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Plastics, social metabolism, and the society-nature problematic

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ABSTRACT

In this article, we contribute to an ongoing discussion in environmental social science around the society-nature problematic, which considers the distinction, or lack thereof, between society and nature. Drawing on the social metabolism approach in environmental sociology, we develop a concise historical discussion of the production and application of plastics. Analysis of plastics development offers valuable insights into how social and ecological systems, while ultimately united in the larger Earth system, must often be analytically differentiated. The case of plastics in the world provides essential nuance and validation for recognizing the distinct conditions created by historically specific social relations of production and how these can transgress against the universal metabolism of nature. Doing so allows for a critical understanding of the social drivers of environmental change, thus identifying potential mechanisms for alternative forms of the systems of production and consumption. We argue that the development of synthetic plastics, like all social phenomena, is an emergent property of the larger Earth system, one that is both rooted in and dependent upon the universal metabolism of nature while materially exhibiting characteristics not found anywhere else in the natural world.

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Introduction

A fundamental debate in environmental social theory and research has revolved around the distinction (or lack thereof) between society and nature, or what we refer to as the society-nature problematic. The society-nature problematic relates to the ways that analysts understand and characterize 'Nature' and whether (or how) we should differentiate social processes from natural processes, humans from the rest of nature, the cultural from the biophysical, and so on (Hedlund, Longo, and Clark 2022). This academic debate has significantly influenced the environmental social sciences and humanities, as well as the interdisciplinary sciences such as sustainability science and human ecology (Latour 1993; Malm 2018, 2019; J. W. Moore 2015; Smith 1984; Swyngedouw 1996). Like all metatheoretical foundations, the formulation of the (inter)relation of 'society' and 'nature' provides a methodological departure point for socioecological analyses. Although these formulations are not always explicitly acknowledged, they are analytically consequential for understanding the drivers and impacts of environmental change.

Drawing on social metabolism theory in environmental sociology, we engage with the society-nature problematic and apply our analysis to the case of plastics. The mounting production and use of plastics and associated waste have become a widespread, multifaceted ecological concern. Plastic materials and the chemicals that make them up have been associated with several socioecological consequences. Plastic waste pollutes landscapes and marine systems, affecting numerous ecosystems and organisms. Chemicals in plastics cause negative health effects on humans and other organisms. Natural scientific literature has well established the impact of plastics on ecosystems in every corner of the world (Geyer, Jambeck, and Lavender Law 2017; Stubbins et al. 2021). As the production of plastics and their effects multiply, social science research on the social drivers of plastics production and consumption is of increasing importance.

There are differing approaches to conceptualizing the society-nature problematic: one that positions the social as interacting within a wider ecological framework and another that erases the distinctions between the social and the environmental (see Hedlund, Longo, and Clark 2022). We situate our

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analysis within the former approach. Hybridists within the 'society-nature problematic' articulate a framework that, generally, might conceive an issue like (micro)plastics as further evidence that – as Haraway (1990, 191) envisioned – we exist in a moment where 'we are all chimeras, theorized and fabricated hybrids of machine and organisms.' Here, 'machine' would be analogous to plastics, especially as synthetic plastics proliferate in ecosystems, food, and increasingly our bodies. From such a perspective, a dualist worldview is at the center of a violent separation of humans from the rest of nature and used to justify the exploitation of nature and humans, and a constitutional aspect of modernity (J. W. Moore 2015).

While a hybrid approach may be fruitful for some analyses, our point of departure rests on a theory that recognizes the utility of analytical distinction, not hybridization, in order to emphasize the emergence and proliferation of synthetic plastics as a material phenomenon whose origins are socially driven and whose physical properties are not easily 'hybridized' within the universal metabolism of nature, be it human bodies, oceans, or other environs. Our analysis emphasizes the benefits of a historical materialist approach, such as social metabolism, for environmental sociological research, thus challenging various strands of post-structural, post-modernist, and post-Marxist approaches that have become increasingly influential in social science research analyzing global environmental change (Longo, Isgren, and Carolan 2025). The materialist conception of history that undergirds our approach emphasizes that humans are, as Bhaskar (2015) argues:

> unilaterally dependent on the physical and biological world from which we emerge … [and] certain material necessities have to be satisfied for any form of social or cultural life. However, the manner in which these prerequisites are satisfied is always socially and culturally dependent. (85–86)

Below, we start by briefly elaborating on the theory of social metabolism. We provide an overview of the approach, and in doing so, we emphasize how it contributes to the debates around the society-nature problematic. We follow this with a discussion of the emergence and remarkable growth of plastics over the last century. Next, we consider social metabolism and plastics and elaborate on how these issues contribute to the discussions associated with the society-nature problematic, and the significance of this analysis for transforming towards more sustainable systems of production and consumption.

Social metabolism

A significant component of sociological research on social metabolism draws on Marxist political economy to develop a critical materialist and dialectical approach to examining socioecological questions. Distinct from other social research that uses the concept of metabolism, such as industrial metabolism or strands of research in human geography, this school of thought was principally developed within the subdiscipline of environmental sociology. This social metabolic research is often associated with the 'metabolic rift' approach emerging in recent decades from the work of John Bellamy Foster (Foster 1999, 2000). In this work, Foster explained that Karl Marx made significant contributions to understanding ecological matters and developed a sophisticated metabolic analysis for assessing socioecological interactions and conditions.

Marx's materialist conception of history was undergirded by a materialist conception of nature, serving as a basis for a unified socioecological critique of the capital system (Clark and Bellamy Foster 2010; Marx and Engels 1998; Mészáros 2000). This framework yields useful insights that historicize biophysical phenomena. For instance, Lewontin and Levins (2007) remarked on urban air quality in industrial cities, and developed the concept of a 'proletarian lung.' In an effort to highlight the analytical power of historical materialism in the *Poverty of Philosophy*, Marx articulated a similar sentiment that soil fertility 'is not so natural a quality as might be thought; it is closely bound up with the social relations of the time' (Marx 1955, 75).

Important for the discussion here, a social metabolic approach analytically embeds social relations in the larger biophysical world and explicitly studies the interchange of matter and energy uniting a society and its ecological context (Burkett and Bellamy Foster 2006). Paying particular attention to scientific debates and discoveries, Marx incorporated the concept of metabolism into his critique of political-economy, explaining that it denoted the 'natural' process of production as the material exchange between humans and the rest of nature. He explained that there is a necessary 'metabolic interaction' between social and the Earth systems, and that labor mediates and regulates metabolic interchanges between human and non-human nature (Marx 1976, 283).

As Foster (2013) has detailed, Marx's analysis on this front involves a triadic structure, consisting of 'the universal metabolism of nature,' the 'social metabolism,' and 'the metabolic rift.' Thus, examining ecological concerns is not a mere 'add-on' or marginal matter to 'traditional' Marxist analysis. As stated, the key point is that a materialist conception of nature was crucial to Marx's (and Engels's) social analysis, which produced the footing for a materialist conception of history (Foster 2000; Saito 2017). Thus, social metabolic analysis is not simply a matter of applying a Marxist angle to ecological concerns.

This social metabolism approach understands Earth's systems as interconnected cycles and processes that sustain and renew the conditions necessary for life; i.e. the universal metabolism of nature (Foster 2013). It emphasizes that human existence is deeply rooted in – and reliant upon – these fundamental ecological functions. It is important to note that a 'universal metabolism of nature,' does not imply a general, single nature (Latour 2004) but should instead be understood as a recognition that non-human nature(s) possess their own distinct qualities and conditions necessary for regeneration, nutrient and chemical (re)cycling, species reproduction, etc., that exist, and would continue to exist, sans human culture and society. Human societies – and all life in general – exist within, depend on, and interact with this earthly metabolism. Marx's materialist conception of history precluded subsuming society into nature – or, as some strands of modern social science have often done, subsuming nature into society (*c.f.* J. W. Moore 2015). Marx's approach was strongly critical of the analytical hazards of both absolute idealism and mechanistic science and was formulated to challenge the problematic tendencies associated with these common approaches (Foster 2013).

Through their productive lives and activities, humans create a social metabolism, or social metabolic order, in relation to the rest of nature which fundamentally requires the interchange of matter and energy. Thus, the social metabolism always occurs within the universal metabolism of nature. However, this interaction is shaped by the historically specific political-economic organization of labor and (re)production of society: that is, the mode of production, productive forces, and corresponding productive relations that humans rely upon to meet their material needs set the terms for this metabolic interaction.

The social metabolism, under what Mészáros (2000) refers to as the 'capital system' – highlighting the structural dynamics of capital – materializes in a manner unlike other previous socioecological systems (i.e. it takes an alienated form). The demands of the capital system, i.e. structural processes and tendencies of capital, are imposed on nature, increasing the pressures placed on ecological systems and the production of wastes, generating distinct metabolic rifts (or ruptures) within both the social metabolism itself and the wider universal metabolism, consisting of various biophysical cycles and processes (Auerbach and Clark 2018; Clausen, Clark, and Longo 2015; Longo 2012). A 'rift' in 'the universal metabolism of nature' does not necessarily imply the 'destruction' of an ecosystem. Rather, it consists of a break in the capacity of non-human-constructed systems in the context 'human historical time' (Mészáros 2008) to, for example, absorb and break down chemicals, chemical compounds, and (in)organic material due to overload (i.e. pollution), loss of key species, and/or habitat degradation. The 'carbon rift' is illustrative in the failing capacity for terrestrial and marine systems to act as carbon sinks, due to an abundance of carbon dioxide in the atmosphere (Clark and York 2005; Müller et al. 2023; NASA 2020).

The social metabolic approach is rooted in a historical materialist method and is necessarily strengthened by dialectical naturalism (Foster 2020). Central to a materialist dialectical analysis is the concept of 'the identity of opposites,' which involves understanding the presence of contradictory and mutually exclusive forces in ecological and social processes (Lenin 1975, 648). It is important to note here that we are not referring to an idealist or discursive dialectical method. The dialectical approach we put forth is a materialist dialectic. It analyzes reality as dynamic, where phenomena are shaped by an internal tension between opposing and asymmetrical forces (both material and ideational). It emphasizes movement, transformation, contradiction, and variation, rather than static or stable states and categories in biophysical and social systems. As Engels (1940) clarified, dialectics runs counter to mechanistic (or vitalistic) analyses. Instead, it stresses processes of emergence, contingency, change, and particularly the relationship between quantitative and qualitative transformations, both social and ecological (Engels 1940; Foster 2020). Dialectical thinking was essential to Marx and Engels' theoretical system, providing insights for developing a critical socioecological analysis. This critical perspective 'encompasses both social and extrahuman dimensions of the environmental crisis' (Foster, Clark, and York 2010), where ecological crisis must be understood as a dynamic process of interpenetrating social and natural systems, and thus humans are both part of and,

possibly, alienated from nature (Mészáros 2000). In any mode of social metabolic reproduction, historical specific production processes and related systems structure the material exchanges across social and ecological systems (Mészáros 2008). This metabolic process operates over multiple spatial scales, from localized ecosystems to the integrated dynamics of the Earth System (Foster 2022; Longo et al. 2015).

We present an analysis that values the role of distinction, or analytical demarcation between 'society' and 'nature,' rather than a hybridization thesis which emphasizes a blending of culture, nature, human, non-human, etc. This latter position was forcefully articulated in, for example, Latour's *We Have Never Been Modern*, wherein he argues that modernity can be characterized as a misguided effort to purify, or distinguish, human and non-human realms. To Latour, 'nature and society are not two distinct poles, but one and the same production of successive states of societies-natures, of collectives' (Latour 1993, 139)., Any distinctions result in a duality between nature and society, according to Latour (1993, 85), and are mere 'convenient and relative reference points that moderns use to differentiate,' or arbitrarily categorize that which is inherently blended and non-distinct. As a result, 'ecological crises,' possess 'no clear boundaries, no well-defined essences,' thus necessitating that we 'must let go of nature' (Latour 2004, 25). This pairs closely with Haraway's (1990) argument on cyborgs, that the distinction between the natural and the synthetic is 'thoroughly ambiguous,' in an era where the replicants of Blade Runner are perhaps more projection than science fiction.

Such arguments have been extremely influential in fields of environmental social science (e.g. J. W. Moore 2015; Swyngedouw 1996). And, indeed, the ubiquity of plastics and their messy entanglement with organisms and ecosystems could suggest such a hybrid orientation. Nevertheless, we posit that it is necessary to emphasize the material bases of these processes – for example how these human-produced materials often cannot be effectively assimilated without harmful outcomes and, thus, produce ecological rifts in non-human systems. Indeed, the very notion of a 'rift' suggests an inability to effectively hybridize or produce 'cyborgs,' i.e. where the synthetic and organic are impossible to differentiate. We argue that to fully understand this synthetic age requires analytically compartmentalizing the distinctly social, particularly political-economic, forces that paved the way for synthetic proliferation. Synthetic plastics, we argue, pose a threat precisely because they cannot be integrated or absorbed by nature's universal metabolism without deleterious outcomes. Moreover, synthetic plastic's unique material qualities also help to account for its tremendous proliferation in an era of accelerated global capitalist development. It is these incompatibilities, these failures to absorb and hybridize social forces and ecological cycles, that we endeavor to better comprehend as the socioecological repercussions are growing. In the subsequent sections, we detail these properties and then provide an analysis drawing on the social metabolism framework. In doing so, we argue that synthetic plastics, like all social phenomena, is an emergent property of the larger Earth system, one that is both rooted in and dependent upon the universal metabolism of nature while exhibiting characteristics not found anywhere else in the natural world.

Plastics and the Anthropocene

State of plastics in the world

Synthetic plastics emerged as a true material force during the Second World War, making rapid advances in development during the post-war period. Compared to the level of production and use today, mid-century, post-war plastic production barely registers on a graph. In 1950, when thermoplastic synthetics were emerging as a material force for not only industrial and electrical but also consumer goods, global plastic production reached roughly 1.5 metric tons (Mt). At that time, plastic production and consumption were largely confined to industrialized nations. By 2022, production ballooned to over 400 Mt (Statista Research Department 2024), a more than 26,500% increase over 72 years, with a compound annual growth rate of over 8%, outpacing that of virtually any other material (Buffington 2018; Geyer 2020; UNEP 2018). The growth and prolific diffusion of synthetic plastics have sharply accelerated within the last few decades, swelling at the start of the twenty-first century. Indeed, according to one estimate, 'More plastic was produced in the first decade of the twenty-first century than in the entirety of the last' (Taffel 2016, 360).

The increase in plastics production directly correlates with the growth in global solid waste generation. Cumulative plastic primary production, at negligible levels in 1950, reached about 9 billion tonnes by 2017

(Geyer 2020). As Humes (2012) argues, the two complementary trends that have led to the growth in solid waste generation are the concomitant rise in plastics and disposable products largely made of and/or packaged in plastics. Today, the largest outlet for plastic production is packaging, which accounts for about 42% of plastic non-fibrous output. Packaging is also the sector that has the shortest product lifespan, an average of less than a year, meaning it is used and then quickly disposed of (Geyer, Jambeck, and Lavender Law 2017).

Because synthetic plastics are essentially non-decomposable, they end up contaminating terrestrial, marine, freshwater, and atmospheric ecosystems. The majority of cumulative plastic waste generation, 4900 Mt, was discarded as waste, ending up either in landfills or as refuse in the environment (Geyer, Jambeck, and Lavender Law 2017). A significant portion ends up, because of its durability, lightness, and inability to decompose, eventually accumulating in marine ecosystems, often by way of riverine systems (Carney Almroth and Eggert 2019). Synthetic plastic, rather than biodegrading, breaks into smaller and smaller pieces, creating micro- (smaller than 5 millimeters) and even nanoparticles (smaller than 0.0001 millimeters) (Sutton et al. 2019). This has created a kind of 'plastic soup' within marine ecosystems, particularly in ocean gyres, which are sites of matter accumulation because of ocean and wind currents. Plastics travel hundreds and thousands of miles to one of the five ocean gyres, slowly breaking up into smaller particles along the way (Buffington 2018; Carney Almroth and Eggert 2019; C. Moore and Phillips 2011). Recent estimates put the total number of plastic particles in the world's oceans at 5.25 trillion, with a combined weight of 270,000 tons (Eriksen et al. 2014). Researchers have estimated – and reports widely circulated – that by 2050, the mass of plastic in the oceans may outweigh that of fish (Taffel 2016).

The plastic that has not been discarded as waste is either still in use, recycled, or incinerated. Incineration is not a benign method of disposal, as it generates microplastics and other secondary pollutants such as heavy metals (Shen et al. 2021). About nine percent of the cumulative plastic waste has been recycled. While rates of plastic waste diverted from municipal solid waste (MSW) and refuse to recycling plants are increasing, the reality is that:

> Recycling delays, rather than avoids, final disposal. It reduces future plastic waste generation only if it displaces primary plastic production; however, because of its counterfactual nature, this displacement is extremely difficult to establish. Furthermore, contamination and the mixing of polymer types generate secondary plastics of limited or low technical and economic value. (Geyer, Jambeck, and Lavender Law 2017, 2)

The plastic recycling that does occur is mainly downcycling, meaning the repurposed plastic is turned into a new product that itself is nonrecyclable, thus merely delaying its inevitable disposal, as the quote above states. Further, the environmental and human health costs of plastic recycling itself are high. Plastic recycling is energy- and resource-intensive and often outsourced to the global South, where environmental and labor regulations are scarce. Much of the plastic waste exported from the global North to the global South is not, in fact, in a recyclable state, and ends up accumulating or being burned as a cheap source of fuel, with disastrous environmental and human health effects (Liboiron 2021; Minter 2015).

The human and environmental impacts of profligate plastic production, consumption, and waste are manifold, while much is still unknown. Fauna across the food chain ingest plastic, from blue whales to zooplankton, disrupting digestive and other metabolic systems, causing suffocation, death, and other potential health effects. Since plastic cannot be metabolized, it concentrates in organisms over time through bioaccumulation. Through biomagnification, larger organisms accumulate high volumes of plastic through the consumption of smaller organisms (Miller, Hamann, and Kroon 2020). The disruptive effects of micro-plastic pollution are difficult to comprehend, but recent studies suggest that microplastic pollution has a sizeable impact on photosynthetic absorption, with microplastic exposure leading upwards of a 12.12% reduction of photosynthesis in plants and algae (Zhu et al. 2025). In humans, plastic flakes have been found at increasingly concentrated levels in brains, kidneys, and livers, with especially high levels of concentration present in the brains of deceased dementia patients (Nihart et al. 2025).

Plastic production is energy-intensive and toxic, and intimately intertwined with 'fossil capital,' a historical production system of fossil fuel extraction, refinement, and use (Malm 2016). Discarded plastic acts as a kind of 'toxic sponge,' which absorbs persistent organic pollutants, making them even more dangerous to consume (Freinkel 2011; Meikle 1995). Plastics, and the host of additives they contain, have been found to be mutagenic, carcinogenic, and teratogenic (Blackburn and Green 2022; Daltry, Merone, and Tait 2021). The

Table 1. Production, use, refuse triad for synthetic thermoplastics.

Production	Use	Refuse

• Mechanized and energy-intensive injection-molding
• High capital-to-labor ratio
• Dependent on fossil fuel production and byproducts
• Created via organic chemistry
• Polymerized chemical monomers
  ○ Ethylene
  ○ Propanol
  ○ Vinyl Chloride
  ○ Styrene
  ○ Etc.
	• Raw material of production
	• Circulating capital (Marx 1978)
	• Producer, as opposed to consumer, goods
	  ○ Purchased by producers, rather than consumers, of commodities
	• Used as packaging, durable and single-use consumer goods, construction material, etc.
	• Short lifespan
	  ○ A plurality of plastics is used for packaging, which has a lifespan < 1 year
		• Non-biodegradable according to most timescales
		• Breaks down into smaller particles
		  ○ Microplastic < 0.5 mm
		  ○ Nano-plastic < 0.0005 mm
		• The majority (est. 79%) is discarded as waste in landfills or the natural environment
		• Est. 12% has been incinerated
		• Only marginally recyclable and rarely recycled (est. 9%) (Geyer, Jambeck, and Lavender Law 2017)

scale and scope of the contemporary plastic crisis are so concerning, so without precedent, and so rapidly advancing, that it raises fundamental questions about the social conditions that have spurred and facilitated its emergence and proliferation, as well as the changing character of socioecological processes. Table 1 highlights some notable characteristics of synthetic thermoplastics in production, use, and refuse.

The Great Acceleration and the synthetic age

Slowly emerging in the first half of the 20th century, the birthplace of modern synthetic plastics was principally the United States. During the Second World War, its emergence was marked by a pivotal change in the global political-economic structure, order, and character. Two of the central changes that occurred were the rise of the United States as the dominant capitalist-imperialist world hegemon, and, relatedly, the transformation of the material (and energetic) underpinnings – the nature of production, and the materials of production – of society (Hedlund and Longo 2024; Lotta and Shannon 1984).

Here, we argue that the emergence of the so-called 'Plastic Age' (Fenichell 1996) is a central factor in the advent of the proposed geological epoch: the Anthropocene. This proposition is based on the argument that humans have become the dominant driving force behind the change in the Earth's system. There are differences of opinion regarding the periodization of the Anthropocene, with some contending that it emerged with the beginnings of the Industrial Revolution in the late 18th century – roughly coinciding with James Watt's invention of the steam engine, the beginning of accelerated anthropogenic CO2 emissions, and the origins of fossil capital (Malm 2016). These disagreements are part of what led to its demise as an 'official epoch in the Earth's geological timeline' (Witze 2024).[1] However, there is continued debate and a mounting case that the Anthropocene's origins can be properly traced to the post-World War II 'Great Acceleration' period (Foster 2022; McNeill and Engelke 2016; Steffen et al. 2018). The Great Acceleration, beginning around 1950, was marked by a precipitous rise in CO2 emissions, resource and energy use, deforestation, urbanization, population growth, globalization, as well as synthetic production and consumption (McNeill and Engelke 2014).

Importantly, the argument for using the Great Acceleration rather than the Industrial Revolution as the start of the Anthropocene is based on more than just a general understanding of a change human interaction with ecosystems: it is based on this periodization's potential for verifiable stratigraphic markers (Foster 2022; Waters et al. 2016). The leading candidates for these 'golden spikes' that signal the shift from one epoch, the Holocene, to the other, the Anthropocene, are radionuclides from nuclear weapons testing and use, and synthetic plastics (Zalasiewicz et al. 2016). Zalasiewicz et al. (2016) argue for using plastics as a stratigraphic indicator of the emergence of the Anthropocene Epoch via the Great Acceleration, as plastics are easily identifiable as sedimentary deposits; are durable; are historically novel, thus distinguishing this period from all others; and because their widespread production and diffusion in the environment generally correlate with the trajectory of the Great Acceleration period.

Plastic proliferation, during the post-Second World War and Great Acceleration period, and global environmental crises were interpenetrating phenomena, each closely linked with a larger shift to what

Foster (1994) calls the Synthetic Age. The Synthetic Age represented a 'qualitative transformation' in the composition of economic goods produced and consumed. It is marked by the rising 'replacement of the products of nature with synthetics' (Foster 1994, 113). The synthetic shift went beyond plastics: a panoply of fuels, fibers, paints, adhesives, elastomers, pesticides, fertilizers, and detergents derived primarily from petrochemicals, themselves the product of breakthroughs in organic chemistry and the scientific-technical revolution, began to displace their counterparts derived previously from non-synthetic sources.

While the political-economic dynamics associated with the Second World War spearheaded this synthetic displacement, the profitability of synthetics solidified their domination (Commoner 1971; Geiser 2001; Lotta and Shannon 1984; Magdoff 1969; Mah 2022). Synthetics, and the technologies that develop and produce them, generally increase economic productivity per unit of output, as they essentially reduce the quantity of labor required for production (Commoner 1971; Foster 2013). This political-economic dimension of synthetic plastic production not only involves a reduction of labor costs but simultaneously expropriates greater quantities of matter and energy from nature. In the following section, we utilize the framework of social metabolic theory to explore this interrelation and its effects, particularly in how it generates toxicity and metabolic rifts.

Social metabolism and the society-nature problematic in the synthetic age

The emergence of the Synthetic Age provides important insights regarding the modern social metabolism and the society-nature problematic. First, it is worth considering what makes synthetic plastics unique. All related 'natural' raw materials – glass, metals, rubber, wood, etc.—are originally derived from earth systems, either from unearthed minerals or vegetation. Most are then transformed through human labor, energy, and other technologies in some way, sometimes significantly. Often, they are chemically altered to better suit their material purpose. For example, rubber is derived from the sap of heava trees. Transformed via the chemical process of vulcanization, it becomes hard rubber, a raw material that can be used for a plethora of industrial and commercial purposes (Tully 2011). But hard rubber is still a (chemically altered) material that originated from plants, and thus not technically a synthetic raw material. What distinguishes synthetics from non-synthetic materials is that the former is composed, at a molecular level, of configurations that cannot be found anywhere else in nature and generally cannot be decomposed, processed, or safely absorbed within the universal metabolism of nature.[2] These synthetic materials are human engineered and without precedent until very recently in Earth's history.

Synthetic plastics are polymers, which are abundant in nature. The unique, long chain-like, polymeric, macromolecular composition of polymers, developed through the stochastic processes of evolution, include bone, wood, hair, shell, starches, and proteins (Andrady 2003; Geiser 2001; C. Moore and Phillips 2011). Non-synthetic or natural polymers, particularly in the flora kingdom, 'predominate as the structural component of organisms' (Williamson 1994, 5). Yet, 'for every polymer produced in nature by living things, there exist enzymes that have the specific capability of degrading that polymer' (Commoner 1971, 153). Methods in modern organic chemistry enabled humans to bypass the arduous, millennia-spanning evolutionary development and instead combine various molecules into amalgamations not found anywhere on Earth, and importantly *without* a corresponding enzymatic counterpart. Such composites are definitively human-made from the inside out, in ways that make them categorically (though not absolutely) distinct from even chemically modified natural materials.

It is precisely this material novelty that makes synthetic plastics so valuable, so without historical antecedent or analog, so uniquely suited to fulfilling its sector-spanning economic functions, yet so fraught in its ecological assimilation and material configuration (Mah 2022). This dual nature of plastics – as apparent conqueror yet simultaneous despoiler of nature, as material that is analogous to yet radically disparate from bio-based polymers – flows from the very nature of synthetic/non-synthetic, human-made/nature-derived, distinctions.

Thus, polymers are omnipresent in Earth systems, and synthetic plastics are polymers that 'socially evolved,' in a sense, from bio-based polymeric plastics. Therefore, we must consider the analytic role that this distinction plays in understanding not only plastics as a material but the larger political-economic context within which it arose, as well as the contemporary environmental moment. Without it, we contend, it is nearly impossible to understand that the emergence of synthetic plastics was largely driven by

requirements of capital accumulation, and that this happened within a given economic, political, historical, technological, and cultural setting.

Natural plastics, celluloid, and the society/nature problematic

Celluloid, a so-called 'semi-synthetic plastic,' embodied a transitory phase between plastics of natural origin and synthetics. It therefore highlights the characteristics of both, elucidating their continuities and distinctions. The impetus for celluloid was largely twofold. First, the shortages, both perceived and real, of natural raw materials spurred the quest for a more reliable source of productive material. Second was the demand for a homogenous, consistent, environmentally resistant, easily moldable material amenable to capital-intensive production methods and mass production. As Williamson (1994) states in his analysis of the early origins of the plastics industry:

> This facility to produce moulded products more quickly and therefore more cheaply than their carved counterpart is the prime motivating force behind the development of plastics and the plastics industry as we know them today. (1994: 4, bold in original)

The inability of organic plastics—e.g. shellac, gutta-percha, even vulcanized rubber – to fulfill this role, coupled with their rapidly depleting stocks, was what induced inventors such as Alexander Parkes and John Wesley Hyatt to experiment with nitrocellulose, in search of a generalized plastic mass. As Friedel (1983), in his monograph on the development and use of celluloid states:

> The arrival of the natural plastics was a major episode in the emergence of new materials in the nineteenth century. They were the first significant alternatives to the traditional solid materials of manufacture and reflected a widespread desire for materials that were freed from the limitations of metal, glass, clay, and wood. The natural plastics indicated the possibilities for materials that were easily moldable and yet stable in their final manufactured form, for substances that avoided the coldness, heaviness, and chemical and electrical activity of the metals, that beckoned to artistic imagination while avoiding the fragility, cost, and weight of the glasses and ceramics, and, finally, that were in some way liberated from the stinginess of nature by combining durability and beauty in a readily available form. None of the natural plastics were able to satisfy all of these desiderata, *but they clearly fostered a sense of what was really wanted*. (28, emphasis added)

This dialectic of natural plastics, which portended yet could not fulfill the role of this generalized plastic mass, flows from both its relation to and distinction from synthetic plastics. Made from a certain kind of organic polymer, bio-based or natural plastics are, on one level, quite like the synthetics that later superseded them. They are pliant, easily moldable, can take form once heated, and have a basic degree of plasticity in that they readily take a given form and shape when worked on by human technology and labor. Yet they lack the lightness of weight, colorability, relative durability, reduced cost, and apparent independence from the metabolic imperatives of nature, or the relative imperviousness to biophysical processes. Thus, the distinction between natural and synthetic plastics is relative and, in one sense, a quantitative one – a matter of degree.

Celluloid bridged the gap, historically and analytically, between natural and synthetic plastics, as the first real attempt at creating a generalized plastic mass. A product of nineteenth-century chemistry, celluloid was composed of long-existing nature-derived ingredients – camphor, extracted from the camphor laurel tree – and modern industrial processes and ingredients, such as cotton textile scraps, chemically altering the admixture with a liquid solvent, solid fillers, and the application of heat and pressure (DuBois 1972; Friedel 1983; Meikle 1995). The first plastic material created in a laboratory, celluloid differed from its natural precursors both in its material composition and capital-intensive production requirements.

Celluloid, unlike the labor-intensive, extractive production methods of gutta-percha, ivory, shellac, or hard rubber (although the latter was also chemically altered through vulcanization), 'required considerable capital equipment, largely machinery, and was hence subject to major economies of scale.' The requisite level of capital investment as a barrier to entry meant that its manufacture 'was thus always concentrated in a few large factories, and its supply was in the hands of a few sizable companies' (Friedel 1983, 18). Changes in the nature and composition of raw materials – derived from and interpenetrating with advances in science, technology, greater power of capital through increased concentration and centralization, as well as intense competition between blocs of capital over market shares and production costs – which led to the creation of

celluloid, both caused and resulted from attempts to develop future, fully synthetic raw materials that built upon as well as transcended the properties of former.

Celluloid's partial, yet largely illusory, independence from nature – both in its origins, as a material produced in a laboratory, and in its limited resistance to decay and atrophy – whetted the appetites of inventors and investors for a more thoroughly human-made material. This is clear from Meikle's (1995) description of what celluloid lacked:

> Plastics succeeded as a material of choice for manufacturing in the twentieth century not only owing to lighter, cheaper raw materials but because one-shot automatic molding operations eliminated the cost of separate fabricating, finishing, and assembling operations. But celluloid introduced no such savings. Manufacturing techniques remained those of the nineteenth century, with celluloid fabricators often directly borrowing techniques from the horn or tortoiseshell industries they were displacing. Despite the industry's claim that 'standardization' was 'the keynote of progress,' it remained a labor-intensive, craft-oriented business. Its competitive edge derived from its offering a somewhat more homogeneous raw material, an artificial substitute lacking some of the imperfections and irregularities of natural materials. (18)

Celluloid was a more standardized material than its natural counterparts, with its 'inconsistency and impurity … seem[ing] minimal by comparison with that of natural materials' (Meikle 1995, 26). Yet its fabrication required skilled labor, done by hand and/or with small machines – still largely a form of craft production. It attempted to overcome the irregularities of natural raw materials for production – portending and imperfectly reflecting the desire of capital to simultaneously gain mastery and control over both nature and the production process. Both its promise and its limitations as a material were emblematic of its existence as a partially synthetic plastic.

Synthetic plastics and nature/society dialectic

The emergence of synthetic plastics was the product of multiple intersecting, mutually interpenetrating phenomena. These include the scientific-technical revolution and concomitant advances in organic chemistry and chemical engineering; the rise of fossil capital and centrality of coal, and later oil, as a key source of energy; and the perceived shortcomings of natural raw materials in the service of accelerating, globalizing capital accumulation; among other factors (Braverman 1974; Geiser 2001; Lotta and Shannon 1984; Mah 2023; Malm 2016; Meikle 1995; Reboul 1994; Spitz 1988). Bakelite, the first synthetic plastic, and the wave of synthetic thermoplastics that followed in its wake were simultaneously two things: polymers that were similar in form and function to their natural plastic forebears; and material of an entirely novel and unprecedented kind. Both aspects of this and their interrelation are important in order to understand why synthetic plastics proliferated and why that proliferation is such an ecological quandary. How these materials were integrated and converged into the social metabolic order and the paths of socioecological development that were prompted and materialized are key moments in the rise of the modern synthetic age.

Significant and historic changes in the social metabolic order were marshaled by early thermoset plastics like Bakelite in the early twentieth century, produced from coal byproducts, followed by the thermoplastic explosion in the interwar period. The development and rise of synthetic plastics coincided with an epochal shift in the volume and type of material and energetic throughput. Intrinsically bound to fossil fuel production, synthetic plastics, particularly thermoplastics, are part of an 'integrated production system,' coupled with oil, automobile, and chemical capital (Geiser 2001). The byproducts of oil refinement to produce petroleum fuel provide the raw materials – including olefins such as ethylene and propylene – through which a host of polymeric assemblages are made. These synthetic polymers mimic, expand upon, and transcend an array of natural raw materials, both natural plastics and other materials like glass, metal, and wood. Their appeal as a generalized base material – the physical substratum of contemporary globalized commodity production and exchange – is multilayered. Derived from the excreted waste material of a highly profitable and economically essential production process – oil extraction and petroleum production – it has a built-in competitive advantage over other raw materials. However, though not reducible to this factor, it is synthetic plastics' novel characteristics that make it so economically profitable and socially useful within a social metabolic order that has been so profoundly shaped by generalized commodity production.

It is important to understand every aspect of synthetic plastics that makes them qualitatively distinct from both their predecessors and prior raw materials. These include, as mentioned above, its source as

a byproduct of fossil fuel production, its method of production – i.e. rapid, capital-intensive injection molding, and other highly mechanized forms of machine-based manufacture – its unique material qualities, and its comparative cheapness, which directly relates to its first two aspects. In each of these dimensions, and its totality, these relative distinctions from other materials represent a rupture – the emergence of a novel physical property. Humanmade, its development is difficult to imagine without humans and unlikely without the specific form of socioeconomic organization and level of productive power within which it was created. At the same time, there is continuity between natural and synthetic plastics. This relationship – of both qualitative and qualitative distinction, continuity and rupture, likeness and difference – is best understood dialectically.

Social metabolic dialectics and the role of distinction

The dialectical method emphasizes the significance of contradiction – where things are seen as unities of opposites. In this view, boundaries and distinctions are both essential and relative (Avakian 2009; Levins and Lewontin 1987). Because dialectics prioritizes change, permeability, and fluidity, some have ignored the importance of distinctions within wholes. Holistic approaches, even those invoking dialectics, often fall into the trap of expatiating on interconnectedness while neglecting the relative autonomy of individual elements (Lewontin and Levins 2007). This tension requires both distinguishing among phenomena to allow for meaningful analysis – without reifying the parts – and focusing not just on the relationships between elements but on their interpenetration and contradictions.

The materialist dialectics inherent in a social metabolic approach helps reveal key moments in the existence and historical development of synthetic plastics. This approach emphasizes the importance of analytic distinction to gain a concrete understanding of both the socioeconomic value and ecological liability of this novel material. Synthetics can be considered a categorically social phenomenon, as it relates to the society-nature problematic (Hedlund, Longo, and Clark 2022). Constituting complex molecular arrangements, requiring a high level of development of the productive forces and a particular set of social conditions, synthetic substances could not have emerged, in all likelihood, without human intervention and agency. What makes synthetics relatively 'non-natural' becomes apparent in analyzing how they are created, how they function, and the ecological impacts of their post-use dissemination. In other words, we must always account for nature's 'universal metabolism,' at each stage of a synthetic product's 'life cycle,' from initial production, use, disposal, and failure to decompose. Indeed, in each phase of their existence – production, use, refuse – synthetic plastics are distinguished from their material counterparts.

Of course, synthetic plastics are derived from ingredients found within nature. It could not be otherwise. This raw material source, i.e. byproducts of fossil fuels, can itself be distinguished as a nonrenewable, as opposed to being a renewable (e.g. solar) or replenishable (e.g. wood) source (Geiser 2001). The social metabolic processes that emerged, dialectically and materially are significantly governed by the dictates of a social system predicated on commodity production, capital accumulation, and growth. Society, as stated above, and its artifacts are an emergent form of nature, not ontologically distinct but constituent of properties that are categorically novel. As an emergent property of nature, of matter in motion, society remains rooted in the former, while developing in ways that distinguish it from the whole (Carolan 2005; Longo, Isgren, and Carolan 2025; Malm 2019). While this might appear to be contradictory, that is, in fact, the point. The dialectical method allows us to understand that all real boundaries are simultaneously relative ones (Avakian 2009).

The continuity with prior raw materials – themselves far from 'purely natural,' having been transformed by human labor – and the rupture, through the emergence of synthetics that mimicked yet transcended (relatively) these natural materials, is a clear example of the analytic importance of maintaining, without ossifying, the natural/social distinction. This is a critical component of applying theoretical frameworks, such as social metabolism, that identify dialectical dynamics. Failing to maintain such analytical distinctions risks collapsing social and natural phenomena into an undifferentiated whole, which can obscure the role of human agency, and thus the social drivers and, ultimately, consequences, of environmental change (Hornborg 2017; Malm 2019).

Social metabolic analysis – as a dialectical materialist approach – emphasizes that seemingly opposite conditions, such as production and destruction or wealth and poverty are fundamentally interconnected,

and unified, yet in tension. These opposites exist in a unity shaped by contradiction, where one aspect may be dominant at any given time, but both remain in constant interplay (Levins and Lewontin 1987; Ollman 1993; Wolff 1983). Not all oppositions form such unities, however, and it is critical to analyze under what conditions the relationship between society and nature might be seen as a unity of opposites (Wolff 1983). By focusing on the concrete material conditions of this socio-economic system, rather than the abstract discursive concepts of 'Nature' and 'Society,' the theory of social metabolism allows us to better understand the antagonistic unity between them. This analytical distinction is crucial for examining the contradictions, conflicts, and alienated relations that define the modern social metabolic order.

Taking the example of plastics, it becomes clear that while society is deeply rooted in and cannot be divorced from natural systems, it has its distinct dynamics that warrant discrete analysis. The question is not whether we should distinguish between social and natural phenomena, but how we can do so in a way that recognizes their dialectical unity. Social metabolism offers conceptual mechanisms to maintain this distinction while acknowledging the interconnectedness and contradictions between society and the rest of nature (Malm 2019).

Discussion and conclusion

These extremely recent developments in which plastics have been integrated into every corner of Earth's systems – and the organisms that inhabit them – present opportunities for analyzing socioecological conditions, particularly the social drivers of environmental change. As discussed above, modern plastics are 'organic' because of their carbon-based chemistry. But more specifically they are synthetic polymers. Synthetic polymers can interact with organic and inorganic systems. However, their incorporation or interaction is quite different from non-synthetic materials. Overwhelmingly, they cannot be broken down to their basic elements in any feasible human time frame, and their byproducts are toxic to most organisms, including humans.

The dual inability for synthetic plastics to, one, be produced without human intervention and, two, to biodegrade (metabolize) within human bodies and non-human nature demonstrates a core premise of our dialectical approach to the society-nature problematic. While we recognize the constant interplay of human society, activity, and non-human systems, the initial drive to generate synthetics, their capacity to procure exchange value in service of capital accumulation, and their incomplete assimilation in the universal metabolism of nature speak to their exceptionally social features. Moreover, the environmental effects of synthetic plastic proliferation indicate a key tenet of social metabolic analysis, that the unplanned technological innovation in the service of capital accumulation often leads to disruptions in metabolic cycling of ecological and biological systems, e.g. an ocean ecosystem or the bodies of aquatic animals, respectively (Hedlund and Longo 2024).

A dialectical approach makes these insights possible, as it encourages a clear grasp of the emergent properties of a society. Under a capitalist social metabolic order, generalized commodity production has relied upon chemical structures that enhance and accelerate valorization but exist nowhere else in nature, and thus associate antagonistically with the universal metabolism of nature. In taking this approach, we have argued that the social metabolic demands of a capitalist political-economy act as a structural pressure to move toward materials that are less constrained by ecological limits and, simultaneously, less dependent on human labor power. In turn and over time, the properties of synthetic plastics transcended such limits and more efficiently enabled ongoing, accelerated capital accumulation. Moreover, the production of disposable, synthetic plastics was broadly compatible with a mode of production and consumption – a social metabolic order – that relied heavily on consumer spending and economies of scale. Synthetic plastics are in many ways exemplary of the basic understanding of society's emergence from nature: being both inextricably rooted in and dependent upon, yet forming properties not found anywhere else within, the universal metabolism of nature.

From there, we can see the importance of synthetic plastics for affecting nature's universal metabolism in ways that mark epochal shifts in regulatory capacities and conditions of non-human environments. This transition to a 'synthetic age,' where a great bulk of non-degradable materials are produced via human activity typifies the Great Acceleration and demonstrates that we are, indeed, entering a new geological epoch where human activity is producing qualitatively novel

earth-system dynamics, not fathomable in prior periods. Indeed, developed to meet production demands driven substantially by a capital system, plastics have become ubiquitous. Global production surged from 2 million tons in 1950 to over 459 million tons by 2019, outpacing the growth of nearly all other materials (Geyer, Jambeck, and Lavender Law 2017). Most plastics are not recycled, accumulating and polluting ecosystems as non-biodegradable waste. As novel, human-engineered entities, plastics exceed the Earth's safe operating limits (Villarrubia-Gómez et al. 2024). Scientists now recognize humanity is outside the 'safe operating space,' as plastic production and consumption overwhelm our ability to assess and manage their risks (Persson et al. 2022). These materials leave a geological imprint while disrupting ecosystems, altering biogeochemical cycles, and causing toxic effects on organisms. Despite growing evidence, the full ecological and health consequences remain unclear, another sign that something 'new' is afoot. Indeed, this lack of clarity, we propose, underlies the very nature of entering a new geological epoch – an era of increasing uncertainty and novelty.

The parameters of this new epoch will surely be debated, contested, and redefined over the coming decades. We have, ultimately, argued that this discussion will be better informed by a social metabolic framework that centers such developments on the inner structural workings of the capital system (Mészáros 2000). Plastics are an example of efforts to transcend biophysical limits, shaped in a consequential manner by the pursuit of value. Their enormous growth in production and deployment prioritizes capital accumulation and makes socioecological concerns appear as tertiary consequences to (perhaps) be dealt with later.

This socioecological contradiction between the universal metabolism of nature and the particular social metabolic order of capital suggests we probe for alternative modes of production and consumption, beyond the logic of capital (Mészáros 2000). Such alternatives, we argue, must prioritize general principles that remain antagonistic to a capital system; chiefly, a turn to conscious production focused on meeting social needs and that occurs in a planned, ecologically rational, democratically accountable fashion. Such planning must incorporate the conditions required by nature's universal metabolism as a central concern for novel institutional conditions. This logic mimics a precautionary principle, that new technics (including chemicals) must be proven safe and manageable prior to mass development. Relatedly, development must be centered around use-values, i.e. human need, in ways that do not compromise ecological systems. While meeting human needs always requires some degree of environmental extraction and impact, it is – unlike exchange value – concretely tied to material conditions and limits.

If there is to be some potential to better address growing environmental problems such as plastic pollution, a social metabolic order that takes direct account of ecological sustainability and substantive human development is more likely to advance socioecological well-being. These novel principles for development are, precisely, what a capitalist social metabolic order has (by its own operating logic) eschewed during this 'Great Acceleration' period. Moving beyond capital will therefore require challenging the underlying principles of ceaseless, unplanned, even anarchic, growth and capital accumulation endemic to the existing social metabolic order (Mészáros 2000). Recognizing the historical character of capital, its systemic properties, and the resulting social metabolic order as analytically distinct from the universal metabolism of nature allows for needed insights into the social drivers of plastic production and environmental change and contamination.

Finally, while we focus here on synthetic plastic material, there are other products of human activity that could be analyzed through a similar framework. These include petrochemicals such as petrol, nuclear waste, and so-called 'forever chemicals' such as per- and polyfluoroalkyl substances (PFASs). In particular, we contend that PFASs are an important class for future research, because of their widespread use and diffusion into the natural environment (including human bodies), their unique carbon-fluorine bonds, environmental persistence, and hazardous health effects (Sims et al. 2022; Wang et al. 2017).

Notes

1. After 15 years of debate, the American Geological Society decided against establishing the Anthropocene as an official epoch. Nevertheless, the discussion is still quite valid, as the decision was based largely on technical

disagreements, and the Anthropocene is still considered a useful concept to describe 'the era of accelerating human impacts' (Witze 2024).

2. It is true that contemporary research has found a limited number of fungi that appear to colonize and degrade some synthetic plastic polymers (Ibrahim, Ionescu, and Grossart 2024). This is an important development. Yet the scope and scale of this potential fungal bioremediation is currently quite small compared to the vastness of the synthetic plastic phenomenon.

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