, contributed significantly to higher consumption levels in the West during the 1950s and 1960s' (van der Wee 1986: 57).

more productive employment that also requires more years in school may only pay in high-wage countries: 'Cheap muscles phase away brains and machines in the low wage countries, while brains and machines displace costly muscles in developed countries' (Emmanuel 1975: 25).[12] In the context of Paper 1, this also suggests why there may be a correlation between environmental factor flows caused by higher final consumption and those caused by higher environmental efficiency, i.e., between the income effect and the technology effect. A more productive or environmentally efficient technique may be profitable in high-wage countries but not in low-wage countries, at least if it is also more capital or knowledge intensive. All this assumes that investment decisions are determined by market forces (made by capitalists), which is not necessarily the case. Where investment decisions are made politically or are guided by politically instituted incentives (e.g., Soviet planning, or East Asian 'developmental states', most recently China), leapfrogging to more recent and efficient technologies and more qualified labour is a clear option. (As institutionalist economic historians like to point out, so is holding such investments back).

While Papers 1 and 2 may seem harsh against 'ecological unequal exchange' and to reach conclusions favouring mainstream comparative advantage, they are essentially guided by these three theoretical insights from 'unequal exchange proper'. However, as argued in Paper 1, the income (and technology) effect on environmental factor flows is less visible for those originating in the organic energy economy (because poor and rich consumption is more similar) and more visible for those in the mineral energy economy (because poor and rich consumption is increasingly dissimilar); it is also less visible for apparent than for final consumption or appropriation, because the former includes inputs to goods that are then exported to final consumers, where high-income countries are overrepresented. Finally, in a market economy, the technology effect is not independent of the income effect, although this general rule *may* be sidestepped by politically guided investments.

[12] 'Movements in the commodity terms of trade are of the order of 15 per cent up or down over twenty years, whereas the disparity in the factoral terms of trade is of the order of several hundred per cent. Given this difference in the factoral terms of trade, the opportunity which international trade presented to the temperate settlements was very different from the opportunity presented to the tropics. The temperate settlements were offered high income per head. From this would come immediately a large demand for manufactures, opportunities for import substitution and rapid urbanisation. Domestic saving per head would be large. Money would be available to spend on schools, at all levels, and soon these countries would have a substantial managerial and administrative elite of their own. They would thus create their own power centres, with money, education and managerial capacity, independent of and somewhat hostile to the imperial power - so that Australia, New Zealand and Canada had ceased to be colonies in any meaningful sense long before they acquired formal rights of sovereignty. The factoral terms available to them offered the opportunity for full development in every sense of the word. The factoral terms available to the tropics, on the other hand, offered the opportunity to stay poor' (Lewis 1978: 192).

3.3 Environmental limits and climate as an agent of change in organic energy economies

As noted in section 3.1 above, the energy and environmental economic history tradition on which this thesis leans build on a Schumpeterian paradigm emphasising complementary technologies in consecutive industrial revolutions and their market-expanding phases of globalisation. However, this paradigm is difficult to fit into the preindustrial early modern or medieval periods.

A mineral energy economy is protected from climate impacts on energy supply, if not demand. It is evident, however, that an organic energy economy would be more exposed to both limited land availability and the effects of climate variations on both supply and demand. Here, Malanima's (2006: 101) dual emphasis on population and climate has proven useful: 'The rapid growth of the European population from the second half of the seventeenth century onward, on the one hand, and worsening climatic conditions, on the other, determined an energy crisis and a lowering of living standards, especially in the second half of the eighteenth century and the first two decades of the nineteenth.' This decline in per capita energy availability should be understood as including food, feed, and wood fuels. Because these energy sources were land dependent, Europe's problem can also be phrased as an increasing shortage of land, which was in turn met through an intensification of land use starting in the 16th century, and the overseas expansion leading to the 'Columbian Exchange' (Crosby 1972). For Malanima (2010-11: 19) these developments included the colonization of new lands, the introduction into European agriculture of new, more productive, crops, and new forms of rotation, but also a resort to coal. Based on Eric Jones (1981, Ch. 7) one may also add a number of ways in which Europe added 'ghost acreage' through trade and fisheries, as developed further in Papers 2 and 3. In a general sense, Malanima thus makes a case that population growth (in limiting per capita land/energy and raising total demand for land/energy) and climate cooling (limiting yields per acre and raising per capita demand for energy) contributed to the coal transition by raising the price of land-dependent energy more than that of coal. Paper 4 develops ways to quantify this or similar climate hypotheses.

Malanima's argument on population and land shortage is almost commonplace among economic historians. His engagement with 'climatogenic social change' (as opposed to anthropogenic climate change), on the other hand, has not been much pursued by other energy historians (although cf. Fouquet 2008) and has not fitted into the main paradigms of medieval and early modern historiography.

In Western tradition climate and geography have more commonly been invoked to explain static characteristics of peoples than as an agent of change (Montesquieu, *De l'Éspris des lois*, 1748, but cf. Buffon's idea that the Earth was cooling down; White et al 2018, Ch. 1 & 36; Bonneuil and Fressoz 2016). With the appearance of geology and theories of evolution in the nineteenth century, nature started to be seen as more changing, albeit still mostly slow-moving or cyclic, while humans also started to be seen as subject to the forces of nature. Economists and economic geographers tried to link sunspot or precipitation cycles to business cycles and changing grain prices (Beveridge 1922; cf. Ljungqvist et al 2021: 2, on Eduard Brückner). In the early twentieth century, Ellsworth Huntington linked geography and changing climate to the rise and fall of civilisations, a topic which has continued to tickle scholarly imagination, especially when remote in time or space.[13]

In the post-war period, climate and other natural agents were commonly relegated to the side-line of history. This can be attributed to 'the deep-rooted separation of human and natural history' (Ljungqvist et al 2021: 2), reinforced by the association of environmental determinism and holism with Nazi ideology (Bramwell 1989, Matz 1978). A pioneering, multidisciplinary study by Hubert Lamb (1965: 16) lamented that 'all effects of climatic deterioration between about 1300 and 1600 upon the human economy in Europe, south of 60°N, have usually been attributed by historians (except, significantly, in Scandinavia) entirely to the Black Death and other disorders'. Scandinavians may indeed have been more open to the idea of long-term climate cooling as an agent of change. Svante Arrhenius' interest in the Ice Age led him to investigate the role of CO_2 and to propose that the ongoing burning of coal would cause a warming of the global climate (something he applauded). The fate of Scandinavians on Greenland and Iceland has fascinated Nordic scholars almost as much as that of Polynesians on Easter Island. Gustaf Utterström (1955) could draw on several Nordic predecessors when arguing that climate deserved greater attention from economic historians, notably the effects on agriculture and population of transitioning from a warmer medieval to a colder early modern period.[14] As noted in Paper 4, Lamb inspired historical research at the Climate Research Unit and elsewhere, but in the 1980s interest there shifted towards statistical climatology and climate modelling.

English postwar historiography was instead dominated by schools of thought which downplayed climate, although it could take note of the weather (Jones 1964, Overton 1989). According to Mark Bailey (2021: 3), both Malthusian and Marxist interpretations 'are essentially anthropocentric and deterministic models of long-

[13] Archaeologists have been more open than historians both to adopt methods from the natural sciences and to include climate as an explanatory factor; cf. McCormick 2019: 5, 18f with references. On Roman and Late Antiquity climate studies: Marx et al 2018, Sessa 2019, Harper 2017; on Angkor, Cambodia: Buckley et al 2010; on Ming China: Jingyun et al 2014, Fan et al 2015; on pre-Columbian America: Bocinsky et al 2014, Douglas et al 2016).

[14] The expressions 'little ice age' (LIA) (Matthes 1939) and 'medieval warm period/epoch' (MWP) (Lamb 1965) were so named by analogy to the much colder and drier true ice ages (last glacial maximum, c. 22,000 years ago, being some 5°C colder than the Holocene) and the warmer and wetter mid-Holocene warm period (6000–3000 BCE), seen as milder and shorter-term fluctuations on the longer-term trend of neoglaciation. Lamb's may have been the first quantitative assessment of the decline between the MWP-LIA decline, at least for England, drawing on 'multifarious evidence of a meteorological nature from historical records, as well as archaeological, botanical and glaciological evidence' (Lamb 1965: 14).

term development, in which human agency triggered production crises that in turn generated major and predictable structural changes. External or chance events, such as epidemic disease, do not fit comfortably within such models, except as catalysts or accelerators of trends already in motion.' From the perspective of these two supermodels, he concludes, quoting Hatcher (1981: 5f) 'to admit a [major] role to autonomous disease is to threaten to reduce the aspiring scientific historian to a mere chronicler of the random and bizarre'. This of course assumes that nonhuman factors such as epidemics or climate can only be 'external or chance' or 'random and bizarre', the equivalent of bank robbery to the history of banking (de Vries 1980: 603). Given the limitations of climate reconstructions at the time, historians may be excused for thinking that 'in the long term the human consequences of climate seem to be slight, perhaps negligible, and certainly difficult to detect' (Le Roy Ladurie 1971: 119). Since then, millennial-scale climate reconstructions have taken a giant leap forward, especially in recent decades due to the controversy surrounding the scale of medieval compared to recent warming, and the amplitude of cooling in between.

In interpreting climate-society interactions, there are evident disciplinary differences between 'the two cultures' (C.P. Snow 1959). Historians favour multi-causal explanations and endogenous factors where physical scientists prefer exogenous factors and more direct lines of causality, sometimes leaving them open to charges of reductionist mono-causality (Ljungqvist et al 2021: 15, Campbell 2010: 282). Climate historians have a foot in each camp and try to tread a middle way, building on a conceptual climate-society impact order model first introduced by Ingram et al (1981), modified by Pfister (2005), Krämer (2012, 2015), Luterbacher and Pfister (2015), and Ljungqvist et al (2021). Responses to climatic change and weather extremes are structured into first- to fourth-order impacts, starting from the supply-side bottom. First-order, biophysical, impacts affect biomass production (quantity and quality of primary products)—historically, the food, feed, and fuel energy sources of organic economies (Wrigley 1988, Kander et al 2013)—the built and natural environment, water availability and microorganisms. Second-order impacts refer to the socio-economic effects on livelihoods, economy and health, and concern the availability and prices of primary products, markets and transportation systems, human and animal diseases. Third-order impacts concern the social and demographic implications: changes in mortality, fertility, migration, human well-being, subsistence crises, social conflicts. The fourth-order impacts refer to adaptations and cultural responses. Ljungqvist et al 2021: 15) instead see fourth-order impacts as permeating all levels but also note that 'relatively few […] studies contain a verifiable chain of causation from first-order (bio)physical impacts to third-order impacts related to socio-political change, let alone to fourth-order cultural impacts.'

To the extent that the rapidly expanding community of interdisciplinary scholars studying the 'history of climate and society' (Degroot et al 2022) has been concerned with energy, focus has been on food production and (faltering) supply.

Two of the most studied periods in European climate history are the Great Famine of 1315–1317/21 (e.g., Campbell 2010, 2016) and, especially, the early-modern LIA. Ljungqvist and colleagues (2022) have found a European-wide and interdecadal inverse correlation between early-modern temperatures and grain prices, with regional and short-term aberrations being evened out by trade. Another study has identified anomalous cold conditions—especially in 1550–1710 and interacting with societal stressors—as 'the main environmental backdrop for severe food production crises that could result in famines in pre-industrial Europe' (Ljungqvist et al 2024). A recent overview of medieval and early modern climate historiography in Europe concludes: 'Studies focusing on other (bio)physical impacts, unrelated to food production, are rather few', and none in the review concern the climatic impact on fuel production or consumption (Ljunqvist et al 2021: 7). Emphasis has remained on LIA cooling leading to lower energy (read *food*) supply rather than higher energy demand.

As a scholar of the successful Dutch Republic, Dagomar Degroot is clearly sensitised to the limitations of the gloomy order-impact model. Degroot et al (2022: 11) thus advertised the need for 'process models that generalize mechanisms, and thereby provide novel ways to conceptualize how climatic changes spur large-scale social changes', notably 'how climatic changes influenced the availability, quantity, and character of energy accessible to human populations', regretting that 'such approaches are still in their infancy'. Elaborating on Wrigley's vision of the organic economy, Degroot (2018: 17) concluded: 'The history of climate change is closely related to the history of energy'. The relative success of the Dutch Republic during the chilliest phase of the LIA is partly traced to 'how the Dutch used energy, and how much they had to use' (Degroot 2018: 18). While most other societies were held back by the strictures of organic economies and staple-crop growth that was negatively affected by LIA cooling, the Dutch benefitted 'by exploiting the energy of wind on the relatively friction-free surface of water. Often, weather that undermined the supply of useable energy for farmers and pastoralists actually increased how much energy the Dutch could use on their ships', while entrepreneurial efforts added innovations to 'efficiently harness energy from wind, water, and peat during the chilliest decades of the Little Ice Age'. Of these, Degroot considered especially how changing wind patterns affected waterborne transport and warfare, leaving the relation of peat consumption, domestic heating, and climate unexplored. It nevertheless seems clear that the touchstone in this case, and in studying climate impact on domestic energy use would be the transition to coal in England.

Paper 4 argues that this four-order conceptualisation is biased towards production and supply over consumption and demand (cf. Sahlins 1976). Compared with the focus on supply in the standard order-impact model, Malanima's economic focus suggests that equal attention should be paid to demand, observing (in Kander et al 2013: 72) that 'energy supply and demand are closely related to climate'. Given the physiological need to maintain core body temperature at 37°C, which is as essential for survival as food or water, a warmer or cooler climate would also have 'first-order impacts' on consumption, for example, of energy, clothing, and/or building materials, without first passing via effects on the production of these goods; second-order price effects can follow equally from climate induced changes in demand as in supply, etc. In addition, the freezing of waterways (de Vries 1977, Leijonhufvud et al 2010), shifting wind patterns at sea (Degroot 2018), or more rain leading to muddier roads, can be considered first-order impacts on distribution. An alternative conceptual model could thus start with first order effects on production, distribution, and consumption. Of these, Paper 4 aims merely to consider production and consumption.

Many energy historians have pointed out that the driving force in the early adoption of coal was the rising domestic energy consumption, especially demand emerging from London. For London, William Cavert (2017) could show that non-industrial coal use was already more than 50 per cent by 1575 and 90 per cent by 1650. Robert Allen (2009) even spoke of the coal-burning house as a kind of macroinvention originating in London in the mid-16th century that could then spread to the rest of England, pulling coal consumption along with it. This is presented as an alternative explanation to the traditional wood famine caused by rising populations and rising organic-energy prices. These observations on residential heating as the driver of an early transition to coal, especially around London, were crucial in suggesting a role for climate cooling in the transition to coal. Paper 4 builds on and contributes to these debates by developing alternative ways to quantify both of Malanima's climate-energy links in the English organic energy economy: potential wood fuel supply (=availability) and latent fuel demand (=requirements). Conceptually, this is done via the effects of climate cooling on the length and temperature of the growth and heating seasons (i.e., the opposing trends of growing degree days and heating degree days respectively). The model also incorporates the opposing trends created by population growth, leading to higher overall energy (or fuel) requirements (latent demand) at the same time as it lowers per capita (organic) energy availability (potential supply) by shrinking total and per capita woodland area. However, combining both organic energy supply and fuel demand, it becomes evident that climate can affect other kinds of demand than just fuel, most evidently clothing. Indeed, Paper 4 shows that even with coal, fuel supply would normally not have sufficed to keep houses warm, suggesting that significant extra clothing, or other means to keep warm, would have been required. This climatic impact on fuel production and consumption, clothing and housing would be in line with McCormick's (2019: 23) summary of the Holocene as 'characterized by the march of technologies—shelter, clothing, heating, etc.—that can mitigate climate change to one extent or another.' Future study should thus aim to expand the focus of Paper 4 on fuel and heating to include also shelter and clothing.

4 Methods and data

Much of the effort in this thesis has been to identify, collate and synthesise existing data. Methods of synthesising history are generally poorly developed, if they can even be called methods and not art. As an approximation, we can imagine two main ways: top-down and bottom-up.

In working top-down, you apply a theoretical raster or a hypothesis on historical materials to create your story, or even let them guide your search for materials, testing how much will fit in and either filtering out what does not or leave it in it as decorative dissonance and anomaly. Contrary to a simplified Popperianism the most fruitful approach is rarely to abandon your hypothesis with the first sign of anomalous data. Rather, hypotheses (at least if they are any good) have a trajectory or destiny of their own that needs fulfilling. ‘Give me a fruitful error any time, full of seeds, bursting with its own corrections.’[15] As you solve some problems, new questions may appear that you couldn’t imagine before, and discoveries multiply.

Working bottom-up, you pour your material into a big pool, dive into it, swim around, get up and muse on the side, dipping a toe or two before diving in again, and repeat this process until a pattern emerges.[16] A difference that makes this approach synthetic rather than primary is the nature of the data: the latter likely relies more on primary documents and emphasis may lie on collecting the data in the first place; the former draws more on data collected by others in an attempt to get a broader picture. Contrary to old-style empiricism, it cannot be assumed that patterns are already in the data, and it seems more probable that some innate faculty of the human mind forces itself upon and obliges the researcher to start applying patterns. Of necessity, these patterns cannot be wholly isolated from the materials and data at hand to the imagination. Ideally, you could then start using your patterns as hypotheses or raster to be tested as in the top-down approach. However, it is not

[15] Commonly ascribed to Vilfredo Pareto as a comment on Kepler, this is instead a slightly erroneous rendering of a comment on Pareto’s comment on Kepler, by Curtis Jr. and Greenslet 1945: 55; cf. https://quoteinvestigator.com/2024/08/02/fruitful-error/; accessed 4 May 2025. Pareto’s comment reads: ‘It was a fortunate circumstance for the foundation of celestial mechanics that in Kepler’s time observations of the planet Mars were not very exact. If they had been he would not have detected an ellipse in the curve traversed by that planet and so would not have discovered the laws of planetary movement’ (Pareto 1935: 322f).

[16] ‘Having collected an enormous amount of facts, Innis seems to have ‘leapt’ to a conclusion based on the sudden realization of a pattern in these mounds of facts’ (Watson 2006: 289).

evident that the emerging pattern will always have a ready explanation, which would be the main virtue of a hypothesis.

Applied to the methods of the articles in this thesis, Papers 1 and 2 are closer to the bottom-up and Papers 3 and 4 to the top-down approach.

4.1 Collection, collating, and bottom-up syntheses

Papers 1 and 2 sprang from an effort to systematically review the state of quantitative knowledge on trade-embodied environmental inputs and impacts (environmental indicators or factors), most of which have appeared only after 2006 when I last took an interest in the topic (Brolin 2006). It soon became apparent that there was an overwhelming number of studies for more recent decades, and a decision was made to limit searches to global studies. If the geographical limits had thereby been reached, the question of chronological limits naturally arose, and this remains an organising principle of Paper 1. This also provoked the question about how far back in time more local studies reached, and after setting the limit at national level studies (there are also numerous long-term studies on a municipal level), this became an organising principle of Paper 2. The idea was to leave it at that and apply for funding to fill out the global picture back in time. The papers helped to delimit one another: since global studies reached back at best to about 1950, only those national studies that reached beyond that date would be considered.

For Paper 1, additional questions on which indicators to include or exclude had to be solved, and when deciding to include as many as possible, on how to organise them. (Because of the limited number of studies for the pre-1950 period, the question of which indicators to include posed no problem for Paper 2). This was initially solved bottom-up, drawing especially on multi-indicator studies (and a few reviews that appeared along the way), but eventually became more systematic, organised according to the most important elements of global biogeochemical cycles, borrowing insights from social ecology on material and energy flow analysis, and largely confirmed by studies on planetary boundaries. Figure 5 suggests how indicators fit into an overall ecological economic (or Earth-system) framework, assuming mass and energy balance and distinguishing between inputs into, outflows from, and changing size of the economic system.

As indicators began to crystallise from initial searches, review articles, and multi-indicator studies, various search engines were used to identify more studies. Most commonly this was LUBsearch (for reasons of accessibility, including journal subscriptions) provided by Lund University. At the time (2020; it was replaced in 2025) it allowed simultaneous searches of 135 subject databases and database platforms such as EBESCOhost, JSTOR, Science Citation Index, Scopus, Web of Science, etc, which were also used directly for their featured recommendations and citing articles. Key terms included indicator names, combined with ‘trade’, ‘embodied’, ‘virtual’, ‘footprint’, consumption based’, ‘multi-regional input-output’, adding ‘global’ and ‘international’ when results exceeded several thousand articles. A first filtering was based on titles and keywords for the first two hundred articles for each combination. In doubtful cases, abstracts were perused, and finally whole articles. Within articles, references were perused, and references within references.

Ideally, studies were only retained if (1) they presented empirical estimates of actual flows (rather than being, e.g., reviews, methodological, or policy oriented); (2) these flows referred to totals of the respective embodied environmental indicator (in the case of ‘land’ only including estimates in areal, not value, terms), excluding environmental indicators associated with individual commodities or groups of commodities; (3) the flows were between nation states or groups of nation states, excluding flows on regional or municipal level, or between individual industries or industrial sectors (even when these flows were global); and, finally, (4) they were ‘global’ in the sense that a significant number of countries are included with representatives from several continents. A more complete description of the process, the indicator and key terms, and the criteria for inclusion, can be found in the Appendix to Paper 1.

It was not evident how or even if you could summarise the findings on the trends and direction of trade-embodied inputs and impact of, in the end, over 350 studies in a single article, but an attempt was nevertheless made. Given the interest in expanding temporal horizons, emphasis was placed on studies covering the longest-term for each indicator. This implied a bias for studies of direct flows, based on physical amounts of traded goods taken from United Nations COMTRADE or FAO statistics that reach back to about 1960. Methodologically, these studies commonly apply some environmental coefficient to these physical amounts to get their results. By contrast, studies of indirect flows, such as CO_2 emissions or based on final rather than apparent consumption, have tended to use environmentally extended multi-regional input-output (MRIO) tables. These commonly rely on monetary flows, extended with environmental accounts, and on a global scale are much more limited in time—at the time of writing reaching back at best to 1986 and commonly less (although less comprehensive MRIOs, also using UN COMTRADE, aim to reach back to 1970). The different findings and merits of using the one or the other approach have been intensely debated over the past decades, and hybrid versions have been developed. Paper 1 (Table 1) has tried to stay clear of these debates. The only contribution was an attempt to disentangle the confusing array of terminologies by organising indicators (partly based on the source material used) along a value chain that starts with extraction, passing via more direct flows and variously termed levels of production and consumption, and ends with indirect flows and final consumption (appropriation, consumption-based accounts, or footprints). Because of these differences, attempts were made to reflect on and summarise findings from both approaches for the same indicator. There were additional issues concerning the short time span of especially MRIO-studies—many of a single year—so that the pattern of flows might change between studies comparing different years or periods.

Another problem with comparing studies was that they included different countries and/or used different regional divisions when comparing flows, so that seemingly contradictory conclusions could be drawn from similar flows. On the other hand, different geographical groupings may be relevant depending on indicator, say virtual water or SO_2-emssions. These issues were resolved by returning to the published data (where available) and to the extent possible dividing those into consistent units. This could involve substantial collating, some correction, and in a few instances even recreation of data.

The units used were, on the one hand the division by the United Nations Statistical Data (UNSD) into developed and developing countries and on the other their division into world regions, albeit with some modifications. The former is useful for saying something on rich and poor countries (at least historically) and the latter for saying something on the geographical characteristics and physical endowments.

Using developed and underdeveloped has the benefit of coinciding with the division used in the Kyoto climate accord, which made it a common topic in many studies on trade-embodied CO_2. Another division that might have been more informative although ultimately not used, is the World Bank's fourfold country grouping into low, lower-middle, upper-middle, and high income. A problem with any of these groupings is that they change over time. This would have been accentuated with the fourfold division, which logically would have required reclassification as countries traverse income thresholds. The developed and underdeveloped categories seem more, but not completely, stable. For example, South Africa became 'underdeveloped' only *after* apartheid. Many underdeveloped countries have made staggering progress towards development, notably in East Asia, although only Japan has traditionally been included. The Soviet Union was 'developed' but Russia became an 'upper-middle income' country after its fall (after halving its GDP/cap) and is a founding member of the BRICS countries which are otherwise looking increasingly like the former underdeveloped countries or 'global South'. Many studies draw conclusions on developed/rich vs underdeveloped/poor country trends or direction of flows, even when these are completely determined by China becoming the 'factory of the world' and coinciding with its large-scale elimination of poverty.

Many of these concerns are avoided or revealed when looking instead, or also, at the UNSD world regions. The principal gain in using UNSD world regions is to avoid some of the absurdity in using 'continents', as is still common (unfortunately also in Malanima 2022), where 'Asia' contains two thirds of the world's population, and roughly 100 times more than 'Oceania'. Oceania is nevertheless interesting in being a developed/high-wage region—studies usually only include Australia and New Zealand—that is also a major net exporter of environmental inputs (similar in many ways to North America). Concerning Asia, East, Southeast, and South Asia each have their own group. On the other hand, Western Asia has been combined with Northern Africa as is common, e.g., in studies of virtual water. Similar considerations make it useful to separate Central America & the Caribbean (which is dry and an importer of food) from South America (which is wet and an exporter of food), rather than including both in a common Latin America. Northern Asia, to the extent that some studies had such data, was included in a 'Former Soviet Union and Allies' (FSU-A), which was necessary for comparison with the longer-term studies. In most cases FSU-A coincided with Eastern Europe, including Russia. East Germany was nevertheless united, where possible, with West Germany, to create one, statistically consistent Germany. Trying to use the European Union, or Community, etc, would still involve deciding which countries to include and then what to do with the 'rump'. Many studies end up with a sometimes considerable 'Rest of the world' category that creates uncertainty—for example, also by including major rich and raw materials exporting countries such as Canada or Australia. Using one Europe, including Russia, seemed to invite unnecessary agglomeration and not contribute to understanding. East European sensitivity to being included in the same group as Russia has increased since Paper 1 was written. Such concerns have not been considered either with respect to including China and Taiwan, North and South Korea, or any of them and Japan, within 'East Asia'. The difference between the Middle East & North Africa and the West Asia & North Africa is that the latter excludes Iran (which *may* be a political consideration by the UNSD), which is instead grouped with South Asia. Sub-Saharan Africa could probably have warranted further subdivision but, as can be seen from the study, any trade-embodied flows into or out of this region are already small.

The ultimate groupings are thus a mixture of historical, geographical, and pragmatic considerations. Further subdivision would make already burdened figures overburdened—some might say that this limit has already been transgressed. (A complete list of countries included in each of the figures can be found in the Appendix to Paper 1). I believe that using these groupings, based in a general sense on respectively 'endowments' and 'wealth', was revealing in many ways, and suggestive for future and more analytical studies. It helped see the similarities in scale, direction, and trend between environmental inputs and impacts originating in the organic economy, and their common differences in these respects from environmental factors originating in the mineral economy. This was an example of bottom-up pattern recognition or synthesis.

Finally, partly also in the hope of inspiring future study, the temporal horizons in trade-studies were compared with those of global, non-trade, studies for the same indicator. This involved dividing production-based accounts into the same geographic and developmental groupings, at the same time allowing comparison of the scale of trade-embodied flows to total input or impact. In a few cases, where studies presented their own data only in terms of consumption-based accounts rather than trade-embodied flows, considerable manipulation was required to try to reconstruct these flows from comparison with production-based accounts.

Although this was considered enough for one article, especially since it was presented as a review (which has a higher word limit in many journals), it would have been better if the accompanying interpretation in terms of population densities and GDP/capita had been more systematic and analytic. At the time of writing, this type of analysis was instead projected for follow-up studies. Malanima's (2022) compilation of world energy consumption in 1820–2020 was still unavailable, and at any rate did not include trade-embodied flows, but has been included in section 2 above, divided along the same geographical lines as in Paper 1.

For the period before 1950, there were quantitative estimates for only four trade-embodied environmental indicators: materials (in tonnes), land (in acres, etc), water (in km^3), and energy (in Joules). Paper 2 made a similar distinction as Paper 1 regarding what would count as an environmental indicator. This excluded numerous accounts by economic historians of exports and imports in physical terms (in tonnes) but which did not attempt complete accounts of such material flows, and/or were not explicitly environmental in intent. A complete review of all economic histories and statistical accounts with trade data in physical terms would have been an undertaking on a different scale—basically a research project on its own, for which Paper 2, like Paper 1, was indeed intended as a preparatory step. For 'land' only studies accounting in areal units (not values) were considered. The fragmented nature of many of these studies did not allow sticking to the norm of completeness—only one study took account of ghost-acre exports from the UK, and most only a few selected imports.

For Paper 2, the natural organising principle was along national lines (presented in order of number of publications, meaning first the UK and then the rest of the developed world). At the time of writing more recent studies of Latin America (Infante-Amate et al 2022), but also of France (Magalhaes et al 2019), were still unavailable. Given the absence of quantitative studies on less developed regions, it seemed pertinent to reflect also on the numerous qualitative studies by environmental historians attributing detrimental environmental effects to developing-country exports. The comparison between Great Specialisation (or comparative advantage) and Great Divergence (or ecological unequal exchange) was part of the analysis early on but became the main organising principle only at the very end. Great Acceleration (=early trade insignificant) was added as a reminder of the relatively small scale of trade compared with recent developments in Paper 1, but for obvious reasons this stance was not much represented among scholars devoted to studying early trade. As in Paper 1, the conclusions of the authors themselves are discussed less than their actual quantitative estimates and the conclusions which can or cannot be drawn from them. Thus, again, the paper is more a synthesis than a review.

4.2 Developing quantitative methods for top-down hypothesis testing

Papers 3 and 4 are more concerned with making proper quantitative estimates, and a characteristic is perhaps that they move, relatively effortlessly, between economic and natural-scientific type arguments, in a vein reminiscent of environmental accounting or ecological economics. Paper 3 continues the debate on ghost acres from Paper 2 but brings it back to the period before 1800 and into the context of ocean fisheries and seafood consumption. Since 'fish acreage' has not been estimated before in historical studies, the first thing to do has been to develop a methodology. A precondition for making this attempt is the recent appearance of quantitative estimates (from scholars based at Trinity College, Dublin) of fish catch and seafood consumption in metric tonnes, and the problem to be solved becomes how to translate them into meaningful areal units.

Here, a distinction was made between how much land was 'alleviated' and how much ocean surface was 'appropriated'. The former resulted in a more economic transformation equation (based on the output of milk protein per cow and area per cow), and the latter in a more natural scientific one, based on the surface of net primary production required per unit of fish catch. The resulting estimates for Western, or more properly Atlantic, Europe—Sweden, Norway, Denmark, Iceland, Germany, 'Netherlands' (or Benelux, including Belgium and Luxemburg), Scotland, England (including Wales), Ireland, France, Portugal and Spain—are then compared both with one another and, to illuminate the Great Divergence debate, with estimates of English coal and yield acreages. The latter estimates are also relatively novel. Coal acreage is simply based on alternative woodland yields and the corresponding energy content of coal and air-dry wood. Yield acreage is based on the percentage yield increase multiplied by the area of respective crop: wheat rye, barley, oats, and pulses. This increase was calculated from total output and sown area (excluding fallow lands) from Broadberry et al 2015. The idea is not new, and in the present case was borrowed from Wrigley 2016 who applied it to London consumption. Here, it is applied to England, using yields around 1500 as base, to align with the start of the fish acreage estimate.

Paper 4 is similar to Paper 3 in developing methods that end up being expressed as equations. These equations instead allow using population and woodland area, on the one hand, and per capita fuel requirements and woodland yields, on the other, to determine potential wood fuel supply and fuel requirements. Per capita requirements and yields are related to climate variables which then allows determining the role of changing climate in comparing potential supply and latent demand. The main idea behind this article was conceived while writing Paper 1, although it has taken several years to execute. The study was inspired by the idea that the Little Ice Age cooling contributed to the energy transition to coal in early modern London and England. Coming up with ways to test this proposition has meant that developing the methodology became as important as any conclusions drawn from the results. Starting with the two leading explanations of the transition, Paper 4 suggests shortcomings and complements them by adding climate cooling as an extra stimulant. In the end this meant comparing England and the London supply region along the Thames, on the one hand, in 1300 and 1600 when populations were similar (thereby neutralising this aspect of the traditional explanations), and on the other in the intervening period, especially the rapid and sustained cooling after around 1500, which could help explain the timing of transition in spite of chimneys and coal being available already by the early 15th century (contrary to another aspect in the traditional explanations).

The method constructed for Paper 4 basically consists in deriving two equations: one for potential wood fuel supply (in tonnes of wood equivalents), based on woodland area and woodland yields, and another for fuel requirements, based on population size and requirements per capita. Woodland size is then determined partly from an inverse relation with population size—making the equations inversely related. Woodland yields and per capita requirements are also inversely related, but in this case via climate, where lower temperatures imply lower yields and higher requirements. Yields are determined by drawing on ecological theories relating net primary productivity to temperature and precipitation. (Thus, apart from temperature, the estimate of yields also accounts for the possible impact from changing precipitation). Per capita requirements are derived by relating European per capita consumption estimates for the early nineteenth century to the difference in temperature between regions. When these relations have been established and all the included variables and coefficients determined, then the relevant climate data are inserted into the equations. To see the contribution of coal, English coal production and coal imports to London were translated into wood equivalents (based on the energy content of air-dry wood). Apart from these quantitative exercises, more qualitative efforts have been made to document the medieval occurrence of chimneys in England, distinguishing between urban and rural usage.

The way in which these equations are derived in the paper are of course not how they were worked out over time. Instead, the final relations were the last problem to be solved and the climate reconstructions to be used as ‘data’ inputs the first. In the final version, this ended up being the revised PAGES2k gridded temperature reconstruction in Ljungqvist et al (2019), using the grid that encompassed London and most of its region. These temperatures are then translated, via growing and heating degree days, into woodland yields and fuel requirements. Together with an estimate of woodland area (in Paper 4 derived from benchmark estimates for 1086 and c. 1300 and population estimates, modified from Broadberry et al 2015). All these conversions involve either making reasonable assumptions or deriving regression equations from recent periods and using these to hindcast the unknown variable back in time. Optimally, the reconstructed variable should then be checked against some independent facts—e.g., how many days houses/rooms were actually heated, using how much fuel, etc.—but, in practice, such verification often remains an ideal more than a real possibility. For example, unlike some other early modern cities, London has no surviving records of wood imports (William Cavert, pers. comm.). Certain reality checks can be introduced, such as changing coppicing cycles, reported yields, fuel allowances, or indoor temperatures, and these can no doubt be multiplied in due course (the Appendix also reports findings from house heating experiments, suggesting how much airspace could have been heated by the fuel available). Medieval and early modern economic historians may be more at ease with such lose ends, since this is the case even for many estimates of population, GDP, and (somewhat to my surprise) prices. We are aware that even our best numbers are approximations destined to be revised (just as the present version is a revision of earlier ones, where e.g., woodland area was adopted from Kaplan et al 2009, woodland yields derived from changing coppicing cycles, or by regressing temperature on modelled aboveground net primary productivity over the twentieth century, or where none of these estimates were made, and the argument presented solely in terms of growing and heating degree days, etc.). However, putting things into numbers can also reveal new relations. Part of the point of trying out a hypothesis is that it generates new questions that require answers and perhaps new reality checks. One of the revelations of Paper 4, is that potential fuel supply would have been inadequate for heating requirements even when including coal, so that an estimable amount of indoor clothing would have been required in addition.

5 Results: Summaries of the individual papers

Paper 1 (with Astrid Kander). 'Global trade in the Anthropocene: A review of trends and direction of environmental factor flows during the Great Acceleration', *The Anthropocene Review* (2022), Vol. 9(1): 71–110.

Author contributions: Conceptualisation, literature review, methodology, data curation, formal analysis, validation, investigation, interpretation, visualisation by Brolin. Supervision, project administration, and funding acquisition by Kander. Writing (lead): original and final draft, review & editing, by Brolin. Writing (supporting, mainly on energy and CO_2): review & editing by Kander.

This article aims to synthesise a field of study concerning global trade and global environmental impacts. It contains a systematic state-of-the-art review, identifying more than 350 global studies of trade-embedded environmental inputs and impacts ('environmental factors'). By the article's cut-off date in 2020 there were at least 70 papers published each year that would have qualified for inclusion—suggesting that as of 2025 there would now be at least twice as many studies. Although published a few years ago, the article may still be the only attempt to include all global studies of both bottom-up (applying environmental coefficients to volumes of traded goods) and top-down approaches (using environmentally extended multi-regional input-output tables). For most of the eight major groups of environmental indicators included in trade studies, it also contains a useful overview of global long-term production-based indicators for comparison. (It is unfortunate that at the time of writing, the global and world regional energy and GHG-emission estimates for 1820–2020 by Malanima 2022 were not yet available).

While published as a 'review' (partly because this allowed a higher word limit) and while an apt description in many ways, rather than reviewing conclusions of others, the article aims to synthesise the findings of existing studies through reanalysis or by reorganising their data along common patterns, for as long a period as possible. Part of the article's ambition is thus to inspire extending the temporal horizons of the field. However, in terms of temporal coverage all global studies of trade-embedded environmental factors centre on the post-WWII period—indeed, overwhelmingly on the most recent decades after 1990.

While the article is thereby obliged to focus on recent events, it begins by placing post-WWII global trade in the context of proposed origins of the Anthropocene and 500-years of globalisation. The Anthropocene is/was an attempt to capture humanity's total impact on Earth-system processes in a single term, under the assumption that this impact is now profound enough to qualify for a new geological epoch. Global trade is a neglected topic in these debates, but because of the restrictions of geostratigraphers that the environmental signal should be globally simultaneous, it has come to play an implicit role in several suggested definitions of the Anthropocene. However, trade's role in promoting and shifting environmental burdens around the globe differed substantially between three phases in particular.

First, the Columbian Exchange (1492−1800) was characterised especially by epidemiological, ecological, and agricultural homogenisation—the term 'homogenocene' (Samways 1999, Curnutt 2000, Mann 2011, Conversi and Posocco 2024) actually preceded the 'Anthropocene'—brought about by the transfer of living species, (mostly involuntary) migrants, and diseases, with an early modern global signal in the CO_2-drop produced by reforestation after the depopulation of the Americas (although the deep trough in 1610 proposed by these studies is likely the result of a distorted signal in the Law Dome ice core).

Second, the original proclamation of the Anthropocene dated it to the first (capital-letter) Industrial Revolution, although the CO_2-signal becomes visible only during its market-widening phase: the first globalisation (~1800−1913(/1950). Trade in this era has invariously been interpreted as an exchange of manufactures for food and raw materials but was in truth dominated by the exchange of food and raw materials for other food and raw materials (most notably coal), and what made it stand out was the increased scale of such transfers. The emerging system is perhaps best characterised by its reliance on fossil fuels and a global resource base (Totman 2014), where this resources base is still largely founded in the organic energy economy. While there are no global studies of environmental factor flows before 1950, this is in fact provided for the first time in this article by collecting various estimates in material terms by Paul Bairoch into a physical trade balance between developed and developing countries around 1910. These flows consist mostly of coal exports from the developed world which are balanced by tropical agricultural imports. World grain trade shows up only as grain exports from Argentina (which is classified among the developing countries) to the developed countries but was dominated by intra-developed country trade such as US and Russian (including Ukrainian) grain exports to Europe, and intra-developing country trade in rice. Comparison with intercontinental trade around 1800, suggests a 50-fold increase in physical volume by 1913, similar to the volume increase in monetary terms despite bulk commodities constituting a far smaller share.

Third, the Great Acceleration (post-1950) corresponds to the market-widening phase of the second industrial revolution, where many economic, material, and environmental impact indicators take a sharp upturn. This period is the main focus of the article. For this period as well, an underlying concern in the study of trade and the environment is whether environmental factor flows are (1) to the economic and/or environmental benefit of all, (2) a case of the rich exploiting the poor, or merely (3) the inadvertent consequence of differences in environmental efficiency.

The article tries to illuminate these questions by organising flows according to indicator between groups of countries roughly organised according to geography ('endowments') and development status ('wealth'). The indicators are further grouped according to their proximity to an organic or a mineral energy economy.

We find similarities and systematic differences in the trends and direction of flows between major world regions—organised systematically, as far as possible, across the various studies and indicators—and between developed and developing countries. (The more recent classification into high-, upper- and lower middle-, and lower income countries could have produced even more interesting results, especially if it could have been introduced dynamically, so that countries could move between the groups over time). A major finding is that trends and flows of trade-embodied environmental factors do tend to co-vary depending on whether the environmental indicator is tied primarily to an organic or a mineral energy economy, in turn roughly linked to differences in respectively population density or GDP.

Thus, we find that factors such as land, virtual water, HANPP (Human Appropriation of Net Primary Productivity) and eutrophying pollutants that are related to the organic economy (or direct biomass flows), primarily flow from regions where population density is low to where it is high, and are only secondarily affected by affluence. By contrast, indicators such as energy, airborne pollutant emissions and greenhouse gasses that are related to the mineral energy economy (fossil fuel, metal and mineral use) tend to flow from developing to developed countries. These are in turn explained either by higher consumption rates or greater environmental efficiency in affluent countries, which has similar consequences for net flows. A similar difference can be found depending on the method used in studies, where top-down approaches tend to reflect the final appropriation stage of consumption, and bottom-up approaches reflect flows into intermediate (apparent) consumption. Studies using the former method accordingly tend to underline unequal exchange and affluent country consumption in North America and Europe, while those using the latter tend to emphasise, e.g., rising consumption in and imports into China.

We briefly try to weave the shifting trends and directions of flows among the various indicators during the Great Acceleration into a coherent picture. The early post-WWII period is largely dominated by rising fossil fuel consumption of Western and/or developed countries and the imports required to sustain this. With the oil crisis, and simultaneous computerisation of production, local production of fossil fuels as well as environmental efficiency started playing a greater role. Environmental legislation against SO_2-pollution contributed to a move away from coal and towards natural gas, but the contrasting trends of CO_2 and SO_2 emissions point also to the rising market for sulphuric acid obtained from the process of refining fossil fuels. Other events that become conspicuous in the trends are the collapse of the Soviet Union and the rise of China.

Because of the article's backward-looking perspective—searching to extend the temporal horizon as far back in time as possible—more recent events, such as the halted rise in global trade since 2007 or the recent expanding Chinese trade with the global south (or South-South trade) are only briefly mentioned. This is partly explained by studies often ending their time-series at the latest in 2014 when this trend had just begun. Another issue is that since China is grouped among developing countries, and Chinese exports (e.g., of embodied CO_2) loom so large in North American and European imports, many studies conclude that Western environmental exploitation of poor and developing countries is still predominant, much as it supposedly did in the period before 1950. However, China's role as the factory of the world bears little resemblance to that of less developed and deindustrialising countries of the earlier era. As the article points out, there is much to suggest that before 1950 the industrial nations of the West would also have been net exporters, e.g., of CO_2 and pollutant emissions. A demonstration of this, and other arguments, would require global studies of trade-embedded factor flows also before 1950. To accomplish this feat, the article suggests either geographically extending quantitative long-term national and/or commodity studies, or environmentally extending recently compiled global monetary bilateral trade data for the pre-1950 period. In addition, since the article was written, more has been learnt about the substantial historical greenhouse gas emissions from agriculture, especially cattle and wet rice cultivation, which could modify these conclusions with respect to CO_2-equivalents if not CO_2 per se (cf., Malanima 2022). Similar revisions based on pollutant emissions from inefficient combustion of organic fuels are also possible in the future.

Paper 2 (with Astrid Kander). 'Environmental factors in trade during the great transformation: advancing the geographical coverage before 1950', *Journal of Global History* (2020), 15: 2, pp. 245–267.

Author contributions, etc: same as Paper 1.

This article complements the global focus in Paper 1 by identifying long-term national studies of environmental factors covering the time before 1950, roughly the period of the first globalisation wave or market-widening phase of the first industrial revolution. This was the first use of the term 'environmental factors', as an extension along the line of productive factors, here meaning materials contained within traded goods, or land, energy, water, and pollutants used or emitted in their production. As noted above, environmental factor flows in this period were very much impacted by fossil fuel usage and the geographically extended resource base—i.e., by the transition to a mineral energy economy and a widening reach of the organic economy. But how are these flows to be understood?

Like Paper 1, Paper 2 aims rather at a synthesis of results than at reviewing conclusions drawn by the authors themselves. Indeed, many conclusions of the original authors simply cannot be drawn because of the incompleteness of their underlying results, while several other studies are only marginally concerned with trade at all—yet all results can aid in drawing conclusions of one's own. Paper 2 nevertheless identifies or proposes three conflicting historical interpretations of what characterised flows of trade-embedded environmental inputs and impacts before 1950 and confronts them with existent quantitative estimates.

The first, ‘great specialization’ narrative argues that trade served to lighten pressure on the environment by redistributing environmental services from where they were abundant to where they were scarce. This is easily recognised as following the logic of comparative advantage according to factor endowments. The second, ‘great divergence’ narrative sees an exploitative transfer from poor countries to rich and powerful ones or an environmental load displacement from rich to poor. This can be recognised in the counter-narrative of (ecological) unequal exchange. The third, ‘great acceleration’ narrative dismisses flows as insignificant either way. This is only rarely backed up by actual studies of trade-embodied flows before 1950. However, a notable exception is Paul Bairoch, referred to in Paper 1 above, whose principal argument in this context was that raw material imports into the developed world were insignificant before 1950.

We review long-term national studies of environmental factor flows and find an almost exclusive focus on developed countries, mostly European and especially the UK. Looking at the underlying data, we find that more systematic studies tend to support ‘specialization’ (=comparative advantage) and/or ‘acceleration’ (=trade is irrelevantly small) and very little to support ‘divergence’ (=ecological unequal exchange) in the sense of net flows to developed countries. Notably, both the UK and the US, i.e., the old and new hegemonic and richest countries of the world, were net exporters in terms of material flows and both direct (coal) and indirect (embedded in goods) energy, and in the case of the UK, an evident ‘insourcer’ of pollutant emissions. The UK was a net importer of land, but this is expected from both comparative advantage and unequal exchange and not a very helpful finding. By contrast, it was also a net exporter of land-based ‘ecological footprints’ because the exported coal (either directly or indirectly) is translated into a corresponding woodland area that exceeds the actual land embodied in its imports—again favouring comparative advantage over ecologically unequal exchange. (We also point out that other versions of unequal exchange that merely imply biased flows compared with those expected from endowments may still be valid although potentially hard to test empirically).

These conclusions contrast with those in less systematic and more qualitative studies on individual exports from developing—or ‘peripheral’—countries, which often support ‘divergence’ (notably including Pomeranz 2000). However, as we argue, since these studies have excluded imports by design, such claims can never be demonstrated. Concerning the narratives, there is an obfuscating tendency to blend peripheral countries with poor, underdeveloped, or colonial ones. Now, the peripheries from which the UK or Europe mostly imported were North America, Australia, and the Baltic, and among so called less-developed regions, Argentina. At that point in time most of these regions, including Argentina, were rapidly turning into wealthy settler economies. The exception (as shown in Paper 1 for c. 1910) was in tropical goods which were exported from countries that were both poor and peripheral—but of course also tropical and thus hard to use as evidence against theories of comparative advantage. We suggest that the focus on more complete studies of developed countries but only exports from developing/poor countries may both spring from a mindset where poor countries are mainly of interest as suppliers of rich countries and not as consuming subjects in their own right. Finally, we thus propose widening the geographical scope of long-term national studies beyond Europe (or currently developed countries) and extending existing studies with bilateral trade, and suggest that developing country trade should also be quantified according to existing methods of environmental accounting rather than continuing to focus merely on their exports.

Paper 3. 'Plenty more fish in the sea? Alleviating European land constraints through ocean fisheries, 1500–1800'

Single-authored, unpublished manuscript.

This paper extends quantitative estimates of 'ghost acreage' (used in debating the Great Divergence) more fully into the early modern period and in new directions. This involves estimating the fish acreage of West, or Atlantic, Europe in 1500–1800, comparing them with the coal and yield acreages. As early-modern European populations and organic economies returned to levels before the Black Death, they would increasingly have encountered environmental limits to internal expansion as well as a cooling climate. Growth could be maintained by intensifying land use or by expansion, sending migrants away or drawing in resources from outside. These traditions are represented in economic historical debates by respectively internalist and externalist interpretations of the industrial revolution, modern economic growth, or the Great Divergence in incomes. This article examines a quintessentially external contribution to Atlantic European land alleviation coming from ocean fisheries in 1500–1800. Developing novel ways to estimate ghost acreage, it finds Atlantic Europe's 'fish acreage' from seafood consumption to have hovered at about 7–8 million acres per year. This was more than the contribution from coal until the mid-eighteenth century. However, whereas the coal acreage was concentrated to Britain, the alleviation from fisheries was spread out over all Atlantic Europe, with England's fish acreage being only about 1 million acres, and with by far the highest per capita contribution in the Nordic countries. For comparison, the land alleviation from higher English yields between 1500 and 1800—the 'yield acreage'—was estimated to have been 9–10 million acres, suggesting that intensified land use, together with coal, was of far greater importance for the Little and Great Divergence. This conclusion only refers to land alleviation and does not concern potentially important institutional developments, market access, sea power, etc, sprung from England's (and France's) dominant positions in the Newfoundland fisheries.

The article also distinguishes between the alleviation of land and the appropriation of (the net primary production of) ocean areas, where appropriation turns out to be an order of magnitude greater than alleviation depending on the higher trophic level at which consumption takes place—the consumed fish being the 'tigers of the sea' and being compared with the cows of the land. This phenomenon can be observed more generally also in studies of trade acreage, where yield factors of the importing countries correspond to alleviation, those of the exporting country to appropriation, and the difference between them to the overall societal (world) gains or losses from trade. Judged by this yardstick, the fisheries were an overwhelming societal loss, not to any human community but to the wider community of species.

Paper 4. 'The Little Ice Age energy transition, or: "Did climate cause fossil fuels?"' Single-authored, unpublished manuscript.

This paper focuses on climate (temperature, precipitation) as a potential cause of the mineral energy transition from wood fuels to coal, more specifically how they affect potential wood fuel supply and latent demand. It examines the preindustrial transition to coal, driven by domestic heating, in the London region and England over the medieval and early modern period—or between the Medieval Warm Period and the early-modern Little Ice Age. It seeks to determine the extent to which a changing climate (precipitation and temperature) between warm periods in 1300 or 1500 and a cold period in 1600-1700 contributed to the energy transition to coal in London and England.

Dominant interpretations of the energy transition to coal in London and England in 1550–1700 see it as resulting from a population-resource crisis or springing from rapid commercialisation that led to the invention and spread of chimneys. However, given that populations were as large in 1300, that chimneys became widespread in towns around 1400, and that wood fuels were already twice as expensive as coal, why was there no high- or late medieval transition? This article proposes that in both these instances, climate cooling made a significant and quantifiable difference. The article develops new methods to determine, on the one hand, potential wood fuel supply, from woodland area and woodland yields, and, on the other, fuel requirements from population size and fuel requirements per capita. Woodland areas are determined from existing benchmark estimates for 1086 and c. 1300 and an inverse linear relation with population. Woodland yields and per capita fuel requirements are in turn related climate. This relation also works in opposite ways in that a shorter and cooler growth season will decrease plant (wood) yields while a cooler and longer heating season will increase fuel requirements. Yields are positively correlated with temperature and precipitation, but also limited by the variable that is the least beneficial to growth, which in most cases turns out to be temperature. This is shown, not assumed, by applying three different models that include both temperature and precipitation variables, and the current best historical estimates of either. Fuel requirements are instead negatively correlated with temperature, where cooling increases the days and the degrees in each day that indoor temperatures requires heating to maintain the same level of thermal comfort, i.e., the heating degree-days (HDD). These HDD's can be estimated for different base indoor temperatures but in that case lower base temperatures must be compensated by other means, such as more clothing, sitting closer to the fire, working and (co-)sleeping in the kitchen, etc.

Having derived equations for both potential wood supply and fuel requirements—along the way, estimating woodland area and (modified) population size, identifying the best available temperature and precipitation reconstructions for England and the London supply region, translating seasonal to annual temperatures and precipitation levels, calculating HDD and determining a relation between annual fuel requirements and HDD, etc—then climate sensitive, potential wood fuel supply and fuel requirements at different indoor base temperatures can be determined and compared for both England and the London region. It is clear, and follows already from how the equations are constructed, that the long-term trends are determined by population developments. However, the results also show that climate did have an effect: declining temperatures both pushed down potential wood supply and pushed up fuel requirements between either 1300 or 1500 and 1600–1700 in both England and the London region. When adding effects on both supply and requirements this amounts to as much as 260–330 kg wood-eq/cap/yr, 0.7–0.9 kg wood-eq/cap/day, corresponding to about 17–22 per cent of potential supply in 1300 in the estimate of this study. (This is already considerable, but it should perhaps also be remembered that in Paul Warde's estimate the per capita firewood consumption of sixteenth-century England and Wales was only on the order of 1.1 kg/cap/day). Thus, both the long-term shift from 1300 to 1600–1700 and the rapid short-term shift from 1500 to 1600–1700, was considerable, but there was also an important temperature downswing in the mid-1400s. These shifts can help explain some of the waxing and waning of coal and chimney adoption in urban and then rural settings.

Even more, adding coal shows that it was just enough to halt the decline in potential wood supply, but at a base indoor temperature of merely 12°C in the London region, or even 10°C assuming 90 per cent of coal was used for domestic purposes. This 10–12°C base temperature holds true also for the rest of England when increased industrial use is factored in (coinciding with a dramatic increase in charcoal prices in the latter seventeenth century), and assuming (with the commonly accepted estimate) a declining share from 55 to *c.*40 per cent of coal was used for domestic purposes between 1650 and 1800.

This is perhaps one of the most significant findings from this study, i.e., that the problem of maintaining thermal comfort required substantial additional means, possibly and intriguingly from additional indoor clothing. A follow-up of this study would thus be to quantify the amount of clothing that this requirement corresponds to, with implications for developments in the textile industry as well as the second-hand clothing market. Thus, climate can possibly be shown to have had an impact on both the coal and the textile industry—two primary contenders for most important sector in the British industrial revolution.

Summing up, while both rising populations and the spread of chimneys from urban to rural areas remain crucial for understanding the transition to coal, climatic factors had a measurable effect. Notably, the search for quantitative answer has resulted in new methods of estimating latent fuel demand and potential fuel supply. Comparing these raises new questions for an economic history of thermoregulation regarding how people survived their cold and draughty indoor climate, whether by coal and chimneys, clothing, or co-sleeping, which in turn await quantification.

6 Conclusion

6.1 Answering the research question

What was the role of natural resource appropriation in the transition from an organic to a mineral energy economy? The reply to this question depends on whether you look at the first, early modern English transition, or the later nineteenth- or twentieth-century West-European or world transitions.

In an organic economy, almost all resources—food, feed, fibres, and fuels—will be sourced from the land, the uses of which will therefore be competing with each other. When European populations recovered in the early modern period, they were faced by similar constraints as had the pre-plague economy but also a cooler climate. Depending on where in Europe you lived this would have different consequences. In the south, agricultural yields may have been adversely affected by the cooler climate, but residential heating would have remained a minor concern in the most populated coastal areas, and what problems of wood fuel supply did emerge could likely be solved by imports (as they were in Venice). In the north, heating requirements were already considerable and would have become even more challenging, but more due to the labour involved than to lacking potential supply because the already severe constraints on agriculture already kept population densities low. In between, however, there was a 'Coldilocks region' which was 'just right' for trouble. That is, temperatures were warm enough for high agricultural and pastural output, thereby allowing high population densities, but also cold enough for heating to become vital. England and its largest city appear to have been precisely within this region, which may explain why climate cooling became a more serious concern there. Woodland area was already exceptionally low and continued to decline as populations rose, while climate cooling outtrumped changes in precipitation in lowering yields, just as per capita requirements rose. These strains on domestic heating created a market for coal, not only in urban areas, where chimneyed fireplaces were already prevalent, and coal had occasionally been used for heating at least since the early or mid-fourteenth century, but also in urban hinterlands throughout England. Even with coal, you could not have kept indoors warmer than 10–12°C and would have needed additional layers of (fitted) clothing—climate cooling may thus have affected also the textile industry. What happened next is conventional economic history: to supply rising domestic demand when coal mines kept filling up with water, Newcomen invented his coal-fired ‘atmospheric engine’; as steam engines improved, their uses multiplied, eventually becoming efficient enough for railways, steamships, and uses outside the UK. The first globalisation wave was at hand. But it was also Earth-system history, where CO_2 emissions from coal and declining woodlands contributed to reversing Little Ice Age cooling.

Coal was just one means, specific to Britain, to ward of scarcity in early modern Europe. All over Atlantic Europe, when short of land you went to sea—for fishing, trade, colonies or war, or all of the above. For Atlantic Europe as a whole, the contribution of seafood to land alleviation was greater than that of coal until the mid-eighteenth century. Seafood consumption was spread out over Atlantic Europe, with per capita consumption highest by far in the north, but coal consumption was concentrated to Britain. Looking at agricultural improvements in Britain alone, higher yields between 1500 and 1800 contributed more than the whole European land alleviation from fisheries. There is no comprehensive estimate of British trade acreage before 1832, and only of imports before, but given that coal was already Britain’s greatest export good by volume in the eighteenth century, followed by grains, while total imported and exported tonnage was similar, it seems improbable that net imports could have competed with the land alleviation of either coal or yield acreage—but this remains to be determined. The answer will also depend on whether one accounts in alleviation—using importer yields—or appropriation—using exporter yields. By this account, the appropriated primary production from ocean fisheries was also greater by an order of magnitude than that which it alleviated on land.

The European and world transitions to a mineral economy was also led by Britain, both in the sense that British steam-technologies in transportation drove the widening of markets and globalisation after the Napoleonic Wars, and in the literal sense that Britain produced and exported the lion’s part of the coal that pushed European and world mineral energy consumption above their consumption of organic energies. Even today, fossil energy constitutes by far the greatest part of global trade by volume, something not evident from standard stories in value terms, and this was or became true also in the nineteenth century. This is one thing that upsets so many narratives on trade—not just of ecologically unequal exchange—i.e., that trade was not between (rich) centres exporting manufactures and (poor or rich) peripheries exporting food and raw materials, but mostly in food and raw materials being exchanged for other food and raw materials. This is true already in value terms, as perceptive economic historians have realised long ago, and in physical terms manufactures barely enter the picture, which is why physical trade balances are commonly abbreviated into fossil energy carriers, biomass, metallic and non-metallic ores. (Further environmental accounting of trade flows in historical studies has preferably also been done by applying coefficients—of land, energy, CO_2, SO_2, water, nitrogen, etc—to exchanges measured in physical rather than value terms). Furthermore, also because the drivers of globalisation originated in Britain and was taken up by its closest neighbours, competitors, and trading partners, the trade among developed countries themselves, but also to some extent among the less developed countries themselves, was more important than that between the developed and less developed countries.

This thesis looks at the two main phases in European and world transition to a mineral energy economy—the transition to coal during the Great Transformation in Paper 2, and the transition to oil during the Great Acceleration in Paper 1. What role did trade play in these periods in redistribution and appropriation of natural resources and environmental services?

Two or three main alternative interpretative frameworks, or rather mechanisms or drivers, are contrasted in the Papers to answer this question: one from comparative advantage and resource endowments, where the relative abundance or scarcity of environmental inputs determine net trade flows; another from (ecological) unequal exchange, where the relative wealth or power determine these net trade flows; and a third, where the relative environmental efficiency in the production of exported goods cause similar net transfers from the less to the more efficient producer. For the initiated, the latter phenomenon is what Marx and Marxists refer to as transfers of (labour) value between branches or countries with different 'organic composition of capital', i.e., which are more or less capital intensive, but a phenomenon that has been highlighted again in recent years in very non-Marxist contexts.

If one should summarise briefly the findings of Papers 1 and 2, it would perhaps be that the more organic the economy (the more upstream it is measured, or the lower on Engel's ladder of consumption), the more net flows are determined by relative endowments (resources per capita), and the more mineral the economy (or the more downstream, i.e., closer to final consumers, it is measured, etc.), the more it is determined by wealth (income or GDP per capita) and efficiency (environmental input or impact per income or GDP).

A reason why wealth and efficiency appear to go hand in hand has been touched upon briefly in the Papers and in section 3.2 above. It is not necessarily the self-congratulatory one that more efficient countries also become rich, but that efficiency promoting capital investments (substituting more for less productive technologies) may only be profitable with higher labour costs. Simple correlation cannot determine which is the driver. In fact, the latter logic only holds if investments are determined by the profit motive of private investors, which theoretically would (and empirically has) allowed leapfrogging through various degrees of state involvement. Such political involvement can of course work both ways—liberal institutionalist economic historians seem to believe that it is always negative—and over recent decades we have seen a significant influence of the fossil industry's vested interests not only in the US.

With this latter point we have arrived at the limits of the present thesis, namely the interface between economy or ecology and politics or geopolitics, which is one of the areas left for future exploration.

6.2 Outlook for future research

The technology-centred paradigm in energy history has been most applicable to, and most successful in, studying the series of industrial revolutions of the past 250 years. It is clearly relevant to understanding also the ongoing transition to wind, solar, and new kinds of nuclear energy, as well as batteries, EVs, high-speed trains, nuclear-driven cargo ships, etc. It has been extended to the international arena, interpreted through the lens of market-widening globalisation phases, and environmentally through trade-embodied energy and emissions. Building on this approach, and drawing on a tradition of environmental accounting, Papers 1 and 2 set the stage for further study, deepening the global dimension of environmental factor flows before 1950. The empirical situation is still fragmentary, and a future research project would have to construct the necessary pre-1950 or nineteenth-century database on environmental factor flows.

As noted, Papers 1 and 2 already put in question certain widely held beliefs, both among scholars and in society at large, concerning the character and direction of these flows. For the pre-1950 period, three main traditions of interpretations are identified, where economic historians often have believed in flows being determined by factor endowments, environmental historians assume flows to follow inequality lines between rich and poor countries, but most scholars appear to take for granted that flows were insignificant either way. The articles show both the tremendous rise in trade volumes with the Great Acceleration and the relative importance of trade shares before 1913. While they also point out where ecological unequal exchange has clearly been mistaken and thereby seem to favour comparative advantage according to endowments, they primarily hope to inspire future study.

Contrary to impressions, the theoretical approach inspiring these Papers (as noted above and in section 3.2) and favoured for such future study is an interpretation along lines of 'unequal exchange proper'. International wage gaps can be studied through their distortion of the pattern of specialisation and direction of flows that would have followed from resource endowments, i.e., where comparative costs are determined not just by the relative abundance of an environmental or other factor, but also by the politically, institutionally, historically, etc, determined cost of that factor. These international wage differences are certainly constrained by productivity differences, or else high wages must be protected by transaction costs or tariffs (as in nineteenth-century USA). However, these productivity differences will also tend to follow causally from wage differences that guide the development and international transfer of productive technology and the education of qualified labour (in line with Emmanuel 1975, Lewis 1978, Allen 2009, 2014). Endowments or factors, such as natural resources or organic chemists, are not simply found in a country but must be created (cf. Wright 1990). If market forces reign free, which and how much of each endowment/factor is produced will be heavily influenced by the exogenously given level of wages, e.g., the education and employment of engineers or organic chemists may be profitable where wages are high but not where they are low. Otherwise, non- or managed market solutions and state involvement may achieve similar results (as in the Soviet Union or East Asia). Qualitatively, this can be elaborated and refined ad infinitum, but it is not yet clear how to implement such a study quantitatively, although it would have to build on the accumulated body of historical wage estimates, relative capital and raw material (including energy) costs (cf. Allen 2014). The default hypothesis when international rates of profit and prices of commodities tend toward equalisation—a prominent definition of globalisation—is that non-equalising wages will explain divergence.

The focus on the industrial era in much of energy history simultaneously means that opportunities for fruitful study of energy in the preindustrial era are still abundant. Technological innovations clearly remain important, but focus would have to move beyond industry, with complementary and supporting ideas introduced from medieval and early modern economic historical debates. The discussion of the chimneyed fireplace in the transition to coal is one such technical innovation, while the introduction of climate as a causal agent in organic energy economies is an example of a complementary idea.

The approach to estimate heating requirements and potential fuel supply could be expanded to other countries and other urban regions. A pilot study along these lines has been conducted for the Stockholm region in Sweden. The preliminary findings suggest that climate's influence on general population density should be incorporated into an expanded model. This would be an important addition that would substantially increase its relevance in many contexts, but it is still not evident how it should be implemented and isolated from the many other factors influencing population levels.

The most immediate model extension would be to complement the estimated heating requirements and potential fuel supply by including clothing requirements, using the 'clo' unit to estimate how much clothing would have been required to compensate for insufficient potential fuel supply. Climate has sometimes been invoked to explain the rise to prominence of English sheep, but rarely the expanded demand for woollens. Such a study could be used to inform the study of the textile industry, and, if expanded to other (European) countries, also export trade. If the conclusions of Paper 4 are accepted about climate contributing to the transition to coal, and the expanded framework including the textile industry produces similar results, then two of the most fundamental industries in the British industrial revolution would have been influenced by climate cooling.

Another promising extension of Paper 4 would be an update of Paul Warde's (2007) standard energy history for England and Wales. The new estimate of potential wood fuel supply of Paper 4 could be linked with energy estimates of food and number of animals in Broadberry et al (2015) to produce a new and extended energy history of England for 1270–1870 (compared with Warde's for 1560–2008). This could reveal more on how the coal transition contributed for example to pre-1700 industrialisation (which was a central tenet in Nef 1932, and according to recent studies may have been underestimated in Broadberry et al 2015).

It could also contribute to understanding of the embodied energy in the basket of goods used to determine real wages. As coal came to be used in both brewing beer and baking bread, which constituted the lions share in Allen's 2001 respectable basket of goods, it would have contributed substantially to keeping the prices of these goods down and thereby to raising/maintaining real wages. This suggests a preliminary estimate of coal's contribution to the high-wage economy based on a comparison with counterfactual real-wages where energy input prices have been set as if only wood fuels were available. Coal may have contributed to the respectability basket becoming within reach for more people and stimulated greater industriousness to arrive there.

Such an energy history could contribute also to much extended estimates of trade-embodied energy and/or land, complementing studies that now begin in the early and mid-19th century. It is still an open question whether England/Britain before the 19th century was a net exporter of land (e.g., from exports of grain, land-intensive woollens), trade-embodied ecological footprints (including also direct and indirect exports of coal), or a net importer of either or both (based on tropical, subtropical, and temperate imports). It is time to start treating these questions more systematically, not just pick one or another British import and argue from there.

The study of West European fish acreage in Paper 3 can use more country specific yield factors when estimating the alleviation of land, and estimates of yield acres, such as those performed for England can be extended to other countries. A similar estimate of fish acreage for China or other Asian countries would cast light on the potential role of fisheries in the Great Divergence. Even more, however, studying not only fish or trade but yield acreage also for other countries could cast light on both the Great and the Little (intra-European) Divergence, and on the relative importance of internal, semi-internal, and external variables.

As was pointed out in section 3.3, preindustrial organic energy economies would be more exposed than a mineral energy economy, both to the limits brought on by population growth and declining per capita supply, and to the effects of climate variability on organic energy supply, while being as exposed to climate effects on demand. This suggests that whereas mineral energy economies with augmentable resource supply and sustained economic growth would be more prone to anthropogenic climate and other changes, organic energy economies with nonaugmentable land without sustained economic growth would instead by more subject to 'physiogenic' (from the Greek φυσις = 'nature'; e.g., 'climatogenic') social change.

Following Bruce Campbell's lead to introduce 'nature as an historical protagonist', I suggest three occasions from medieval and early modern history where non-human (natural) agency has already been, or could seamlessly be, brought in to expand on exclusively human stories of (British) economic history, namely Robert Allen's high-wage, cheap energy interpretation of the industrial revolution.

Allen (2009) has written one of the most compelling and influential interpretations of the British industrial revolution: high wages lead to the adoption of labour-saving technology, and cheap fossil energy gave economic incentives to invent, introduce and refine the steam engine; both high wages and cheap coal in turn relied on Britain's, and specifically London's, growth as a commercial centre. However, while Allen's argument stays firmly within economic bounds, in each of these three cases non-human agency has already been proposed:

1) The transition to a high-wage economy (as well as a consumer society) depends partly on the demographic catastrophe of the Black Death (viruses and rodents) (Herlihy 1997: 47f; Pamuk 2007; Voigtländer and Voth 2013; Fochesato 2018: 94, 100–11; Jedwab et al 2022; Belich 2022; for an overview of explanations of the consumer revolution extending from the Black Death to 1800, cf. Sear and Sneath 2020; and for real-wage trends, Allen 2018).

2) The transition to a cheap fossil energy economy and domestic consumer revolution can be linked to the cooler climate of the Little Ice Age, as argued in Paper 4 and elsewhere (e.g., Dresbeck 1971a, 1971b, 1976; Malanima 2003, 2010-11, Kander et al 2013, Rackham 2003, Spufford 2006; for links between energy and the consumer revolution, cf. Saelens et al 2024). Potentially many other aspects of the commercial revolution, e.g., woollens, may also be linked to the cooling climate, insufficient heating, and draughty rooms to evacuate (coal) smoke.

3) The early-modern northwest European commercial revolution was also related to the discovery and interaction with a vast new land area in the New World and elsewhere, which was deemed by Kuznets (1966: 3) to be the 'epochal innovation' of the early-modern era.[17] This involved a back-and-forth homogenising 'Columbian Exchange' (Crosby 1972) of animals, plants, and pandemic diseases. The pandemics caused the Great Dying of native Americans (Mann 2011), while the consequent reforestation caused a drop in CO_2-levels, which in turn contributed to deepening the LIA (Ruddiman 2003, Lewis and Maslin 2018, Koch et al 2019, King et al 2024). When Europeans eventually settled the northern part of the continent, they were thus met not only by uncommonly severe winters, both compared to European latitudes and to previous centuries (White 2017), but also by vast forests that stimulated an exuberant use of energy and resources (Henriques and Borowiecki 2017). However, for the first 300 years, the repopulation of the Americas was dominated by the forced migration, mostly to tropical and subtropical regions, of African slaves who brought with them not only their cultures but also their cultivars (Carney and Rosomoff 2017). The discovery of, and interaction with, wind patterns and ocean currents thus shaped the triangular trades. The most well-known (or infamous) of these carried alcohol, pearls, manufactures, etc, from

[17] Cf. Kuznets (1966: 3) 'the innovation of a breakthrough by Western Europe to the New World' whose potential of growth it took 250 years to fully develop, providing 'a flow of precious metals, new agricultural and other products, and the possibility of settlement outside the circumscribed area of Western Europe'.

Western Europe to West Africa, slaves from West Africa to plantations and mines in the Caribbean and Americas, and from there slave-produced goods, such as sugar, tobacco, and cotton back to Europe. Domingues da Silva (2016) has shown how wind and sea currents set the pattern of the clockwise North Atlantic triangular trade, and its counterclockwise South Atlantic counterpart, separated in the upwelling equatorial regions by the by the so-called doldrums. He also shows also how they thereby linked specific regions of departure in West and Central West Africa that became sources of slaves to specific disembarkation regions in the Americas at the receiving end. The contribution of embodied land and labour from these trades has been considered vital to the alleviation of British land constraints and the industrial revolution (Pomeranz 2000, Inikori 2002; but cf. Papers 2 and 3). The same mastery of wind and ocean currents also made possible the early modern fish revolution (cf. Paper 3; Holm et al 2021, 2022, 2024; Hayes et al 2025; Bouchard 2022; Mehler et al 2019), which also had its triangular trade involving dried cod, sacks of wine, etc. Finally, in addition to the contribution of potatoes, maize, and other food crops to raising food production, the American variant of long-fibred cotton, which was the result of millennia of Amerindian biological innovation, was crucial for the mechanisation of the textile industry during the British industrial revolution (Russell 2011: 104). Such innovation (or co-evolution) continued over the course of the industry's development (Olmstead and Rhode 2008).

As can be seen, the potential interconnections between the economic system, the Earth-system, and their inhabitants, can be multiplied indefinitely, enough for several research programs on non-human agency, nature as protagonist, or the co-evolution of economies and nature in the late medieval and early modern era. The present thesis has only addressed a few.

These are projects that look further back in time. At the other end, the ongoing shift from a fossil to an electric energy economy suggests many possible inroads. The potential links between energy transitions and shifts in hegemonic Great Powers have already been mentioned on several occasions: did coal and steam turn the UK into the dominating world power of the nineteenth century, and did they turn Germany into its foremost continental contender? Did oil, the combustion and diesel engines somehow contribute to the US and the USSR replacing them as the dominant powers of the twentieth century? Why would solar energy, batteries, electric vehicles, etc, turn China into a Great Power of the twenty-first century? That geopolitics and not just economics may play a role here is suggested by China's decision, as oil imports peaked, to become energy independent and electrify its economy. China's rise as an electrostate and global power, also via its Belt and Road involvement in electrifying the global south, is topical enough to soon risk becoming a cliché. Maybe China's importance will be diluted into a multipolar world by the rise of India, Indonesia, etc. However this may be, it is perhaps time for economic historians to again probe the relation of the energy and techno-economical base to the ideological and (geo)political superstructure, hopefully in the long-term perspective of previous transitions, including links between energy, economic and military power, international and domestic power struggles, the influence of vested interests on politics, etc.

Bracketing these speculations, and staying within the confines of this thesis, what could an Earth-system perspective possibly add to this subject, other than the possibility that China's shift to electricity could possibly be an outgrowth of its preference for stability and therefore dislike of pending climate mayhem? Accepting a position where the economic system is embedded within the Earth-system could present an additional challenge to incorporating the political and geopolitical sphere. Geopolitics was never a strongpoint of environmental or social critics of mainstream Growth & Development ideals, and even ardent ecological realists and degrowthers who have discarded Growth & Development as ideology must acknowledge the possibility of it re-entering through an international-relations realism. An ecological counterpoint would need some 'higher realism' also in the sphere of geopolitics for a world where the economy is embedded at both ends by Earth-system processes and feedbacks.

The energy and technologies perspective might not have been fully exhausted just yet. Astrid Kander has observed that different development blocks can be either energy expanding or energy saving, and that whereas coal and oil were energy augmenting, the 1870s electricity and 1970s ICT blocks have been energy saving. Taking another step back from the multiple industrial revolutions of the Schumpeterian tradition, then, there is the possibility of even longer waves—as was suggested already by an early reviewer of Schumpeter's *Business Cycles* (1939), and implicit in the old notion of one big Industrial Revolution. First the topic of this thesis, namely, the prolonged transition from an advanced organic economy to a fossil energy economy, in itself involving a decarbonising move from coal to oil, gas, and prospectively hydrogen gas, which has no carbon at all, only two protons and two electrons. Then another, equally long and partially overlapping transition that dispels with proton energy carriers altogether: the electric energy economy, which moves from being a subsidiary to the fossil economy, making it more efficient with electric motors, generators, and transmissions, telecommunications and computers, to eventually displacing it via photovoltaics, batteries, EVs, etc. Why would this move occur?

Maybe an answer could be inspired by some ecological model of succession, i.e., about what happens over time to species and ecosystem characteristics after a major disruption leaves plenty of unused resources. Early stages of successional systems tend to have species with fast rates of nutrient (resource) consumption, a reduced role for decomposer organisms, lower stability and diversity. Late stages have the opposite characteristics, the shift being driven by a trade-off in competition for nutrients in early succession, and for light in late succession (Odum 1969, Tilman 1985). These models suggest interesting parallels to energy transitions including a reminder regarding the role of decomposers. There is a neglected sustainability shift within the ever-present organic energy economy—neglected but almost equally important, given its considerable environmental impact (Campbell et al 2017; Paper

1; Wedderburn-Bishop 2025)—from a plant/animal to a fungal energy economy, where the products of especially herbivore consumers (meat, leather, etc) are complemented/replaced by the mushrooms and mycelia of decomposers. However, the analogous successional shift within a mineral economy from the discovery of how to benefit from abundant fossil resources to a solar ('electric') energy economy should be clear. Perhaps geopolitics could be incorporated into such a model without becoming either Darwinian or idealist, simply more realist.

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Postscript

Postscript: The *fleurs du mal* parable

The climate crisis is the most familiar and best documented of our environmental crises. Figure P1A shows different global temperature estimates for the Holocene and Common era, including instrumental measurements until 2017, which by 2025 are traversing 1.5°C above the 1850–1900 average. Figure P1B shows a temperature proxy (benthic ^{18}O, indicating how much ice there is on land) and CO_2 for the past 800,000 years (remember that Homo sapiens sapiens appeared some 300,000 years ago). A *c.*100,000-year periodicity of ice ages became established around 400,000 years ago, with brief (10,000–15,000 years) warm interglacials, both of which are also clearly visible in the CO_2 record. The temperature proxy in Figure P1B takes a bit longer to establish itself and does not reach sufficiently into the present to record recent warming (cf. Figure P1A), but the CO_2 record has been updated to *c.*2000 and had by 2024 reached 427 ppm. The fossil fuelled change in CO_2 now even exceeds that between a glacial maximum and an interglacial, which corresponds to about 4–8°C (the latest one *c.*5°C).[1] This is one of the crises that brings humanity into unchartered territory.

The temperature reconstruction by Marcott et al (2013; Figure P1A), Ruddiman's (2003) early anthropogenic hypothesis, and Lovelock's Gaia theory, specifically his Daisyworld model (Watson and Lovelock 1982), are the three main inspirations behind the proposition to expand the sphere of feedbacks from the economy to the Earth-system. I shall treat them in turn.

First, in a pioneering reconstruction of Holocene temperature from proxy data, Marcott et al (2013; Figure P1A), found that global temperatures had been declining for seven thousand years from the very warm mid-Holocene thermal optimum until the recent warming. The trend was driven by changes in the northern hemisphere and likely reflected the slow-moving orbital trend of declining summer insolation (Lasker et al 2004; Wanner et al 2008; Esper et al 2012) together with feedbacks that include the increasing albedo (reflectivity) from sea ice formation and glaciation. Indeed, the term the 'little ice age' originally referred to the neoglaciation

[1] Most (90%) of the excess heat trapped by anthropogenic greenhouse gasses has so far gone to warming world oceans—that this might end and the oceans shift from sink to source of heat is one possible tipping point. Unfortunately, according to James Hansen, because they have underestimated the cooling effect of SO_2 emissions, the latest Intergovernmental Panel on Climate Change (IPCC) may also have underestimated temperature sensitivity to CO_2 emissions.

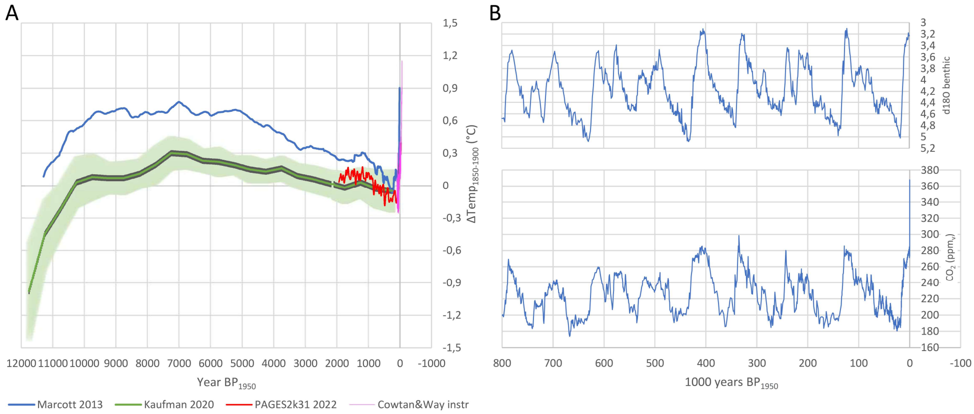

Figure P1. Geological scale of current transformations
A. Holocene and Common Era global temperature. B. Benthic 18O and atmospheric CO_2 since 800,000 BP. Sources: Bereitner et al 2015; Berger et al 2016; Kaufman et al 2020; Marcott et al 2013, PAGES2k Consortium (Neukom) 2022.

that began several thousand years ago but culminated in the early modern period (Matthes 1939). Another feedback was simply the decreased evaporation of water as temperatures declined—water vapor is the Earth's most abundant greenhouse gas, but it is a follower not a leader. This also implies a very-long-term declining trend in global precipitation towards extreme draught during glacial maxima. (The dust from these draughts, sweeping onto and darkening the glaciers, have even been proposed as a mechanism that brings glacial expansion to a halt). In previous glacial-interglacial cycles, CO_2 functioned as both forcing and feedback, driven by its greater solubility in colder ocean water, and vice versa, but perhaps also by peat becoming locked into permafrost. In the very long run, these three factors—cooler temperatures, decreasing precipitation, and lower CO_2-levels, together with expanding glaciers and desserts—all conspired to make life increasingly hard for photosynthesising plants and for net primary productivity (NPP) on land (although not necessarily in oceans).

From early on Marcott et al (2013) stirred debate because climate models could not reproduce the trends for the early- to mid-Holocene and instead predicted that temperatures should have risen continuously at least until the medieval warm period (MWP, *c*.950–1300 CE). Model-advocates maintained that the northern-hemisphere, especially sea-surface, proxies that created the falling temperature trend are summer biased and thus prone to be more sensitive to changing summer insolation. Proxy-advocates retorted that northern hemisphere insolation and its feedbacks have driven previous glacial cycles, and charge that modellers have simply been unable to recreate these feedbacks correctly. The difference between proxy-based and modelled temperature reconstructions, referred to as the Holocene temperature conundrum, has been subject to debate for more than a decade

(Kaufman and Broadman 2023). Updated proxy-based reconstructions show a much weaker mid-Holocene warm period but the trend is still similar (Kaufman et al 2020; Figure P1A). New ingenious proposals to resolve the conundrum appear continuously but need not concern us here. Instead, the debate is instructive in pointing to a real-world struggle between different climate forcings and feedbacks, with northern-hemisphere insolation and feedbacks on the side of cooling, and greenhouse gasses and their feedbacks on the side of warming.

In previous glacial-interglacial shifts humans were still migrants, but during the Holocene gradually became sedentary agriculturalists, settling to the limits of cultivation, and greatly expanding their populations. With settled agriculture as the way of life and declining temperatures, precipitation, and CO_2 seemingly inevitable—judging from previous interglacials—a confrontation of declining yields with rising needs to feed and keep warm these populations seems inescapable at some point.

However, a contributing reason for the modelled rising trend is that CO_2 and other greenhouse gasses did not, unlike in previous interglacials, continue downwards but started rising again. This can (barely) be seen as a minor dip in Figure P1B (bottom), declining from 270.1 ppm CO_2 in 11,436 BP to 257.6 ppm CO_2 by 7,038 BP, after which the trend started moving upwards until a brief halt at 283.9 ppm CO_2 in 420 BP (1530 CE). These observations had already led Ruddiman (2003; Ruddiman et al 2014, 2020) to formulate his early anthropogenic hypothesis that agricultural deforestation, wet-rice cultivation, and the domestication of animals caused CO_2 and CH_4 to rise and thereby pushed up temperatures—at least compared to what they would have been. Human land-use and the expansion of the organic energy economy caused an interglacial anomaly in the carbon budget, releasing greenhouse gasses, which together with their feedbacks began opposing the downward solar forcings (Ruddiman et al 2016). In effect, agriculture thereby contributed to maintaining temperatures at a level more beneficial to agriculture (Vavrus et al 2021)—agriculture begot agriculture. In the superhuman struggle between climate forcings, humans entered the on the side of warming and were rewarded in the effort by continued population increase.

Everything seemed to be going well until the trend reversed due to a constellation of climate forcings and feedbacks, including the downward northern insolation trend, clusters of volcanic eruptions, solar irradiation minima, changing oceanic and weather systems. These were aided also by the Black Death and later the Columbian Exchange of germs, which depopulated and reforested the Americas, thereby drawing CO_2 levels down again until the eighteenth century.[2] The Little Ice Age

[2] Already in his original presentation of the early anthrogogenic hypothesis, Ruddiman (2003) suggested that reforestation following the Black Death and depopulation of the Americas after Columbus could partially explain the decline in CO_2 levels and temperature. Lewis and Maslin (2015) continued this argument and proposed 1610 as the starting point for the Anthropocene based on a conspicuous dip in CO_2 in that year following a steep decline from the mid-16th century. Koch et al (2019) suggested that at least 47-67%, but possibly much more (Kaplan et al

(LIA) meant that the climate-cooling forces again gained the upper hand, and temperatures reverted towards Ruddiman's 'natural' trend. In Europe, where populations instead had started to recover to levels before the Black Death, the decline in CO_2 and temperatures (although the long-term trend of hydroclimate and precipitation appears harder to establish), would have contributed to decreasing yields and raising requirements for shelter and heating compared with before the Black Death. However, the introduction of fossil fuels with the coal-burning house—as this thesis shall argue, partly due to these climate shifts—and a renewed rise in CO_2-levels as populations and the organic economy recovered and expanded world-wide, brought the downward temperature trend first to a halt, then, during the fossil economy's expansive phases over the 19th and 20th centuries, upended the 'natural' interglacial trend completely, in one of the most ominous transformations of Earth-system processes.

The third piece in the argument is inspired by Gaia theory, or more specifically the so called Daisyworld model. This is a main reason why the approach proposed here could qualify as 'Earth-system economic history'. The origins of Earth-system science, as distinct from biocheochemistry or global ecology, etc, can be traced to James Lovelock's Gaia theory or geo-physiology, with Earth-system science emerging as an attempt to make its integrative approach more respectable (for a brief history of Earth-system science, cf. Steffen et al 2020, with excellent references). The first textbook on Earth-system science, now in its fourth edition, cautiously introduced Gaia-theory in the first chapter, and devotes the whole second chapter to Lovelock's Daisyworld (Kasting et al 2023). The system of self-regulating positive and negative feedbacks that it describes is clearly at the heart of Earth-system science. The problem is how to integrate the economic system, with its own positive and negative feedbacks, into such a system. The conventional environmentalist or ecological economic position is that this is something we need to achieve for the future to solve our environmental problems. The idea here is rather that the economic system is already integrated into the Earth-system.

According to Lovelock's theory, the Earth is a homeostatic physiological system that behaves as if it were a living organism, maintaining the surface temperature of the planet and recycling nutrients (in soil, water, and forests) with the 'unconscious goal of regulating the climate and the chemistry at a comfortable state for life' (Lovelock 2007, pp. 15, 17). The principle behind this unconscious regulation is described in his toy model Daisyworld (Lovelock and Watson 1982; Watson and Lovelock 1983). In it, the Earth is faced with the external forcing of an ever-warmer sun, but global temperature is stabilised and habitability prolonged by two

2011), of this decline could be traced to the reforestation of the Americas caused by large-scale depopulation and the shrinking of the organic energy economy after European arrival. However, as recently argued by King et al (2024) it seems that the 1610 dip is likely due to some problem in the Law Dome ice core, and that the decline from the mid-1500s was slower and extended over the whole 17th and 18th centuries with a minimum around 1700. This, in turn, made the reforestation explanation of the decline much more plausible.

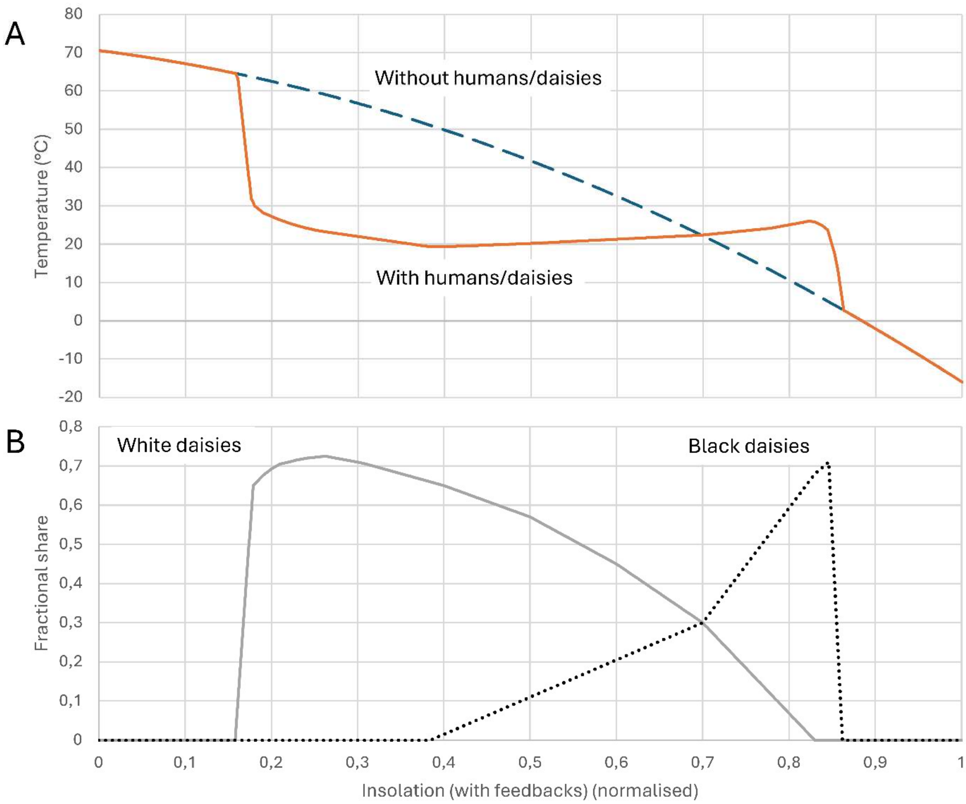

Figure P2. ***Fleurs du mal*** **parable**

A Daisyworld with declining insolation. Note: This is only an illustration, mirrored after Watson and Lovelock 1983, but a consistent 'toy model' could be created also for the case at hand. White daisies have no corresponding meaning in the parable, so in a proper representation the full red line should follow the striped one rather to where the lines cross. However, a scenario with future warming based on anthropogenic GHG-emissions and feedbacks (instead of insolation) would again suggest the original direction (here, from right to left)—a Pheonix parable with anthropogenic white daisies rising from the ashes of the fossil energy age.

different species of daisies. Both daisies have a preferred temperature for growth at 22.5°C (in the middle of the growth range between 5°C and 40°C), which also, unintentionally, becomes the temperature around which the Earth fluctuates. When the sun is young and cool, black daisies thrive because they absorb more radiation from the sun, heat their local environment, giving them an advantage over white daisies, and ultimately darken and warm the whole earth, preferably on the safe side somewhat above 22.5°C. As the sun grows larger and hotter over time, white daises, which reflect radiation and cool their local environment, become increasingly competitive, eventually taking over completely, and thereby whitening and cooling the Earth to a temperature somewhat below 22.5°C. Finally, the sun becomes too hot even for a planet inhabited only by white daisies, the system breaks down and the Earth reverts to following the abiotic temperature trend.

Rather than trying to make the model more realistic—for example, using bacteria producing respectively methane (or carbon dioxide) and oxygen, or integrating it with the NASA Bretherton diagram of the Earth System (Bretherton 1985; National Research Council 1986), etc—subsequent elaborations have been very faithful to Daisyworld's toy-model origins, while adding things such as multiple species, exogenous shocks, genetic mutations, etc.[3] I therefore feel free to reinterpret its logic as applicable to the much shorter timeframe of interglacial cooling. (One could also use the timeframe of the past 5–50 million years which has also been cooling with ever lower levels of CO_2).

In this alternative interpretation of the model, which I refer to as the *Fleurs du mal* parable (Figure P2), the daisies can be exchanged for the black devils and white angels in M. C. Escher's famous etching, working their ways through the conduit of human economies. The external forcing is instead represented by a *cooling* sun, in the form of orbital forcing on northern hemisphere insolation and its sea-ice and other feedback mechanisms, which on a millennial timescale would drive temperatures towards a new ice age. This prehuman interglacial pattern corresponds to Daisyworld's abiotic Earth.

Enter the snake, the neolithic fall, and human agriculture, which can be assumed to have a similar ideal temperature as daisies. The deforestation accompanying the expanded organic energy economy releases carbon bound up in biomass (wood, soil, and peat) while methane is emitted by domesticated cattle and wet-rice cultivation. The radiative forcing of greenhouse gasses is accompanied either by even more CO_2 being emitted from warmer oceans, or at least no additional absorption from colder waters (similarly, peat bogs may have shifted from being a sink, when increasingly frozen into permafrost, to becoming neutral or even a source of CO_2 or CH_4). Agriculture serves as black daisies/devils, maintaining temperatures at, or raising them to, levels where they become a stimulus for further agriculture and even higher populations. Depending on the resolution of the Holocene temperature conundrum, this either leads to a continuous rise in global mean temperatures, until the medieval warm period or simply hinders global, especially northern-hemisphere, temperatures from falling even lower.

[3] Nevertheless, Lovelock clearly had the long-term evolution of carbon dioxide in mind when constructing his model. He thus suggests that a level of perhaps 30% carbon dioxide would be required to explain the 'faint young sun paradox' of the Earth having temperatures suitable for life when the sun was 25% cooler than today. Over time, as the sun has grown to its present size and luminosity, carbon dioxide has shrunk to being a mere trace gas at about 0.03%. At this low level, Lovelock argues, the capacity of a CO_2-based system to regulate temperature is severely circumscribed, and may be approaching the limit of its potential, as witnessed also by the wild temperature fluctuations of increasingly severe Ice Ages over the past 5 million years. During the last Ice Age CO_2-levels sank as low as 180 ppm, close to the limits of effective photosynthesis, at least for common C3-plants.

By the end of the medieval warm period, however, the cooling forces and feedback responses begin to gain the upper hand through a combination of long-term orbital forcing, clusters of solar minima and volcanic eruptions, possible shifts in weather and ocean circulation patterns (plus feedbacks in sea-ice and snow cover, etc), together with epidemics that reduce population and change land-use, thereby altering the atmospheric levels of greenhouse gasses. This pushes Holocene climate into its deepest phase of neoglaciation to date, the Little Ice Age. The agricultural organic economy which had stabilised temperatures through the Holocene appeared to have reached its limit—with effects most noticeable in that 'Coldilocks' region where temperatures were mild enough to permit dense populations, yet sufficiently cold to require substantial indoor heating.

In the more populous parts of northern Europe, this meant being caught between the scissor blades of lower growing degree days for food, feed, fibres, and (wood) fuel, and higher heating degree days required to maintain thermal comfort—which happens also to be 22.5°C. The solution found in late medieval and early modern England was transitioning from wood fuels to coal for domestic heating—and fitted woollen clothing—thereby partly unhinging London and English growth from the land constraints of an organic economy. The internal driving forces behind this growth may well have come from London's rising prominence as a commercial centre, from the specialised production stimulated in its vicinity, and the rise of capitalist relations of production in the countryside. However, the expanding London and England market for coal in turn led to bottlenecks in coal mining and stimulated the invention and introduction of steam pumps to evacuate water from the mines. Enter Newcomen's steam engine, and the rest is (economic) history.

Charles Baudelaire may have been the first to see the modern metropolis as a flower—evil at that. In terms of Lovelock's model, coal-heated London functioned as a black-daisy/-devil urban *fleur du mal* responding to (northern hemisphere) cooling. In this case, the drive to raise local/domestic temperatures to maintain thermal comfort, in a convoluted and inadvertent manner via intra-economic feedbacks, thereby also raised global temperatures.

As we progress along that path, the future warming trend that was originally driven by anthropogenic GHG-emissions will trigger feedbacks that, once set in motion, will again suggest the original direction (from right to left in Figure P2). It remains to be seen if Peter Berger's 'rumour of angels' is true, and human societies—perhaps by transitioning from black to white energy, i.e., primary electricity—can also adopt the role of white daisies—making for a Pheonix parable with anthropogenic white daisies rising from the ashes of the fossil energy age.

References

For full references, see the introductory Kappa.

Studies in Earth-system economic history

The urgency of global climate change and other geological-scale anthropogenic impacts also suggests new perspectives on economic history. This thesis argues for the inclusion into economic history of more Earth-system centred feedbacks, both in terms of environmental and climatic consequences and environmental and climatic causes, where consequences in one realm may again become causal in the other. More specifically this cause-consequence interplay between the Earth-system and the economic system is traced through the transition from an organic to a mineral energy economy, first in the original domestic energy transition in London and England, then for Western Europe and the world in the market-expanding globalisation phases of the first and second industrial revolutions. Since the original driver for adopting coal was domestic heating, which would have been profoundly impacted by the cooling climate of the Little Ice Age, the thesis develops methods to quantify both climate (temperature, precipitation) effects on potential wood supply and of changing temperatures on fuel requirements in England and the London region over the 1200–1800 period. The results reveal not only this climate effect, but also the shortcomings of fuel supply even when including coal, suggesting potential links between climate and both the coal and textile industries. The early-modern shortcomings of an organic economy were tentatively solved by geographical expansion, including into oceanic fisheries. The thesis also creates methods to estimate the land alleviation and ocean appropriation of seafood consumption in Europe, 1500–1800. The alleviation is compared favourably against coal for Europe as a whole until the mid-18th century, but unfavourably with the alleviation from either coal of yield increases in Western England over the same period. Finally, having identified decades of empirical study into trade-embodied environmental inputs and impacts over the past two centuries, the thesis finds converging patterns between those linked to the organic energy economy, best explained by comparative advantage according to resource endowments, and those linked to the mineral energy economy best explained by unequal exchange according to wealth and/or environmental efficiency. The Kappa and a postscript place the individual papers within both Earth-system and economic historical context, and proposes new avenues for research.

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