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The symbiosis of sociometabolic regimes and capital-labour relations in late capitalism

AUTHOR:
Eduardo Veciana

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SECO ◉ Socio-Economic Research Centre
Department of Social Sciences and Business, Roskilde University
Universitetsvej 1, 4000 Roskilde, Denmark
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1. Introduction

The trajectories of biomass, fossil fuel, metal, and mineral use in high-income economies show a rapid post-1950s rise in resource consumption and physical stock accumulation, followed by saturation from the 1970s (Wiedenhofer et al., 2013). Although material footprint growth resumed in some countries around the 1990s, stagnation has prevailed since the 2000s. As illustrated in Figure 1, these footprint-adjusted trends indicate a material use plateau, even when accounting for outsourced environmental pressures. This raises key questions: What explains the acceleration and subsequent saturation of resource use since the 1970s? Do these patterns reflect a structural transition toward stable material consumption or a temporary disruption in the logic of unlimited accumulation?

Figure 1. Evolution of Domestic Material Consumption and Footprint: This graph shows growth followed by stagnation (around 1973) of material footprint (MF) and domestic material consumption (DMC) disaggregated into biomass (BIO), fossil fuels (FOS), metals (MET) and non-metallic minerals (NON). MF attributes all resource extraction (including extraction abroad) embodied in domestic consumption. Source: Own elaboration with data from (Cahen-Fourot & Magalhães, 2023; Steck et al., 2021; UNEP, 2025).

To analyse long-term resource use, ecological economists increasingly employ the concept of sociometabolic regime (Krausmann et al., 2008; Schandl & Schulz, 2002). This framework redefines socioeconomic development as a transition between socio-environmental systems. Sociometabolic regimes capture biophysical resource flows and physical stock accumulation shaping future resource use (Fischer-Kowalski & Haberl, 2015; González De Molina & Toledo, 2023). Flows constitute the material basis of socioeconomic reproduction, sustaining households, labour, capital, and the wider economy (Fischer-Kowalski & Haberl, 1997), whereas stocks comprise the technical infrastructure of production, including machinery, buildings, and energy conversion technologies (Sieferle, 2002). Together, flows and stocks drive environmental pressure through degradation, waste, and emissions.

Current material flow analyses largely attribute the sociometabolic shift to productive forces—from coal- and oil-based manufacturing to more resource-efficient technologies, internationalised production, and tertiarisation (Fischer-Kowalski & Hausknost, 2014). Yet this perspective often overlooks social relations as historically specific interactions among social blocs enabling technical and structural change (Magalhães, 2022; Petit, 1999; Schaffartzik et al., 2021). By contrast, originating works view social metabolism as labour-mediated (Marx, 1977; Mészáros, 1995; Pineault, 2025). Despite this, most sociometabolic research rarely treats labour as a core regulatory element. When considered, it is typically framed as a byproduct of prevailing energy systems rather than as a shaping force (Fischer-Kowalski, 2023; Sieferle, 2002).

To develop a socioecological understanding of labour, I draw on ecological revisions of Regulation Theory, focusing on the wage-labour nexus. From this perspective, sociometabolic patterns of production and consumption are steered by institutional forms mediating social compromises between capital, labour, and broader social blocs (Zuindeau, 2007). Among Regulation Theory's five institutional forms[1]—the monetary regime, wage-labour nexus, form of competition, state form, and international regime—the wage-labour nexus is central to social metabolism because it directly structures societies' embeddedness in nature at the point of production (Pineault, 2023b). It encompasses "the type of means of production; the social and technical division of labour; the ways in which workers are attracted and retained by the firm; the direct and indirect determinants of wage income; and [...] the workers' way of life" ((Boyer & Saillard, 2002), p. 345). This study concentrates on two broader dimensions of the wage-labour nexus: (1) the (re)productive and unproductive organisation of work, involving the forms of corporate and state management of labour, and (2) labour institutions, which shape power and income distribution between capital and labour (Bakshi et al., 1995; Boyer, 1993).

Historically, the transition from Fordist to Neoliberal wage-labour nexus was intertwined with shifts in energy systems and material use. Fordism—defined by the nuclear family model, collective bargaining, and productivity-linked wages—relied on an energy-industrial complex supplying cheap, high-quality energy (Cahen-Fourot & Durand, 2016; Huber, 2013). This dependence contributed to labour's declining structural power, as the oil crises of the 1970s prompted Neoliberal reforms such as financial deregulation, wage restraint, and increasingly flexible and segmented labour markets (Mitchell, 2009; Pellegris & Court, 2025). Extending these ecological revisions of Regulation Theory, I argue that the wage-labour nexus mediates investment and consumption dynamics and is thus embedded in material flow patterns (Malm, 2018). My contribution is to move beyond viewing social metabolism (via energy systems) as causally shaping the wage-labour nexus, underscoring instead a persistent socioecological symbiosis where labour and sociometabolic regimes mutually shape one another.

[1] For an overview of Regulation Theory's core concepts in relation to ecological economics, see (Driouich & Kallis, 2025; Zuindeau, 2007).

Understanding historical labour dynamics through a social metabolism lens is crucial for both theory and practice. Although sociometabolic regimes have been extensively described, their regulatory processes and links to production and consumption remain underexplored (Padovan et al., 2022). This gap has contributed to a vision of the green transition that relies predominantly on technology-driven decarbonisation. Yet, environmental justice movements demonstrate that large-scale decarbonisation projects often encounter resistance when they reproduce precarious conditions (Zografos & Robbins, 2020). Moreover, improvements in resource efficiency frequently increase overall energy use rather than reduce it, unless accompanied by limits on material consumption (Fressoz, 2024). These dynamics underscore the need to rethink labour relations to decouple work from material accumulation while shielding workers from structural transformation.

With this approach, I examine how the transition from Fordist to Neoliberal wage-labour nexus relates to shifting patterns of material use in high-income countries. I conceptualise this relationship as symbiotic, defined by (1) a dynamic, bidirectional, long-term relationship and (2) a historically specific relation, varying across periods of crisis and stability in capital accumulation. Econometrically, I provide evidence of symbiosis through cointegration and time-varying causality analyses of labour and metabolic time series for the United States and France (Castellacci & Natera, 2013; J. Foster & Wild, 1999). These cases were chosen because of data availability and because they clearly exemplify the post-war Fordist wage-led model followed by a shift toward finance-led globalised capitalism (Hassel & Palier, 2023). Their broadly similar economic structures allow for holding of macroeconomic dynamics relatively constant, enabling a focus on institutional and material differences over time.

Given that social metabolism and the wage-labour nexus cannot be captured by a series of indicators, I complement the quantitative analysis with a historical periodisation of symbiosis. In this way, I illuminate social compromises mediating capitalism's overproduction tendencies (Baran & Sweezy, 1966; Braverman, 1998), thereby stabilising material accumulation. In both Fordism and Neoliberalism, metabolic change was intertwined with corporate and state management of labour to align productive capacity and demand, although in distinct ways: Fordism relied on an industrial-managerial social bloc that promoted the coupling of family wages and productivity alongside Keynesian demand management. This social compromise was ultimately constrained by its dependence on extensive sociometabolic regimes. Consequently, under Neoliberalism, the shift toward an intensive sociometabolic regime enabled the continuation of high levels of environmental pressure, although in a saturated form. An extractive rentier bloc consolidated this material trajectory by discouraging fixed capital formation and advancing wage-productivity decoupling through shareholder-oriented labour governance, the commodification of knowledge and asset-price Keynesianism.

These findings make three main contributions to the literature integrating Ecological Economics, Social Metabolism, and Regulation Theory. First, while environmental labour history has documented society–nature symbiotic relations, this study proposes an econometric operationalisation of symbiosis through cointegration (J. Foster & Wild, 1999; Kallis & Norgaard, 2010). Second, it advances ecological revisions of Regulation Theory by highlighting how sociometabolic regimes are not merely a constraint on the wage-labour nexus but are also fundamentally shaped by it (Cahen-Fourot & Magalhães, 2023; Huber, 2013; Magalhães, 2022; Pellegris & Court, 2025; Zuindeau, 2007). Third, it contributes to social metabolism research by foregrounding its political-economic dimensions (Schaffartzik et al., 2021).

The remainder of this paper is organised as follows. Section 2 reviews the theories on socioecological transitions. Section 3 sets out the theoretical framework linking the wage-labour nexus to sociometabolic regimes. Section 4 details the research design. Sections 5 and 6 present the results and develop a periodisation of the wage-labour nexus across sociometabolic regimes. The conclusion discusses limitations and summarises the main findings.

2. Theories of sociometabolic transitions

Long-term studies of material flows link sociometabolic transitions to factors such as new energy carriers (Gierlinger & Krausmann, 2012; Krausmann et al., 2008), structural changes (Infante-Amate et al., 2015; Kovanda & Hak, 2011; Krausmann et al., 2011), globalization (Magalhães et al., 2019), regulatory modes (Schandl & Schulz, 2002), and economic systems (Krausmann et al., 2016). However, these factors remain underexplored, as most studies focus on describing material flows without connections to political economy theories. In turn, I survey explanations of sociometabolic transitions and find four perspectives focusing on productive forces: Ecological Modernisation (EM), Treadmill of Production (ToP), Ecologically Unequal Exchange (EUE), and the material saturation hypothesis. While these theories can explain patterns of material stocks and flows, they overlook the ways in which productive forces are embedded in capitalist social relations, particularly in the historical evolution of wage labour. Even when labour relations are acknowledged—notably in ToP and EUE theory—they are treated statically, either within Fordist mass production or within global economic frameworks.

The dominant explanation for material consumption patterns relies on a linear model of structural change across development stages rooted in EM theory (Spaargaren, 2000). Consumption stabilisation in high-income countries is attributed to resource efficiency and tertiarisation (Carolan, 2004; Fischer-Kowalski & Hausknost, 2014). Reduced resource intensity reflects the institutionalisation of environmental concerns at firm and policy levels. This "ecological rationality" of internalising environmental costs through new institutional arrangements and technology justifies the continuing growth of industry and consumption. In this view, EM is linked to the Environmental Kuznets Curve, which posits that environmental degradation initially rises with industrialisation but improves beyond a certain income threshold (Jorgenson, 2016). "Advanced" economies exhibit expanding service sectors and greater societal emphasis on post-material values.

In practice, empirical support for EM theory is limited. Efficiency improvements partly reduced material intensity since the 1970s, driven by better technologies in response to higher energy prices due to oil shocks (Fischer-Kowalski & Hausknost, 2014). Structural shifts from heavy to light industries, especially via microelectronics, also played a role (Kander, 2005). However, resource efficiency is shaped by social relations, a factor often overlooked in EM theory. For instance, the rise of services and light industries is associated with de-industrialisation and thus the weakening of labour bargaining power in heavy industry (Escher & Stegmueller, 2023; Di Carlo et al., 2024). Thus, EM assumes human exemptionalism, implying that technological progress can overcome ecological limits without generating inequality or conflict (Bugden, 2022; J. B. Foster, 2012). EM also conflates resource efficiency with reduced material consumption, a premise challenged by research on decoupling (Haberl et al., 2020).

ToP theory sharply contrasts with EM by framing economic development as the primary driver of environmental degradation (Gould et al., 2004; Schnaiberg et al., 2002). Emerging from post–World War II analyses of monopoly capitalism, it explains how profit-driven investments intensify resource- and chemical-intensive production. This locks economies into a treadmill of continuous production and consumption that escalates environmental harm. Slowing this treadmill can mitigate environmental pressure (Keil & Kreinin, 2022; Obach, 2004), yet this does not indicate an internalised ecological rationality among firms. Rather, it reflects counterforces such as labour-protective institutions, the growth of low-productivity sectors such as public services, and environmental advocacy. Many environmental regulations, for instance, arise from worker demands over workplace health rather than from firms' intentional greening strategies (Barca, 2014).

However, a paradox emerges: material consumption stagnated in high-income economies since the 1970s, yet labour bargaining power—which could slow the treadmill of production—also declined. By focusing on the Fordist era, ToP equates production disruptions with counterforces to profit maximisation, overlooking shifts in wage-labour organisation. High-income economies have arguably transitioned from a productive treadmill to a 'stagnation-accumulation treadmill,' where slow growth coincides with expanding financial capital (Clark, 2024). This financialization arose from the crisis of the Fordist wage-labour nexus, shifting work organisation from worker–manager to manager–shareholder balance (Krippner, 2005; Tauss, 2012). Thus, slowing resource-intensive production signals not only a technical break but also a social reorganisation.

Both EM and ToP emphasise national production, often overlooking global dynamics. In contrast, EUE theory highlights the asymmetric flow of energy and materials from the Global South to the North, driven by Northern appropriation and Southern dependence on resource extraction (Dorninger et al., 2021). Since the rise of global value chains and structural adjustment programs, Northern firms have increasingly offshored production to exploit wage gaps and weaker environmental regulations (Althouse et al., 2023). Financialization further accelerates this internationalisation, shifting resource-intensive production abroad and creating apparent domestic "dematerialisation" (Schaffartzik, 2024).

Despite the relevance of EUE theory, it does not fully explain the stabilisation of material consumption in high-income economies. Consumption-based studies show that even when accounting for offshored production, material consumption and stock additions have stagnated since the 1970s (Cahen-Fourot & Magalhães, 2023). The collapse of colonial arrangements, driven by national liberation movements, likely triggered a crisis of capital accumulation in the Global North, contributing to this stagnation (Mitchell, 2009; Patnaik & Patnaik, 2021). However, patterns of labour and resource appropriation from the colonial period persisted into the Neoliberal era (Hickel et al., 2022), and despite ongoing unequal exchange, material accumulation in high-income countries did not return to post-war levels. Consequently, other factors besides the internati

Critiques of logistic models align with debates on long-wave theories, which explain cycles of capital accumulation through endogenous economic factors (Kondratiev), exogenous shocks such as imperialist conflicts or colonisation (Trotsky), entrepreneurial innovation (Schumpeter), and inflation (Dupriez) (Mandel, 1995). Biophysically, economic upturns correspond to the introduction of new fossil fuel technologies, while downturns follow stagnation in domestic material consumption (Malm, 2018; Schaffartzik & Duro, 2022). Mandel (1985, 1995) reconciled these views, arguing that waves are shaped by historical and institutional (or 'partially independent') factors mediating capital dynamics, technology, and extra-economic influences, ultimately reflected in profit rates. This underscores that material and energy patterns are inseparable from social relations such as the wage-labour nexus.

In summary, four explanations account for material stagnation: resource efficiency (EM), counterforces to profit maximisation (ToP), international appropriation (EUE), and technological diffusion (saturation). They emphasise production forces, including electrification, tertiarisation, global value chains, and market limits. The observed patterns of material stocks and flows likely reflect a combination of these factors, which are underpinned by social relations, particularly the evolution of wage labour. ToP highlights labour bargaining power while EUE underscores dependence on international division of labour for apparent "dematerialisation". Ultimately, waves of material accumulation reflect the level and use of profits—historically shaped by wage labour—to enable reinvestment in productive capacity or financial capital.

3. Analytical framework

Environmental history demonstrates that the wage-labour nexus and sociometabolic regimes are historically interdependent.[2] To examine this relationship, I propose a coevolutionary framework grounded in the concept of symbiosis between social relations and material use. I argue that this symbiosis manifests in corporate and state strategies for subordinating labour and nature to the imperative of synchronising demand with growing productive capacity. As a result, the symbiosis of the wage-labour nexus and sociometabolic regimes is historically specific, as it shapes the viability of economic systems, that is, its social reproduction over time. From this perspective, symbiotic modalities can be distinguished by environmental pressure and the capital orientation of the wage-labour nexus.

3.1. Socioecological coevolution and symbiosis

Sociometabolic change can be defined through interdependencies between evolving economic and ecological systems. This coevolutionary perspective rests on three assumptions. First, it rejects the neoclassical view of macroeconomic evolution as cumulative marginal adjustment, instead emphasising discontinuous shifts in system configurations (Fischer-Kowalski & Haberl, 2007). Second, although instability and uncertainty prevail, they are temporarily stabilised through systemic interdependencies, producing multiple historically contingent equilibria (Gowdy, 2013). Third, sociometabolic change is driven by endogenous processes rooted in internal system dynamics and interactions (Norgaard, 2017). Under these assumptions, sociometabolic change is not a gradual modernisation processes driven by exogenous shocks, but the outcome of socioecological symbiosis

A symbiotic relationship refers to long-term interactions between physically associated systems and may occur with or without coevolution (Penn & Liu, 2018). In the coevolutionary case, social and ecological subsystems not only interact but mutually shape one another's development (Kallis, 2007): social relations adapt to metabolic constraints and thereby influence the evolution of material use. In contrast, weak symbiosis involves sustained physical interactions without coevolution, meaning that social and ecological systems do not causally influence each other's evolutionary trajectories.

[2] Material flows have historically shaped labour arrangements, as seen in fertilisers enabling coercive labour during the Age of Abolition (1780s–1880) and oil extraction weakening labour's structural power (Melillo, 2012; Mitchell, 2009). Conversely, the organisation of work and bargaining power affect firms' investment decisions and household consumption, influencing patterns of material use (Barca, 2014; Malm, 2018; Pineault, 2023b).

In Social Ecology, symbiosis primarily describes interrelations in material use, though its ecological implications remain debated. Industrial symbiosis emphasises efficiency, where one firm's waste becomes another's input (Savini, 2023). By contrast, material symbiosis critiques circular economy and renewable transition models, showing that, historically, new energy carriers supplemented rather than replaced existing ones (Fressoz, 2023). Reconciling these views requires accounting for social and power relations structuring material linkages (Fressoz, 2016; Schaffartzik et al., 2021). I therefore adopt socioecological symbiosis to analyse interactions between societal material bases and relations of production. While this paper focuses on symbiosis between sociometabolic regimes and the wage-labour nexus, other social relations may also be relevant[3].

- Hypothesis 1: The wage-labour nexus and sociometabolic regimes are in symbiosis across time, indicating a dynamic, bidirectional long-term relationship.

Socioecological symbiosis differs from biological or engineering approaches by emphasising individual and collective agency. Sociometabolic regimes are characterised by firm and household routines that sustain material flows through habitual consumption and investment. While agents can redirect material flows in line with cultural systems, these patterns also reflect biophysical processes and infrastructure (Fischer-Kowalski, 2023). The wage-labour nexus also embodies collective agency, particularly when cross-class interactions form sociopolitical groups with shared expectations of public action concerning labour institutions. Consistent with Gramscian approaches in Regulation Theory, the stability of the wage-labour nexus depends on the organizational power of political coalitions forming a dominant social bloc (Ward, 2003). This bloc emerges not from an ex-ante design but through social conflict embedded in ideology and socioeconomic structures, leading to a unifying political project (Amable & Palombarini, 2008; Boyer, 2018).

[3] The concept of symbiosis here is similar to the idea of institutional complementarity, establishing that "certain institutional forms, when jointly present, reinforce each other and contribute to improving the functioning, coherence or stability of specific institutional configurations, varieties or models of capitalism" (Amable, 2016). The main difference is that sociometabolic regimes encompass not only institutions but also biophysical processes.

3.2. Symbiotic mechanisms as temporal fixes to overproduction tendencies

As illustrated in Figure 2, I identify mechanisms explaining the symbiotic relationship between the wage-labour nexus and sociometabolic regimes. These mechanisms operate through production and surplus absorption processes underpinning the temporal stability of capitalist economies. Drawing on social reproduction theories, a central constraint to continued accumulation is the tendency toward excess capacity or surplus—that is, the widening gap between output and socially necessary consumption and investment[4] (Aglietta, 2000; Baran & Sweezy, 1966). I argue that synchronising production and surplus absorption manifests in distinct modalities of socioecological symbiosis, expressed through investment determinants, consumption norms, and physical stock accumulation (Ekers & Prudham, 2017; Pineault, 2023a). On the one hand, production relies on continuous material flows and generates specific labour requirements for the creation of surplus. On the other hand, the wage-labour nexus structures the forms through which this surplus is absorbed and materially sustained.

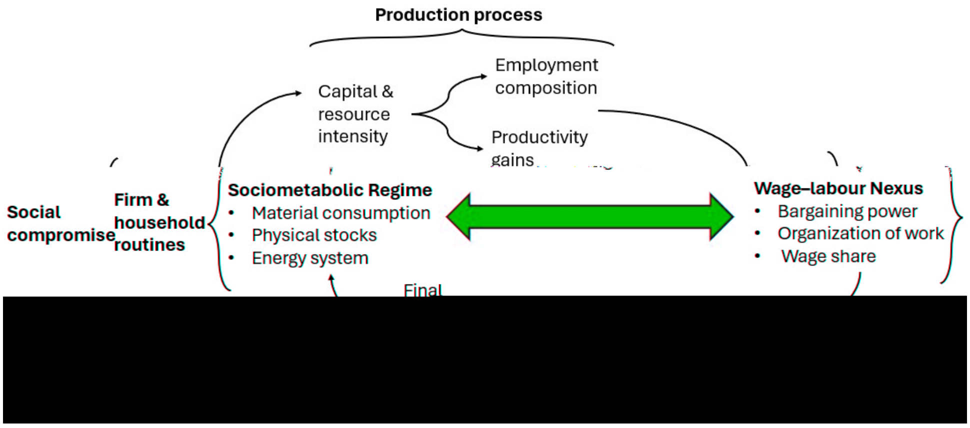

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Figure 2. Symbiosis Framework

The first mechanism, shown in the upper part of figure 2, links firms' interactions with the environment to the social compromise shaping labour conditions. Central to this relationship is the claim that the quality of energy carriers and energy-conversion technologies determine much of productivity growth[5] (Jackson, 2019; Rezai et al., 2013). In other words, this relation constitutes a "metabolic constraint at the point of productive transformation", expressed as a "biophysical limit to efficiency of the machine process" (Pineault, 2023b). The relaxation of this metabolic constraint enlarges the surplus available for distribution and, in turn, can create conditions under which capital is more inclined to accommodate labour demands. At the same time, the material and energy intensity of production reduces labour bargaining power through employment composition. This is seen as capital- and resource-intensive processes tend to substitute labour leading to higher unemployment (Mair et al., 2018). Replacing labour with capital also reflects new growth-driving sectors with stability requirements shaping labour market policy (Amable et al., 2019). Critically, the durability of the capital-labour compromise further depends on governmental strategies to manage unemployment arising from capital and resource intensity.

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[4] Overproduction derives from the tendency towards the socialisation of labour in capitalist economies reflected in the growing monopolization of the economy and the "radical reduction in market-allocated labour under late capitalism, as compared with directly allocated labour" (Mandel, 1986).

[5] Energy quality can be expressed in terms of exergy or in terms of energy return on energy invested (EROI). These measures are defined by energy systems and shape productivity gains.

In the reverse relation, illustrated by the absorption process, the wage-labour nexus shapes material flows through consumption and fixed capital formation. Overproduction constraints are temporarily overcome through two channels of labour management. First, when demand channelling new investments weakens, coalitions ensure surplus absorption by subordinating labour to habitual consumption (Pineault, 2023a). This relies on wage compromises and reorganising productive, reproductive, and unproductive labour time (toward marketing, advertising, privatised care, and product differentiation) to increase sales or financial rents (Berthonnet & Clos, 2024; Braverman, 1998). Wage and labour time compromises, in turn, determine the household division of labour, purchasing power, and associated material use. This is consistent with Regulationist accounts that emphasise a "social consumption norm," namely class, gender and race-based expectations, habits, and values formed through labour reproduction and socialisation (Aglietta, 2000; Huber, 2013; Koch, 2019).

The second absorption channel is given by fixed capital formation, a major component of physical stocks determining future material flows. This reflects firms' investment decisions driven by profit shares and capacity utilisation (Lavoie, 2017). These factors are themselves structured by the wage-labour nexus, insofar as labour's bargaining power, together with the intensity and duration of work, shapes both profit distribution and rates of capacity utilisation (Rochon & Rossi, 2023; Trezzini & Pignalosa, 2021). Additionally, government strategies for unemployment mitigation, especially through large infrastructure projects, further structure demand for fixed capital. In this way, states also manage labour by sustaining demand and employment through infrastructure spending, military expenditures, and welfare provision. Together, these two (consumption and investment) channels tied to the wage-labour nexus generate material counterparts in stocks and flows, constituting socioecological fixes to production–demand mismatches. Such fixes arise from social struggles across sociopolitical blocs and are therefore inherently political–economic processes (Ekers & Prudham, 2017).

3.3. Historical specificity and viability regimes

Overall, this framework aligns with demand-led growth models and the Kaldor–Verdoorn law, which describe feedbacks from rising demand to productivity (Kaldor, 1966; Lordon, 2002; Tridico & Pariboni, 2018). Although empirical evidence in some cases supports a wage-led Kaldor-Verdoorn relationship, the aim is not to assert a functionalist view in which improved working conditions and environmental pressure reinforces one another.[6] Rather, symbiotic modalities vary historically, meaning that improved working conditions may reinforce, reduce, or leave material-use patterns unchanged. This is consistent with cross-country diversity in accumulation regimes with varying dynamics between wage share, demand and investment.

- Hypothesis 2: The symbiosis between wage-labour nexus and sociometabolic regimes is historically specific, taking distinct forms that correspond to alternating periods of crisis and stability in capital accumulation, such as the transition from Fordism to Neoliberalism.

[6] There may be an implicit growth-dependency trilemma: it may be impossible to achieve more than two of the following simultaneously—a labour-oriented wage-labour nexus, high productivity driven by continued capital accumulation, and a sociometabolic regime with low environmental pressure (De Oliveira & Lima, 2022).

In this view, sociometabolic regimes appear not only as material expressions of accumulation regimes (Cahen-Fourot & Magalhães, 2023), but also as a condition to their viability through interaction with institutional forms. Following Aglietta & Espagne (2024, p. 17), I define viability regimes as “relations of dependence on nature” reproduced through institutions and thus constituting historical configurations that ensure social reproduction over time. Consequently, symbiotic modalities shape the form and duration of accumulation regimes as these are contingent on the stability of the wage-labour nexus and other institutional forms (Marie & Michel, 2025), as well as the continued availability of materials and the expansion of physical stocks for surplus absorption.[7]

3.4. Four modalities of socioecological symbiosis

The coevolution of the wage-labour nexus and sociometabolic regimes can be grouped into four coexisting symbiotic types. The first is a resource-dependent compromise (quadrant 2, Figure 3), where the viability of the wage-labour nexus relies on high environmental pressures. Fordism exemplifies this, combining strong unions, solidaristic bargaining, and productivity-linked wages (Aglietta, 2000; Boyer & Saillard, 2002; Lipietz, 1997) with rapid expansion of resource-intensive production.

Figure 3. Classification of symbiotic relations

[7] Pineault (2023b) identifies two additional metabolic constraints that are not considered here but are still reflected in sociometabolic regimes: source depletion and sink saturation.

The Fordist wage-labour nexus became unstable as demand saturated, corporations offshored production, and workers were deskilled, thereby undermining productivity gains (Brenner & Glick, 1991; Petit, 1999). Fragmented labour relations followed, marking a Neoliberal phase of extractive exploitation (represented in quadrant 1) characterised by deregulation, wage restraint, outsourcing, and precarious contracts (Hassel & Palier, 2023). Financialization further weakened the Fordist wage-labour nexus by subordinating workers and managers to indebtedness and shareholder imperatives (Slater & Spence, 2014; Tauss, 2012). Although stock accumulation has stagnated and resource efficiency has increased, high material consumption persists. Other quadrants have historically coexisted. Quadrant 3 reflects green precarity, where job insecurity accompanies lower environmental pressure, often linked to green sacrifice zones and cost shifting (Martínez-Alier, 2012). Quadrant 4 represents a socioecological compromise in which labour protections and low environmental pressure jointly stabilise sociometabolic viability.

4. Research design

The goal of the analysis is to examine the symbiotic dynamics between the wage–labour nexus and sociometabolism indicators through cointegration and time-varying Granger causality methods. These methods are adopted because they can be coherently situated within a coevolutionary framework, as demonstrated in the evolutionary econometrics' literature (Castellacci & Natera, 2013; J. Foster, 1991).

4.1. Empirical strategy

In line with the analytical framework described in section 3, symbiotic relations are defined by three characteristics: (i) a persistent long-run structural relationship despite (ii) periods of short-term disruption and stability, and (iii) bidirectional dynamics. The first two characteristics are captured through cointegration methods, which identify whether a linear combination of variables exhibits stable statistical properties over time, indicating a persistent, long-run linkage (Engle & Granger, 1987). In this case, an error correction model can be specified to test how short-run deviations are corrected toward the long-run equilibrium relationship.

The third characteristic is captured through Granger causality methods, which assess whether one time series contains predictive information about another beyond what is already contained in its own past (Granger, 1969). To account for temporal discontinuities, I apply time-varying Granger causality methods that identify shifts over time (Shi et al., 2016). However, it is important to note that Granger causality does not imply structural causation; it measures statistical precedence rather than direct cause-and-effect relationships.

To explore mechanisms, I complement the inferential analysis with a periodisation study that identifies the modalities of symbiosis through continuity and discontinuity across time (Boyer & Saillard, 2002; Huber, 2013). To do this I first operationalise the quadrants in figure 3 through the relation between DMC and the wage share, then account for historical heterogeneity by examining the interplay between institutional configurations and national trajectories of material accumulation. Overall, this approach highlights how systemic contradictions in the wage-labour nexus and their institutional fixes correspond to oscillations between expansion and stability in material consumption.

4.2. Data and measurement

The analysis draws on time-series data from the United States and France, covering labour and sociometabolic indicators from different open databases, as described in Supplementary Table 1. These countries were selected based on data availability and because they illustrate the post-war Fordist wage-led growth model and its subsequent transition toward financialized demand-led regimes (Hassel & Palier, 2020). Both economies share broadly comparable levels of industrialisation and post-war growth trajectories, which helps to hold macroeconomic conditions relatively constant.

Figure 4. Evolution of Domestic Material Consumption. This graph shows how the saturation of domestic material consumption (DMC) is largely driven by the decrease since 1973 of nonmetalic minerals (NON) while other series of biomass (BIO), fossil fuels (FOS) and metals (MET) remain constant or decrease slightly over time. Source: Own elaboration with data from (Cahen-Fourot & Magalhães, 2023; Streeck et al., 2021; UNEP, 2025).

Sociometabolic regimes are operationalised using two variables: per capita domestic material consumption (DMC) and gross additions to stocks (GAS). DMC is calculated as total resource extraction plus the physical trade balance and can be disaggregated into material categories (excluding water and air), including biomass, fossil energy carriers, metals, ores, and non-metallic minerals[8]. The portion of DMC incorporated into an economy's in-use physical stocks constitutes GAS, comprising infrastructure, buildings, machinery, and household goods. GAS differs from net additions to stocks as it captures physical expansion before any end-of-life material outflows are accounted for.

[8] DMC captures domestic material consumption but excludes indirect flows, that is, materials extracted abroad along the production chain to satisfy final demand. Consequently, DMC attributes environmental pressures to producers rather than consumers. A footprint-adjusted approach, incorporating raw material equivalents in the physical trade balance, can reverse this, accounting for upstream extraction and global dynamics; however, such data are available only from 1970 onwards.

Figure 5. Evolution of Additions to Material Stocks. This graph shows how the saturation of gross additions to stocks is largely driven by the decline in additions of infrastructure and buildings to stocks. Source: Own elaboration with data from (Wiedenhofer et al., 2024).

To identify which components of DMC and GAS drive the results, I additionally include their disaggregated indicators. Figures 4 and 5 show that material patterns are largely shaped by non-metallic minerals and fossil fuels in the case of DMC and by buildings and infrastructure in the case of GAS. These disaggregated indicators were included as they represent the most relevant dimensions of DMC and GAS.

Table 1: Summary Statistics (1950–2017)

Variables	Mean	SD	Min	Median	Max
Social Metabolism					
Domestic Material Consumption (Tons/capita)	17.9	5.1	8.0	16.6	28.0
Gross Additions to Stocks (Tons/capita)	8.0	2.6	1.6	7.7	12.9
Non-metalic Minerals Consumption (Tons/capita)	6.7	1.9	1.6	7.2	10.9
Fossil Consumption (Tons/capita)	5.0	2.6	1.6	5.8	8.8
GAS Infrastructure (Tons/capita)	5.8	2.1	0.7	5.7	9.8
GAS Buildings (Tons/capita)	1.6	0.4	0.7	1.7	2.5
Wage-labour Nexus					
Union Density (% workforce)	15.7	6.5	7.8	14.7	30.9
Manufacturing Share (% employment)	19.4	5.1	8.7	20.2	25.8
Wage Share (% of GDP)	62.3	3.7	55.1	63.1	68.7
Productivity Growth (%; growth output/worker)	2.7	2.1	-3.0	2.4	9.6
Female Share (% workforce)	49.7	6.7	38.0	49.2	60.0

The wage-labour nexus is operationalised along two dimensions: the organisation of work and labour institutions. The first dimension captures how work is organised within firms, including the within-firm division of labour, as well as the macro allocation of productive, unproductive, and reproductive work. I measure this using indicators of labour productivity growth and the shares of manufacturing and female employment in total employment. The second dimension of labour institutions, reflects the distribution of income and power between capital and labour and is captured through indicators of union density and the adjusted wage share of total income.

Figure 6. Wage-labour Nexus Indicators: This graph shows how all indicators—share of manufacturing employment (memp), union rate (union), share of female employment (fememp), labour productivity growth (prodgrowth) and the wage share (wshare)—decline or saturate around the 1970s. Source: Own elaboration with data from (Andrea, 2021), AMECO, OWD, Pen World Tables.

5. Empirical Results

5.1. Cointegration Analysis

Unit root tests (ADF, PP, Zivot–Andrews; see Supplementary Tables 2–5) show that most variables are stationary in first differences (except productivity), with material variables exhibiting structural breaks. Consequently, I test for cointegration by applying the autoregressive distributed lag (ARDL) model as it can accommodate both I(0) and I(1) variables (Pesaran et al., 2001). Establishing cointegration requires two steps: first, assessing via the bounds test whether a long-term stable relationship exists between labour and social metabolism indicators, and second, testing the stability of this relation via an error correction model (Pesaran et al., 2001). The ARDL bounds test model is specified as follows:

$$\Delta Y_t = \alpha + \sum_{i=1}^{p} \beta_i \Delta Y_{t-i} + \sum_{i=0}^{q} \gamma_i \Delta X_{t-i} + \theta_1 Y_{t-1} + \theta_2 X_{t-1} + \delta D_t + \varepsilon_t \quad (1)$$

Where Y_t is the social metabolism indicator of a country (DMC or GAS) representing the dependent variable.[9] Y_t is expressed as a function of its lagged values and the lagged values of the independent variables comprised in the vector X_t, containing labour indicators. I additionally incorporate a year-break dummy (D) to account for structural breaks identified in the Zivot–Andrews test (Supplementary Table 3 and 5) (Gregory & Hansen, 1996). p, q are lag orders for Y_t and X_t, respectively, determined by Akaike information criterion (AIC). Variables β_i, γ_i are the short-run coefficients and θ_1, θ_2 are the long-run coefficients. Six models for France and the United States derived from Equation 1 are estimated separately for the distributive and organizational dimensions, and all indicators of the wage-labour nexus, both with and without a year-break dummy.

The bounds test is carried out for all six models with a joint F-test of the following null hypothesis: $H_0 = \theta_1 = \theta_2 = 0$. The results in Table 2 show initial evidence of a long-run relationship between material and labour variables. In both the US and France, the F-tests are significant, suggesting that all dimensions of the wage-labour nexus have a long-run equilibrium relationship with DMC, even when accounting for structural breaks. The only exception is in model 2 for the US, indicating that the distributive dimension alone might have a weak long-term relation. Moreover, the F-tests are generally significant for the other material use dimensions. Supplementary Tables 12 and 13 reveal a stronger association with fossil fuel consumption in the U.S. and infrastructure in France.

[9] The choice of social metabolism as the dependent variable is motivated by its more parsimonious measurement structure, involving fewer indicator dimensions than the wage-labour nexus. Within the ARDL framework, the designation of variables as dependent or explanatory does not imply a causal ordering; rather, it reflects a conditional modelling strategy aimed at testing for the existence of a long-run equilibrium relationship among the variables.

Table 2: ARDL bounds tests for the US and France DMC

Equation	USA	FRA
(1) DMC = *f*(UNION, WSHARE)	4.54*	12.36***
(2) DMC = *f*(UNION, WSHARE, BREAK)	3.61	9.06***
(3) DMC = *f*(MEMP, FEMEMP, PROD)	5.61***	6.06***
(4) DMC = *f*(MEMP, FEMEMP, PROD, BREAK)	9.63***	4.79**
(5) DMC = *f*(UNION, WSHARE, FEMEMP, MEMP, PROD)	4.08**	5.39***
(6) DMC = *f*(UNION, WSHARE, FEMEMP, MEMP, PROD, BREAK)	4.49***	11.00***

Note: *, **, *** represent statistical significance of the bounds (Wald) test F-statistics at the 10%, 5%, and 1% level, respectively. The lag length is selected by AIC with a maximum length of five. Insignificant lags were removed.

In light of the statistically significant bounds test results, the ARDL model is reformulated into an error-correction specification (equation 4) to jointly estimate the long-run coefficients and model the short-run adjustment dynamics. The estimation was performed in two stages. First, the long-run coefficients are estimated using a static regression in levels (equation 2). Second, short-run dynamics are analysed through an error correction specification, in which the error correction term (ECT) is constructed from the residuals, ε_t, of the estimated long-run levels equation (Equation 2):

$$y_t = \alpha_0 + \alpha_1 x_t + \varepsilon_t \qquad (2)$$

$$\frac{\sum_{j=0}^{q} \theta_j}{1 - \sum_{i=1}^{p} \phi_i} \qquad (3)$$

$$ECT_t = y_t - \hat{\alpha}_0 - \hat{\alpha}_1 x_t \qquad (4)$$

$$\Delta y_t = \mu + \sum_{i=1}^{p} \phi_i \Delta y_{t-i} + \sum_{j=0}^{q} \theta_j \Delta x_{t-j} + \lambda ECT_{t-1} + \varepsilon_t \qquad (5)$$

Where λ and α_1 are the main coefficients of interest. A negative and statistically significant error correction term (ECT) indicates the speed at which deviations from the long-run equilibrium are corrected and, therefore, confirms the existence of cointegration among the variables. The long-run coefficients, α_F, capture the long-run impact of X_{FP} on Y_t. Based on equation 4, six models are again estimated separately for France and the United States, covering both dimensions separately and all indicators of the wage-labour nexus, specified both with and without a year-break variable.

The results of the long-run coefficients and the ECT are presented in Tables 3 and 4 for the US and France, respectively. Given that the ECT is negative and statistically significant across all model specifications, the results provide consistent evidence of a stable cointegrated relationship between DMC and the wage-labour nexus in both the United States and France. Moreover, all long-run coefficients in Model 6 are statistically insignificant when all dimensions of the wage-labour nexus and structural breaks are jointly considered for both the US and France. This indicates that despite evidence of cointegration, no statistically significant long-run relationships are observed between individual wage-labour nexus variables and DMC. This is because the models may be unable to disentangle or accurately identify individual effects since they do not rule out all potential endogeneity biases.

Still, the models remain adequate for identifying cointegration, as the standard diagnostic tests are insignificant. Specifically, I examine serial correlation using the Breusch–Godfrey LM test, heteroscedasticity via the BreuschPagan procedure, functional form misspecification with the RESET test, residual normality with the Jarque–Bera test and parameter stability using the CUSUM test. The results indicate no evidence of serial correlation except in Model 6 for France which shows weak significance for the Breusch-Godfrey LM test. However, the other models show no serial correlation, and all other diagnostic tests are insignificant, suggesting that the models are stable over time and well specified.

Table 3: ARDL Long-run Coefficient Estimates for US DMC

Dependent Variable: DMC						
Independent Variable	(1)	(2)	(3)	(4)	(5)	(6)
UNION	-0.07	-0.17	-	-	0.77	-1.23
WSHARE	1.42^{ÛÛÛ}	1.48^{ÛÛÛ}	-	-	1.10^{ÛÛ}	5.58
PROD	-	-	4.24^{ÛÛÛ}	9.22	1.10	4.29
MEMP	-	-	1.14^{ÛÛÛ}	2.18	-0.51	0.07
FEMEMP	-	-	0.62^{ÛÛÛ}	2.08	0.49	-1.45
1973BREAK	-	-1.80	-	-19.32	-	-16.54
ECT	-0.48^{ÛÛÛ}	-0.40^{ÛÛÛ}	-0.43^{ÛÛÛ}	-0.12^{ÛÛÛ}	-0.61^{ÛÛÛ}	-0.21^{ÛÛÛ}
Diagnostics Tests						
Breusch-Godfrey	1.60	2.3	2.98	2.08	3.73	3.31
Breusch-Pagan	16.23	18.32	16.50	19.67	25.62	28.11
RESET	2.37	1.29	1.17	1.36	2.34	0.03
Jarque-Bera	2.79	1.85	1.27	0.28	0.72	2.97
Stability Analysis						
CUMSUM	stable	stable	stable	stable	stable	stable
CUMSUMQ	stable	stable	stable	stable	stable	stable

Note: Û, ÛÛ, ÛÛÛ represent statistical significance at the 10%, 5%, and 1% level, respectively. Lags length is selected by AIC with max length 5. Insignificant lags were removed.

Table 4: ARDL Long-run Coefficient Estimates for France DMC

Dependent Variable: DMC						
Independent Variable	(1)	(2)	(3)	(4)	(5)	(6)
UNION	1.04***	1.04***	-	-	1.44	0.82
WSHARE	-1.21***	-1.21***	-	-	-2.61	-0.02
PROD	-	-	0.31**	0.27**	1.15	1.83
MEMP	-	-	0.47***	0.45***	0.51	-6.09
FEMEMP	-	-	0.47***	0.45**	0.24	-5.80
1980BREAK	-	0.02	-	-0.20	-	-7.01
ECT	-0.26***	-0.26***	-1.02***	-1.03***	-0.27***	-0.19***
Diagnostics Tests						
Breusch-Godfrey	1.11	1.09	1.70	1.11	4.57	4.98*
Breusch-Pagan	4.99	5.03	17.32	18.60	24.93	26.91
RESET	0.00	0.00	0.08	0.29	0.62	2.25
Jarque-Bera	1.07	1.08	0.00	0.00	0.71	1.57
Stability Analysis						
CUMSUM	stable	stable	stable	stable	stable	stable
CUMSUMQ	stable	stable	stable	stable	stable	stable

Note: *, **, *** represent statistical significance at the 10%, 5%, and 1% level, respectively. Lags length is selected by AIC with max length 5. Insignificant lags were removed.

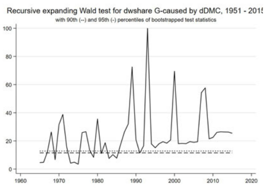
5.2. Time-varying Granger Causality

In this second part of the analysis, I estimate Granger causality in both directions using the time-varying approach of Shi et al. (2020), which can accommodate structural changes and evolving causal relationships. This method is based on the following lag-augmented vector autoregression (LA-VAR) specification of Toda and Yamamoto (1995) and Dolado and Lütkepohl (1996):

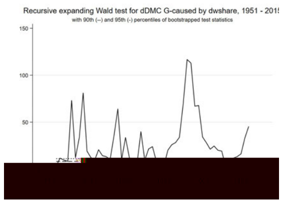
$$y_t = \alpha_1 + \beta_1 t + \sum_{i=1}^{k} \gamma_{11}^{(i)} y_{t-i} + \sum_{i=1}^{k} \gamma_{12}^{(i)} x_{t-i} + \sum_{j=k+1}^{k+d} \gamma_{11}^{(j)} y_{t-j} + \sum_{j=k+1}^{k+d} \gamma_{12}^{(j)} x_{t-j} + \varepsilon_{1t} \quad (6)$$

$$x_t = \alpha_1 + \beta_2 t + \sum_{i=1}^{k} \gamma_{21}^{(i)} y_{t-i} + \sum_{i=1}^{k} \gamma_{22}^{(i)} x_{t-i} + \sum_{j=k+1}^{k+d} \gamma_{21}^{(j)} y_{t-j} + \sum_{j=k+1}^{k+d} \gamma_{22}^{(j)} x_{t-j} + \varepsilon_{2t} \quad (7)$$

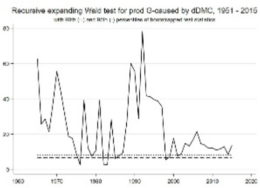
Where U and T are the social metabolism and labour time series, $Ù_1$ and $Ù_2$ are intercepts, while $Û_1$ and $Û_2$ capture deterministic linear trends[10]. The lag order G represents true lag length of the underlying VAR(G) model. To construct the lag-augmented VAR(G + @) and thus account for trending variables, the specification includes additional @ lags, where @ is the maximum order of integration of variables. The main coefficients of interest are $Ú(E)$ and $Ú(E)$ for $E = 1, \ldots, G$ given that the other coefficients associated with the additional d are not included in the testing restrictions (Baum et al., 2022). Using Wald test, the joint significance of these coefficients determines the Granger causality of each equation.



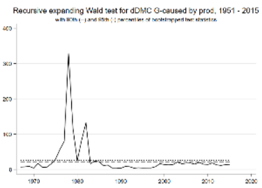
(a) FRA: DMC \ WSHARE



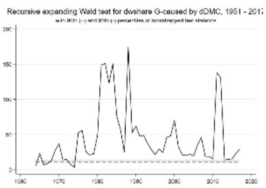
(b) FRA: WSHARE \ DMC



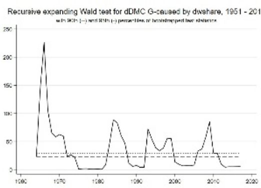
(c) FRA: DMC \ PROD



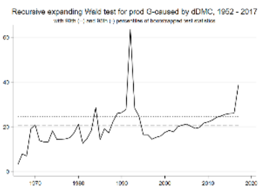
(d) FRA: PROD \ DMC



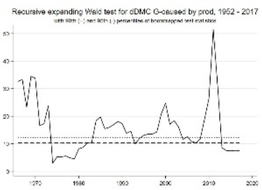
(e) US:DMC \ WSHARE



(f) US: WSHARE \ DMC



(g) US: DMC \ PROD



(h) US: PROD \ DMC

Figure 7. Time-Varying Granger Causality for France and the United States. This graph shows how the time-varying Granger causality between DMC and wage-share and between DMC and labour productivity is bi-directional across time. The Y-axis represents the Wald test statistic and X-axis the time period from 1950 to 2017. Dot lines represent 90% and 95% critical values. Results were generated using the TVGC STATA module (Otero et al., 2024). Parameters: linear trend, 2 lags in the VAR model (AIC selected), differentiated variables (d=1), window = 20% of sample, heteroscedastic-robust variance-covariance matrix, and 6 bootstrap critical values.

[10] I only focus on the wage share and productivity given they are the only variables with data that goes back to 1950 and is large enough for the time varying analysis. In the case of the wage share, I use a different source based on FRED (share of labour compensation) which is adjusted for self-employment as the AMECO source.

To track the temporal evolution of Granger-causal relationships, I employ Shi et al.'s (2020) supremum Wald statistic sequences, which repeatedly estimate the model using different sample subsets. Three algorithms generate these sequences, differing in their window construction (Otero et al., 2024). The forward-expanding window approach incrementally enlarges the sample over time, while the rolling window approach employs a fixed-length window that moves sequentially through the sample. The recursive-expanding window integrates these two methods by estimating regressions across all expanding subsamples that terminate at each observation and conducting inference using the maximum Wald statistic at each point in time. Simulations suggest that the rolling and recursive-expanding procedures perform best (Shi et al., 2020). As a result, I mainly report the recursive-expanding window procedure and include the other procedures as robustness checks in Supplementary Figure 1 and 2.

Figure 7 presents the time-varying Granger causality results for France and the United States. It plots the time-varying Wald statistics alongside their corresponding critical values. When the Wald statistic exceeds the threshold, the null hypothesis of no Granger causality is rejected, indicating a significant Granger causal effect during that period. In the case of France, causality running from the wage share to DMC is most pronounced during the 1970s and again around the year 2000, whereas the reverse causal relationship—from DMC to the wage share—emerges as statistically significant only from the 1980s onwards. A broadly similar pattern is observed for the United States. Causality from the wage share to DMC is strongest at the end of the 1960s and becomes more volatile in subsequent decades, while causality from DMC to the wage share appears only from the 1980s onwards.

With respect to the relationship between DMC and productivity, the results also point to a discontinuous and time-varying bidirectional causal structure. For France, Granger causality running from productivity to DMC is relatively persistent over time and is particularly pronounced from the late 1960s to the mid-1970s, as well as around 1990. In contrast, the reverse causal relationship—from DMC to productivity—exhibits less evidence of significance, except for a brief episode around 1990. The results for the United States display an opposing pattern. Causality from productivity to DMC is only evident around 1990, whereas causality from DMC to productivity appears to be more consistent over time.

5.3. Identifying Modalities of Symbiosis

The results provide evidence of a symbiotic relationship between the wage-labour nexus and sociometabolic regime. In this subsection, I further qualify this symbiosis by examining how its specific modality evolves over time through an analysis of the relationship between DMC and wage share. Figure 8 operationalises the quadrants introduced in Figure 3, with the vertical line set at the median wage share and the horizontal line fixed at 7.21t per capita, representing both the planetary boundary and the per capita material use requirements to satisfy twice the level of decent living standards for global population in 2050 (Hickel & Sullivan, 2024; O'Neill et al., 2018).

The figures indicate a modest decline in DMC over time, most notably in the United States. Nevertheless, the relationship between material use and the wage share remains predominantly above the 7.21-tonne threshold, while shifting from a high to a low wage-share configuration over time. A comparable pattern emerges when considering the material footprint (purple line), although at a substantially higher level of material use. Consistent with the framework outlined in Figure 3, this pattern suggests a transition from resource-dependent compromises toward extractive exploitation, with both the United States and France undergoing this shift from the 1980s onwards. In other words, the wage-labour nexus became increasingly capital-oriented while remaining environmentally extractive.

Figure 8. Relation Between Material Use and Wage Share. This graph shows how a decline in the wage-share over time was accompanied by a stagnant or declining per capita material use. Moreover, the levels of material use are above the dotted line across time, representing the planetary boundary threshold and the per capita material use requirements to satisfy twice the level of decent living standards for global population in 2050. This relationship can be situated in the four quadrants represented in figure 3. Source: Own elaboration with data from (Cahen-Fourot & Magalhães, 2023; Streeck et al., 2020, 2021; UNEP, 2025).

6. Periodizing socioecological symbiosis

The evidence supports the two hypotheses from section 3 in two key patterns. First, both dimensions of the wage-labour nexus are cointegrated with DMC, with particularly strong long-run associations for fossil fuel consumption in the United States and infrastructure stocks in France. These patterns underscore the central role of cheap energy and infrastructure expansion in supporting dominant industrial sectors, notably automobile manufacturing. The labour requirements of these sectors underpin wage-labour compromises that enable surplus absorption through sustained investment and consumption.

Second, there is evidence for bidirectional Granger causality between DMC and both the wage share and labour productivity. During the Fordist period, causality from the wage share to DMC is more stable, reflecting the role of wage growth in supporting mass consumption, whereas in the Neoliberal period the reverse relationship becomes more pronounced, indicating a saturated sociometabolic regime and the degradation of working conditions. This saturation is further reflected in the peak of bidirectional causality between DMC and labour productivity around 1990, coinciding with declining energy quality and a reconfiguration of the wage-labour nexus along Neoliberal lines.

To further situate these empirical patterns historically, I analyse the symbiotic mechanisms driving the synchronisation of demand with an expanding productive capacity. This implies characterising the Fordist and Neoliberal periods in terms of the evolving interdependence between the wage-labour nexus and sociometabolic regimes.

6.1. The Fordist period of resource dependent compromises

During the Fordist period, high-income economies operated under an extensive sociometabolic regime characterised by growing environmental pressures. This was partly driven by industrial mechanisation, standardisation, and a drive for economies of scale which made labour highly productive (Hall, 2024). These productivity gains generated additional surplus for further accumulation of physical stocks as long as consumer demand remained high. Consequently, material use was intertwined with corporate and state management of labour to synchronise mass production with mass consumption. Three key sociometabolic specifications characterised this period: a resource-dependent industrial-managerial dominant social bloc, institutionalised wage-productivity coupling, and Keynesian demand management policies.

The extensive sociometabolic regime during Fordism reinforced a labour-protective wage-labour nexus. The extensive characterisation meant that production scaled up through expanding total energy and material throughput, driven by large investments in physical stocks. This reflected the strength of the manufacturing sector and high productivity gains, forming the basis of the dominant social bloc, embodied in a compromise between industrial capital and an expanding salaried workforce. As resource-intensive industries rely on large fixed capital and are embedded in value chains, they are particularly vulnerable to work disruptions. Consequently, given that heavy industry functioned as the growth engine during Fordism, it also constituted the foundation of labour's structural power within this period.

In France, the Fordist compromise was expressed in the Monnet Plan, the first postwar modernisation plan of coordinated investment implemented under the Commissariat général du Plan. Although formally in force from 1947 to 1952, the Monnet Plan established a system of indicative planning. It was politically supported by a dominant social bloc uniting state technocrats, organised labour, and segments of industrial capital, which structured labour management through successive plans until the late 1970s. Its institutional counterpart in the United States was the extension of the New Deal order which protected industrial capital from recession while linking organised labour to mass consumption under the Democratic Party dominance. In both cases, Fordism was resource-dependent as industrial capital conceded autonomy only insofar as the compromise secured stability, mass consumption of materials, and productivity gains.

The Fordist wage-labour nexus both depended on and intensified an extensive social metabolism by sustaining mass consumption alongside expanding production. A core principle was the widening division between conceptual and manual labour (Braverman, 1998). This worker–manager split enhanced efficiency while enabling new sales-oriented occupations, including advertising, product differentiation, and planned obsolescence (Baran & Sweezy, 1966). To secure these sales, industrial capital conceded to the institutionalisation of wage-productivity coupling. Rising wages and expanding sales resulted to a consumption norm centred on household and car ownership, reinforcing the extensive sociometabolic regime (Huber, 2013). This pattern was anchored in the traditional nuclear family—with the male breadwinner and female homemaker—transforming households into key sites of mass consumption (Berthonnet & Clos, 2024; Fraser, 2022).

In the United States, the Fordist consumption norm crystallised with the United Auto Workers–General Motors “Treaty of Detroit” (1950), which became a model across industries. This compromise granted workers a share in rising productivity and improved their working conditions. At the same time, it also subordinated workers to managerial control, furthering the Fordist division of labour toward the sales effort. In France, a comparable institutionalisation emerged with the guaranteed minimum industrial wage (SMIG), later replaced by minimum wage growth (SMIC) in 1970, which linked wages to productivity. Increased purchasing power was further supported by a wage-labour nexus structured around family wages (Périer, 2012). This organisation of reproductive work was seen in the single-wage allowance in France and the Social Security Act in the United States, which allocated social benefits along gendered and racial lines (mainly directed towards white, male-breadwinner families).

The Fordist industrial-managerial bloc also reinforced an extensive sociometabolic regime through the support of active state labour management. Dominant Keynesian demand-management ideologies pursued surplus absorption and full employment through public expenditure (seen in military spending and large infrastructure projects) enabling economies to operate closer to full capacity while intensifying environmental pressures. Under these conditions, private investment in physical stocks was encouraged, and organised labour was less likely to oppose resource-intensive technological change.

A key example of state management of surplus labour can be found in highway construction (Baran & Sweezy, 1966). In the United States, the National Interstate and Defense Highways Act of 1956 launched one of the largest public works programs, planning a 41,000-mile network financed by the Highway Trust Fund. In France, highway spending similarly formed a central component of modernisation planning. In both cases, major unions supported these initiatives under the Fordist wage-labour nexus of full employment and state-led investment. As a result, highway construction exceeded social needs and generated substantial environmental pressure. The Fordist symbiosis proved unviable as it created internal contradictions that ultimately produced a crisis and regime shift. On the production side, these contradictions manifested as declining productivity gains and the fragmentation of the industrial–managerial social bloc (profit squeeze). The decline in energy quality and cheap additions to physical stocks contributed to slowing productivity gains (Jackson, 2019). This trend not only reflected the rise of national liberation movements in the Global South but also the weakening of the dominant social bloc domestically. Internationalisation of production and the associated de-industrialisation increasingly resolved stagnating profits by weakening industrial labour's structural power.

On the surplus absorption side, contradictions arose with the erosion of the family wage and a decrease in capacity utilisation. As markets saturated and productivity gains slowed, wage stagnation led to overproduction. Moreover, social movements increasingly undermined the nuclear family ideal as the foundation of disciplined and productive labour (Federici, 2021). Rising female employment coincided with welfare state retrenchment, producing a care crisis (Berthonnet & Clos, 2024). This occurred as families could not maintain subsistence with only a single member working, reflecting the inability of demand to meet productive capacity. Finally, the oil shocks of the 1970s and stagflation acted as immediate triggers of a crisis rooted in the contradictions of the Fordist wage-labour nexus and extensive sociometabolic regime.

6.2. Neoliberal period of extractive exploitation

Neoliberal socioecological symbiosis emerged as a reaction to the internal contradictions of the Fordist wage-labour nexus and sociometabolic regimes. Since the late 1970s, sociometabolic regimes have become saturated and more intensive, meaning resources were used more efficiently without rapid throughput growth. This shift partially reflects technological advances in energy systems, as well as the tertiarization and internationalisation of production. At the same time, these accumulation patterns were fundamentally interrelated to the adaptation of corporate and state management of the labour process to the Fordist crisis. On the production side, surplus generation increasingly took the form of rent and was relatively decoupled from material production (Riley & Brenner, 2025). On the absorption side, under conditions of saturated markets and rising idle capital, surplus was increasingly absorbed through expanding employment in finance, insurance, and real estate (Magdoff & Foster, 2014). Three socioecological specifications characterised this transition: an extractive rentier dominant social bloc, wage-productivity decoupling under shareholder priorities, and asset-price Keynesianism.

The Neoliberal dominant social bloc was fundamentally extractive: it no longer fully relied on expanding domestic material throughput, yet it sustained high levels of material consumption through rent extraction and intensified labour exploitation. It emerged as a compromise among the weakened Fordist managerial bloc, financial capital and transnational corporations which overcame profit constraints linked to resource dependency and labour's structural power (Duménil & Lévy, 2016). Energy systems characterised by declining energy quality from coal and oil limited productivity-based profit growth. Consequently, sectors decoupling profits from productive investment became dominant, reflecting a weaker relationship between per capita energy use and labour productivity (Pellegrini, 2023). Stagnant additions to physical stocks reflected employment growth in labour-intensive sectors such as finance and insurance. Thus, the break with the extensive sociometabolic regime favoured a dominant social bloc detached from domestic resource dependence. This dominant social bloc excluded much of the workforce as expectations shifted toward financial rather than productive gains.

The Neliberal bloc took form in liberalising structural reforms to restore accumulation. In the US, the social compromise originated with the Volcker Coup of 1979, when the Federal Reserve sharply raised interest rates to prioritise rents over employment, restructuring class power in favour of finance (Duménil & Lévy, 2016). In France, insufficient support for European integration made Neoliberal restructuring incremental, culminating in a dominant social bloc with Sarkozy's 2007 flexicurity reforms (Amable et al., 2012). These political projects united support across the political spectrum amid ideological shifts following the collapse of Eastern Bloc communism and the failure of Keynesianism to resolve stagflation. Ultimately, this gave rise to an extractive social bloc that resolved the Fordist crisis by privileging shareholder value and abandoning reliance on domestic mass production.

The Neoliberal compromise and its configuration of the wage-labour nexus both rested on and reinforced intensive but stagnating sociometabolic regimes. This was evident in surplus-absorption strategies centred on finance, insurance, real estate, and care, which pushed firms to restructure labour and secure profits primarily through financial channels (Durand & Gueuder, 2018). Labour became subordinate to managerial and shareholder priorities through stock buybacks, "downsize & distribute," "merge & monopolize," and subcontracting, all of which discouraged investment in physical capital (Reddy, 2025). These surplus extraction strategies remained effective insofar as labour was displaced and wages decoupled from productivity. This dynamic was especially visible in the Neoliberal care crisis, where labour shifted into low-wage, low-productivity sectors through the professionalisation of reproductive work largely performed by female and racialised workers (Berthonnet & Clos, 2024). As inequality rose, material consumption declined while debt-driven consumption norms intensified.

Liberalising reforms promoting flexibility and lower wages coincided with shifts in capital–labour relations. Labour lost structural power tied to heavy industry due to deindustrialisation, subcontracting, and tertiarisation. Beyond these structural shifts, however, a capital-oriented wage-labour nexus was actively institutionalised, fostering the rise of "unorganizable" and "materially light" sectors. In the U.S., this included the rise of professional union-avoidance firms and legal frameworks (Logan, 2006). In France, similar dynamics emerged through decentralised, firm-level bargaining which fragmented labour power (Howell, 2009).

State labour management further facilitated the commodification of knowledge and expanded employment in financial and precarious service sectors, reducing material consumption and investment in physical stocks. State surplus management took the form of asset-price keynesianism (Brenner, 2006), defined as indirect demand stimulation through private credit expansion and financial deregulation, ultimately relying on public deficits to stabilise accumulated corporate and banking debt. Correspondingly, infrastructure and welfare expenditures declined, discouraging consumption and fixed capital formation. The prioritisation of credit easing and intellectual property protection further redirected investment toward intangible assets, reinforcing intellectual and financial monopolisation (Riley & Brenner, 2025). This marked a capital-oriented restructuring of the wage-labour nexus.

The United States played a primary, driving role in the creation of international agreements such as the Trade-Related Aspects of Intellectual Property Rights, which reinforced the commodification of knowledge (Pagano, 2014). In addition, states privatised the care sector through subsidies in response to unemployment and the care crisis (Berthonnet & Clos, 2024; Ndomo, 2025). Together, these strategies reoriented the wage-labour nexus toward capital by expanding precarious service employment, separating workers from the intellectual content of their labour, and professionalising reproductive work through migrant labour exploitation.

Neoliberal symbiosis also faces internal contradictions leading to its current unviability. In production processes, the central contradiction lies in the failure to restore productivity gains despite relative decoupling from material use. This is reflected in rising energy expenditures since 1999 and persistently low profit rates (Pellegris, 2023). Moreover, as fixed capital depreciates and is replaced, productive capacity is expanded even when little net investment occurs, thereby perpetuating overproduction (Magdoff & Foster, 2014). At the same time, unlike Fordism, Neoliberalism exhibits weak surplus-absorption capacity. While surplus capital flowed to financial and monopolised sectors, this absorption mechanism did not stimulate further demand as it dampened fixed capital formation and created financial instability. The resulting wage-labour nexus concentrates surplus further, intensifying the contradiction between high productive capacity and a saturated sociometabolic regime.

7. Conclusion

As the need for a sociometabolic bifurcation toward decent living within planetary boundaries becomes increasingly urgent, two competing interpretations of how such a shift could unfold have emerged. The first associates the evolution of material use in high-income economies primarily with structural changes in production processes. From this perspective, a socioecological transition relies on either resource-efficient market innovation or unleashing productive forces from private property toward state-led green investments. The second interprets the acceleration and stagnation of material use as rooted in the co-evolution between the technical routines of material use and social compromises. It recognises the role of productive forces in bringing sociometabolic change but stresses that these technical processes are embedded in social relations.

Through a historical analysis of socioecological symbiosis, I provide evidence for this second interpretation. By extending ecological revisions of Regulation Theory, I argue that sociometabolic regimes are not only constraints on the wage-labour nexus but are also fundamentally shaped by it. Moreover, this symbiotic relationship is historically specific, crucially shaping the synchronisation of production and consumption, and thus the viability of accumulation regimes. Quantitatively, this is evident in cointegration and time-varying bi-directional causality between material and labour time series. Qualitatively, Fordism interrelated extensive routines of material use and rising energy quality with a managerial social bloc pushing family wage-productivity coupling and Keynesian demand management. The Neoliberal period emerged as an adaptation to the metabolic constraints and overproduction tendency that caused the Fordist crisis. Thus, Neoliberal socioecological symbiosis differs fundamentally from its predecessor, relying on a tertiarised and intensive sociometabolic regime which depended on and reinforced a dominant social bloc that reoriented the wage-labour nexus toward financial interests.

However, the analysis is limited to high-income countries and a predominantly national perspective, lacking full engagement with the diversity of socioecological symbioses across countries. While the article considers footprint measures of material consumption, these are not included into the empirical analysis due to data limitations. Therefore, further research should compare results based on footprint and domestic consumption measures to better capture how domestic and extra-national social compromises articulate, explicitly incorporating Global North–South dynamics into the framework. This could be done by highlighting the link between the international regime (imperialism and international division of labour) and the wage-labour nexus[11]. Moreover, the symbiosis framework would be more complete with an analysis of how different accumulation regimes—particularly those diversified in the Neoliberal era—are supported by specific interactions between the wage-labour nexus and sociometabolic regimes. The analysis also risks over-homogenising labour by implicitly treating workers as a unified category and would benefit from further incorporating the agricultural sector, informal forms of work and labour footprints as integral elements of the wage-labour nexus.

[11] Arguably, the Fordist international regime adds evidence to the category of resource dependent social compromises given the crucial role of gold and the associated labour exploitation in stabilizing the Breton Woods system (Green, 2026). The structural changes associated with Neoliberalism contributed to solving this metabolic constraint linked to gold.

Despite these limitations, this study provides evidence for an alternative explanation of sociometabolic change with significant implications. While Fordism is often celebrated as the glorious years of improved living standards, it depended on an extensive and inherently unviable sociometabolic regime. This implies that a socioecological bifurcation cannot simply entail a return to mass-production-dependent welfare models. The analysis further suggests that material saturation in high-income countries did not arise from deliberate technical fixes under Neoliberalism but from its internal contradictions, including low consumption and investment patterns. A key implication is that addressing Neoliberal contradictions and ecological viability requires reconfiguring the wage-labour nexus to decouple the satisfaction of basic needs from growth imperatives, thereby removing the pressure to align demand with the unlimited expansion of productive capacity. While the pathways to achieve this remain contested, emerging research increasingly highlights the reorganisation of work around socially necessary sectors, such as care and public services, which are typically characterised by lower productivity. This shift entails a break with the productivity–output treadmill through the emergence of new forms of labour power, which appear to arise not from productivist or domestic structural foundations but from organizational capacity rooted in community networks and solidarity-based cross-national alliances.

Declaration of Competing Interests
The author declares that he has no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability
Data and supplementary figures and tables are available in a separate repository based on Open Science Framework, available here:
https://osf.io/6utgn/overview?view_only=c0cc188a045c43fba4a64ee069961239

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The nature, pace and outcomes of process - es of capitalist transformation

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- The political economy of natural-resource extraction, with implications for political instability
- The objectives and effects of changing economic policies, from industrial policy to w ˜ > ˜ V ˆ > • À i } Õ • > Ì ˆ œ ˜

SOCIO-ECONOMIC RESEARCH CENTRE

ROSKILDE UNIVERSITY
UNIVERSISTETSVEJ 1, POSTBOX 260
4000 ROSKILDE, DENMARK