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INTRODUCTION

Recent advances in social metabolism research: Sources and methods

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ABSTRACT
Social Metabolism research emerged in the 1970s and has since evolved into a dynamic field of social science research on pressing environmental and sustainability challenges in the twenty-first century. Historians began using these methods to evaluate socio-ecological transitions of societies and compare patterns of resource use over time and across space. This introduction explains the central tenets of Social Metabolism research and briefly explores the five research articles in this issue that are pushing the field in new directions with exciting sources and innovative methods.

KEYWORDS
innovative methods; new sources; social metabolism; socioecological research

Purpose of the special issue

This special issue strives to achieve two main goals: first, it introduces historians (academics and students) to the field of social metabolism research and its central tenets, and second, it brings attention to new sources and methods for scholars already familiar with the field. Many of the questions that inform the work published in this issue are ones that have interested historians for several generations. Others are inspired by pressing contemporary questions related to the environmental and sustainability crises in the twenty-first century. The contributions they make offer, simultaneously, both new socioecological support for established historical interpretations and novel insights into dimensions that have not yet been explored. Beyond presenting new quantitative results on resource use in diverse historical contexts, the authors provide detailed accounts of the sources from which their data is derived, and the choices they needed to make to assemble data from different sources into standardized time series data that can be compared over time. They also describe the methods and indicators they developed to analyze the resulting datasets, as well as the assumptions that were necessary to extrapolate from available evidence and fill in gaps in the sources.

Sources and methods for social metabolism research

In this special issue we present five new studies of historical social metabolism research, and we highlight some of the strategies that historians have taken to prepare sources and methods for this interdisciplinary endeavor. Social metabolism methods use quantitative sources to create robust, extended time-series data to quantify how societies changed as biophysical entities through the exchange of material, energy, and substances with their environments. The social metabolism concept serves both as a metaphor and a methodological framework. As a metaphor, it conceives of social systems (e.g., countries, rural communities, cities) as entities that exchange materials, energy, or substances, with their natural environments, as well as with other societies, to sustain themselves, thrive or grow. As a conceptual framework, the approach has been operationalized in environmental accounting and offers a number of quantitative, systematically comparable indicators on resource use and associated environmental impacts that enable scholars to evaluate the socio-ecological transitions of societies and compare patterns of resource use across cases.

All historians must define the scope of their work, indicating to their audience what periods of time, geographies, peoples, and questions, are considered in their analysis. By and large, historians accept that factors outside of their scope will be left for others to explore. Social metabolism researchers use the concept of system boundaries to provide a rather explicit definition to the scope of their analysis. Scholars define these systems to reflect social, economic, political, and environmental realities of people's lives in the past. However, the choice of which boundaries to

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use is also shaped in significant ways by the sources available, which in turn have been shaped by the historical purposes and systems of social power that created the sources in the first place. The articles in this issue cover a variety of different spatial boundaries from a specific city in the case of Toronto, to two regional case studies in Western Galicia (present day Poland) and the Landes of Gascony (France), and three national case studies, one covering Spain and two on the United States. All five articles use long time series data, stretching from the nineteenth into the twenty-first centuries, the shortest of which covers 35 years and the longest 220 years.

Convincing historical interpretations rest on the evidence that scholars bring to bear in arriving at answers to their questions. These questions, and the answers the evidence allows, more often expand upon existing historiographical knowledge rather than offering a fundamentally new way of understanding the past. Histories build upon, even as they challenge, well-established and broad patterns of the story. Like other types of historical work, scholars of social metabolism research are constantly engaged in efforts to identify and incorporate new sources to add nuance to our understanding of the past. What social metabolism does exceptionally well is integrate sources that can be used to measure and evaluate change in concrete material and comparative terms, which provide context to, raise new questions about, and complement research on how people experienced and perceived those changes in strictly social terms. Knowing that certain land use practices, forms of resource extraction, and patterns of economic activity existed, and that they became increasingly formalized, bureaucratized, capitalized, and industrialized over the course of the nineteenth and twentieth centuries, suggests the type and extent of their impacts. But assessing the material dimensions of these changes, their environmental impacts in specific places, and the ecological and social sustainability challenges that this created, requires quantitative sources to measure change over time, across space, and at different scales.

A history of social metabolism scholarship

Social metabolism is a highly interdisciplinary methodology that has developed into a diverse set of sophisticated approaches, including standardized environmental accounting rules. It was pioneered in the late twentieth century, particularly by scholars working in Europe, and in the last 20 years, environmental historians have used this quantitative approach to highlight major trends in the flow of material and energy that structure resource extraction, land use change, trade, economic livelihoods, waste, and emissions. The field has contributed to a biophysical reading of industrialization processes of the past two centuries.

The history of social metabolism scholarship has grown from its roots in mid-twentieth century systems ecology to more formal energy analysis in the 1970s and more recent applications in socioeconomic systems and policy. Ecological research was transformed in the 1950s and 1960s as scientists such as Howard T. Odum (1970, 2007) introduced the concept of ecosystems as thermodynamic systems. The laws of thermodynamics explain how energy flows through ecosystems, and how ecosystems maintain their organizational states. Odum emphasized that as ecosystems receive energy from the sun, it is captured by primary producers (i.e., plants), transferred through various food webs, and dissipated as heat. This approach allowed ecologists to see ecosystems as complex networks, fostering methods for modeling ecological dynamics and laying the groundwork for systems ecology. Odum's focus on energy balance in ecosystems was influential in shaping environmental studies beyond traditional ecology.

This energy-centric view spread across disciplines in the 1970s, catalyzed by global energy crises like the OPEC oil embargo. Energy analysis became an interdisciplinary field, combining insights from ecology and economics to address the total energy requirements of production and consumption. This analysis, formalized through events like the 1974 Workshop on Energy Analysis in Sweden, expanded to include indirect, or embodied, energy (Slesser et al. 1977; Slesser 1978). Scholars began examining how energy is required across entire production chains, from raw material extraction to final product consumption. This holistic approach provided a more comprehensive view of the ecological costs of economic activity, challenging traditional economic metrics that often overlooked these energy inputs. As they quantified the "real" costs of energy, environmental and social scientists began to influence national energy policy and planning.

Various concepts of social metabolism emerged around the same time, as scholars sought to define the flows of energy and materials that sustain human societies. Physicist Robert Ayres and economists Allen Kneese and Nicholas Georgescu-Roegen conceptualized societies as systems that metabolize environmental resources, mirroring biological organisms' energy use but at human scales (Ayres and Kneese, 1969). Georgescu-Roegen's 1971 work, *The Entropy Law and*

the Economic Process, argued that societal consumption follows thermodynamic laws, ultimately expelling waste back into the environment. In the 1980s, geographers such as T.P. Bayliss-Smith (1982) and Vaclav Smil et al. (1983) began to examine agricultural energetics in pre-industrial and industrial societies, respectively, while economic historians such as Rolf Sieferle (1982) and E.A. Wrigley (1988 and 2004) argued that societal energy transitions were a fundamental aspect of the transformation from one sociometabolic "regime" to another. Energy transitions highlighted how societies exchanged renewable energy sources, such as biomass, for modern energy carriers, such as fossil fuels, which provided greater energy density but were finite resources. This transition represented a shift from using renewable "flows" to depleting "stocks" of energy, and additional concepts borrowed from systems ecology.

The 1990s saw further development of social metabolism studies through ecological material and energy flow accounting (MEFA), particularly at the national scale. MEFA studies measured the inputs and material outflows of select national economies (Adriaanse et al. 1997; Matthews et al. 2000). Scholars like Marina Fischer-Kowalski (1998) used these methods to trace long-term trends in social-ecological systems, analyzing national economies' material inputs and outputs. This approach allowed for tracking the consumption of various resources, such as wood, minerals, and food, and comparing the experience of different nations (Fischer-Kowalski 1998; Moriguchi 2007). This analysis has expanded to analyze rural regions in terms of their biomass metabolism in agriculture and forestry (Gingrich et al. 2018), urban contexts, in terms of provisioning cities with resources, and their associated outflows (Krausman 2013; Barles 2015), and small island states (Chertow, Fugate, and Ashton 2013; Singh et al. 2023). The adoption of MEFA has enriched the understanding of how material and energy flows shape and are shaped by societal structures.

The interdisciplinary study of social metabolism has had significant applications in economics, policy, and global sustainability studies. In 2011, the European Union adopted the System of Environmental Economic Accounting (SEEA), which standardized reporting on material and energy flows. Eurostat, the EU's statistical agency, collects and maintains these data, providing historical insights into resource use across the EU from 1970 to 2023. Modern social metabolism studies consider both societal energy use and ecosystem energy flows as changed through human interventions. A prominent measure is human appropriation of net primary productivity (HANPP), which quantifies how much of the potential biomass that could be produced by plants each year is claimed by human activity. These studies have found that, global HANPP doubled in the twentieth century, and that currently humans use about a quarter of all terrestrial plant biomass, an extraordinary impact given the vast diversity of species sharing the planet (Haberl et al. 2013). Social metabolism thus enables comparisons of how efficiently nations and other human systems convert environmental resources into economic outputs, offering insights that are critical for understanding current sustainability challenges and exploring options for social-ecological transformation.

Addressing limitations in social metabolism sources

Social metabolism research is ultimately interested in understanding how societies interact with their environments in material terms. Drawing on a blend of hard science and social science methods that stand in for broad patterns of change over time, the authors in this special issue focus on a diverse list of innovative indicators. These indicators include flows and stocks of carbon to trace the availability of local forest resources needed to care for livestock, greenhouse gas equivalents released by expansive and intensifying agriculture, physical trade balances of timber products, per capita intensity of on-farm energy consumption, and the frequency and scale of commodity deliveries that fed and fueled urban residents.

Including quantitative analysis provides a means of assessing the qualitative descriptions from people at the time who may otherwise have been motivated to exaggerate either the positive or negative aspects of change. As Daheur and Le Noë argue, "quantitative information presented here does not compete with the qualitative but is rather meant to supplement it" (Daheur and Le Noë 2024, 18). Indeed, the ability to narrow the focus of social metabolism research, in terms of both temporal and spatial scales, is largely determined by the availability of sources. Social metabolism methods can help identify the gaps in our knowledge by recognizing how the more readily available and abundant types of sources, particularly government statistical records, reflect and privilege certain patterns of land use resource extraction and economic activity at the expense of others that were not monitored by modern bureaucracies. For example, as Darrobers, Gingrich, and Magerl point out, trade statistics rarely provide resolution finer than the annual and national level, but the consistency with

which governments kept records means that researchers can aggregate biophysical flows from numerous commodity categories to calculate estimates of major trends and their socioecological impacts (Darrobers, Gingrich, and Magerl 2024, 2). To fill in the gaps, or provide finer-grained analysis, social metabolism scholars must cobble together evidence from myriad sources that are often quite obscure or idiosyncratic. Historians have long known that peasants relied on forests to feed their livestock, landowners left land to reforest once timber imports replaced domestic consumption, and that countless ships transported key commodities from distant resource hinterlands to cities. But the consequences have been difficult to evaluate and compare. The authors in this special issue draw on a wide variety of detailed records to offer a more precise accounting of the social, economic, and environmental changes that historians have known only in broad terms.

The authors in this special issue demonstrate that social metabolism research is an on-going exercise in identifying what data is missing and how methods could be refined to better reconstruct the historic flows of material and energy. As Daheur and Le Noë point out, the purpose of social metabolism research is to provide "an overview of the issue based on a relatively limited number of quantitative sources. The results obtained are admittedly imperfect" (Daheur and Le Noë 2024, 18). Indeed, there is no perfect or complete information, and we can never evaluate precisely what happened in the past. Some places and some questions are more easily studied than others, because records were created and survive that allow us to measure resource use and economic activity. In each of the articles in this special issue, the authors have needed to make assumptions to fill in the gaps, or extrapolate from what evidence does survive. In each case, the authors advance social metabolism research by both identifying new sources, and developing new methods to integrate more sources, to reduce the number of assumptions and refine the certainty of conclusions.

Overview of the articles

By focusing on non-timber forest products in Western Galicia and the Landes of Gascony, Daheur and Le Noë (2024) demonstrate how social metabolism methods enable scholars to investigate aspects of resource management and rural land use, which environmental historians of late nineteenth century forestry and forest economies have tended to ignore. As the authors point out, the diversity, pace, and scale of yields created fewer opportunities to employ capital and technology to commodify these resources, which meant they rarely showed up in official government records. The kinds of methods employed by Daheur and Le Noë raise new questions about the place of the forest in local rural economies and the means to answer them. Specifically, they investigate the loss of "various practices such as forest grazing, forest litter collecting, uprooting or stripping of forest vegetation for fodder, and tree pollarding," each of which played a vital role in livestock husbandry-based subsistence. The result is greater insight and a better picture of the consequences of major reform in environmental management that unfolded during the late nineteenth century.

Industrialization is unquestionably the major source of emissions historically. However, as Infante-Amate and Aguilera (2024) demonstrate in the case of Spain, arguments about historic emissions have tended to ignore important emissions from land use, especially emissions of CH_4 and N_2O from the expansion and intensification of agriculture, which complicate this interpretation. For decades, scientists have been attempting to identify the degree to which land use change has contributed to emissions, but without records comparable in detail to those available for energy consumption it has been difficult to estimate the impact of land use change in the same historical timeframe (i.e., into the nineteenth century). Infante-Amate and Aguilera seek to address this gap in our understanding of historic greenhouse gas emissions by assembling the sources and developing the methods necessary to make those estimates.

Darrobers, Gingrich, and Magerl focus on the impacts of resource development felt beyond the specific sites of extraction, particularly in the case of timber products traded over long distances and across borders. Evaluating those impacts in the case of the United States required a method of accounting for ecological changes caused by extraction within a defined territory and the consequence of substituting some portion of that extraction with commodities imported from other, often quite distant, geographies. As Darrobers, Gingrich, and Magerl point out, "Research has shown that globally, higher-income countries tend to import natural resources from lower-income countries, thus externalizing environmental pressures" (Darrobers, Gingrich, and Magerl 2024, 2). They build on these insights by assembling a comprehensive dataset of historical timber products exported from, and imported into, the United States to assess how "trade may, overall, have contributed to facilitating the forest transition [i.e., reforestation] in the United States by means of externalizing wood production abroad" (Darrobers, Gingrich, and Magerl 2024, 10).

As Suits and Moyer (2024) reveal, the aggregate data of US agricultural energy use over the past two centuries present alarming trends starting in the post-WWII period, which reflect what researchers have referred to as the Great Acceleration (Steffen et al. 2015; McNeill and Engelke 2016). But the dramatic scale and pace of change reflected in the aggregate data looks different when normalized in per capita terms. Having assembled a large dataset for US energy use as part of a wider project, Suits and Moyer narrow the focus in their article to energy use in US agriculture and food systems to demonstrate that, even as total energy use in US agriculture rose over the last two centuries, the production of food to feed Americans became less energy intensive over time.

Urban historians have largely taken for granted that the needs of urban residents in the past were met through commerce with surrounding farms, forests, mines, and other resource hinterlands. In using port records to explore the importance of various commodities that fed, fueled, and formed the foundations of Toronto, Watson, MacFadyen, and Willness (2024) show that not only did urban functions rely entirely on external material and energy flows, but that the paths those flows followed were multitudinous and rarely well documented. And whereas national-scale analysis benefits from both the assumption of a relatively self-contained system, and the relative abundance of state-created sources to study it, at smaller scales of analysis, such as the region or a city, internal flows rarely sufficed to account for socioecological needs, and state officials did not keep consistent and comprehensive records of such activity. The Toronto port records provide an imperfect glimpse into an urban metabolism, but one that enables enough to reconstruct particular aspects of urban life and imagine how they connected the city to local and regional hinterlands.

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No potential conflict of interest was reported by the author(s).

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