“Environmentalism without social struggle is just gardening”: the Ricardian dynamics of the metabolic rift

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Abstract

This paper puts forward an ecological interpretation of the earliest model of economic growth in the history of economic thought. Developed by David Ricardo two hundred years ago, it shows how, in a world of limited natural resources, the economy will inevitably evolve towards a steady state of no growth. This paper follows this model to argue that the fundamental problem of anthropogenic climate change is not economic growth per se, as de-growth will occur no matter what, but the distribution of income among workers, capitalists, and landlords. The latter, landlords, are the private owners of the limited natural resources, an often neglected income class in macroeconomic models that in Ricardo's model eventually seize all the economic surplus. Under the simple assumption of a linear decrease in the productivity of labor (i.e. decreasing returns to scale), the dynamic model of economic growth becomes logistic, driven by a single parameter that is shown to be the rate of economic surplus or exploitation. In this sense, the Ricardian model illustrates the critical relevance of class conflict in determining different scenarios of economic decline, either in the form of a smooth convergence towards ecological equilibrium for low values of the rate of surplus or wildly chaotic, ungovernable oscillations in population and economic output for high values of the same parameter. Finally, the model is empirically calibrated with actual values of the rate of surplus computed for many different countries, which anticipates that the decline of the economic system may turn very unstable for most countries if the exploitation of workers remains at such high level.

Keywords: degrowth, dynamical model, class conflict, chaos, ecological political economy, David Ricardo

1. Introduction

"Environmentalism without social struggle is just gardening" is a popular saying coined by Chico Mendes, internationally renowned environmental activist and leader of the Xapuri Rural Worker's Union, a trade union of rubber tappers in the Brazilian state of Acre in the western Amazon (Mendes & Gross, 1989). Born into poverty, Mendes started working at age 9 in debt peonage, learned to read and write by himself at age 20, and was murdered at age 44 by landlords due to his standoffs, or *empates*, with beef-exporting ranchers to prevent the deforestation of the Amazon, the source of the rubber tappers' livelihood. His assassination was the 90th murder of an environmentalist activist in Brazil in 1988.

Mendes' saying and life, among many others fighting for their lands, encapsulates well the conundrum currently faced by the whole of humanity regarding the climate crisis. While "climate change is a global emergency" for nearly two-thirds (64%) of the 1.2 million respondents to the largest public opinion survey on climate change ever conducted [UNDP 2021], the current trajectory of carbon emissions still sets the course for an increase of 3.2C of global warming, in which ecological and economic catastrophe may almost certainly ensue, well beyond the looming tipping points of 1.5C and 2C. Despite UN IPCC warnings that ambitious large-scale structural change of our economies is urgently required in the coming years, carbon-intensive economic activities maintain business as usual and the effectiveness of climate policies such as carbon pricing is actually very limited, leading to pervasive 'climate anxiety' among the population, political advocacy and protests to the extent that some wonder whether civil disobedience is justified (Capstick et al., 2022).

Why is so little done regarding the climate crisis, considering its extreme severity, acknowledged by a majority of humanity as it calls for widespread climate action? Exploring diverse climate-related issues in governance and modeling, the fossil fuel industry and energy systems, international political economy, militarism, financialization, and inequality, a comprehensive critical review emphasized the cross-cutting, central role of power in impeding determinate climate action (Stoddard et al., 2021) [Supran and Oreskes 2021, Frasca]: climate policy is a socially contested process that collectively arises from power struggles among many interest groups with different, often conflicting, material motivations. Climate policies may ideally be very effective on paper when theoretically proposed, but watered down or even straight rejected, when materially implemented in practice, by an unequal balance of political power tilted towards powerful adverse interest groups. Inequality matters in shaping climate policy: discussing how the struggles of the poor are also ecological struggles for basic needs such as energy, food, and water, Martínez-Alier already highlighted three decades ago the centrality of social movements for environmental justice, inequality, and class conflict in shaping climate politics (Martinez-Alier, 1991, 2003). Conversely, an increase in top income inequality is positively associated with CO_2 emissions (Hailemariam et al., 2020); the top 10% of world income emits 50% of the carbon emissions, which the UN Inter-governmental Panel on Climate Change argues would suffice to curb global warming within sustainable limits (Kartha et al., 2020).

In other words, how do the environmental limits to economic growth at the center of ecological economics, that is, the 'planetary boundaries', actually assert themselves upon society? Not by thermodynamics [Georgescu-Roegen], knowledge dissemination, hard biophysical limits, demographics [Daly, Malthus], or natural resource depletion in itself [Meadows], but they are rather mediated by material, societal, conflicting struggles for income: this paper argues so by presenting a stylized, formal model of economic growth under limited natural resources that follows an ecological interpretation of the earliest growth model known in political economy, developed by Ricardo two-hundred years ago in 1824 to highlight the critical, complex interaction between growth and income distribution – the "principal problem in political economy" according to Ricardo (Ricardo, 1971; Kaldor, 1955; Pasinetti, 1977; Bhaduri & Harris, 1987). Under the classical-ecological view, while economic growth is, of course, the main driver of human-made climate change, whether and how the economy reaches or not a steady state of balance or equilibrium with the environment –how the natural limits to growth eventually assert themselves upon an exponentially-growing economy, that is, the shape of the dynamical trajectory converging towards or gravitating around the steady state– critically depend on the property relations underpinning socio-economic inequality, understood as the social distribution of economic output and thus functional class income in the form of wages, profits, and rent, respectively among workers, capitalists, and landlords, the latter being the private owners of the limited natural resources available: land, but also water, oil, energy, or critical minerals.

In line with what authors in the political-ecology tradition such as Bellamy Foster (2000), Moore (2015), Malm (2016), or Huber (Huber, 2022), this paper argues that a material analysis of economic power that emphasizes the relevance of social class, property relations, and socio-economic inequality is fundamental for ecological economics to properly understand the societal dynamics of the climate crisis and the political economy of climate action and inaction that underpins it – in other words, how the 'metabolic rift' unfolds between the economy and the environment (Foster, 2000).

Overpopulation

The problem of distribution is not new at all to ecological economics, ecological macroeconomics, and ecological growth theory in particular (Rezai & Stagl, 2016; Taylor et al., 2016; Hardt & O'Neill, 2017). However, these have generally been neglected fields of study, as ecological economics rarely addressed the macroeconomic dimension in terms of theory and modeling in its analysis until recently (Spash and Schadl, 2009). While many recent post-growth and ecological macroeconomic models now incorporate income distribution, the social classes explicitly featured are only workers and capitalists as in conventional post-Keynesian modeling. Hence, none explicitly addresses the rentier class based on the private ownership of natural resources as the actual limiting factor of economic growth, underlying Ricardo's original explanation for the tendency of the profit rate to fall. Daly already recognized Ricardo's stylized model as envisioning a growing economy under limited natural resources to eventually reach a steady state of secular stagnation following a 'profit squeeze' due to an increasing rentier income share: economic growth, driven by profit-driven investment by capitalists, gradually dwindles over time as more and more output goes, instead of profit, as rent to the private owners of natural resources. In other words, for Ricardo, de-growth was already the inexorable end state of the economic system when limited natural resources are available; Ricardian analysis thus offers an interesting formalization of the concept of an environmental 'carrying capacity' or 'planetary boundaries' in ecological economics.

Most importantly, a contribution of this paper is to show that the dynamic pathways of convergence towards equilibrium critically depend, in Bhaduri and Harris' interpretation of the Ricardian growth model (1987), on the functional distribution of income, yielding a more desirable 'smooth landing' or a 'Mad Max' dystopian scenario of wildly chaotic, ungovernable fluctuations. As they show, a linearly decreasing marginal productivity of natural resources (the most general assumption of decreasing returns to scale), yields the so-called logistic equation, of widespread use in population ecology. The logistic equation shows very different transitory dynamics depending on its single driving parameter, which is the rate of ecological-economic surplus or, in classical terms, the rate of exploitation. Hence, rather than being utopian as Daly claimed, the issue then is not de-growth, as it will inexorably arrive, but *how we reach it*. Following empirical evidence at hand (Rotta & Kumar, 2024), I describe the starkly uneven paths of ecological-economic decline available for different countries.

The paper is organized as follows. It first reviews the issue of de-growth (Georgescu-Roegen). Then it describes the Ricardian growth model.

2. The political-economic nature of the limits to growth

A most fundamental insight put forward by ecological economics is that an economy cannot expand indefinitely in a world of limited natural resources. However, the actual mechanism by which such limits to growth occur is less clear: we know that the steady state of the economic system is desirable, but we do not know how it is reached.

In his seminal *magnum opus* "The Entropy Law and the Economic Process" (1971), Georgescu-Roegen persuasively challenged the possibility of perpetual economic growth by arguing that economic processes are also physical in nature, so that economic analysis needs to account for the principles of thermodynamics, most importantly the fundamental second law of entropy, which casts a specific direction upon the 'arrow of time', determining the fundamental irreversibility of all thermodynamic processes leading to the inexorable degradation of matter and energy and even a hypothetical heat death of the universe. However, while Georgescu-Roegen's thermodynamic theorization offers a compelling research programme that is foundational in ecological economics, the law of entropy may fall short as a convincing mechanism to explain the impossibility of perpetual growth (Schwartzman, 2008).

Using the thermodynamic concept of entropy, Kåberger and Månsson (2001) show that, even in the long run, entropy production associated with material dissipation need not be a limiting factor for economic development: a simple, quantitative analysis shows that the rate of entropy production caused by human economic activities is practically negligible compared to the continuous natural entropy production in the atmosphere and on the Earth's surface; hence, societal entropy production is well within the range of natural variation. The biophysical world that contains the economic subsystem is not isolated but closed, as it constantly exchanges solar energy with its surroundings (Schwartzman, 2008). Hence, by converting low-entropy, high-temperature energy in the form of solar radiation to high entropy, low temperature heat, work can be produced to recycle *de facto* indefinitely within a human timescale (Ayres, 1998; Kåberger & Månsson, 2001; Schwartzman, 2008).

In terms of growth theory, ecological economists have long argued that economic growth can only be understood in terms of material throughput and, in particular energy or, in Ayres' reformulation, 'exergy', i.e. the maximum amount of useful work that can be extracted from a system or energy source (**?**Rezai & Stagl, 2016). In two important articles at the beginning of the 1990s, Herman Daly contended that scale, rather than allocation or distribution, must be the main focus of environmental macroeconomics, where scale refers to the rate of physical exchanges or throughput, measured by population times per capita resource use, between the world and its economic subsystem (Daly, 1991, 1992). Under this view, 'optimal scale' should be another macroeconomic policy goal like full employment and price stability, although optimal is ambiguous as it can be defined from a narrow utilitarian, extractive, anthropo-centric perspective or from the broader perspective of the sustainability for the biosphere (Daly, 1991). Importantly, Daly's argument that these goals are fundamentally independent was critically received, noting that scale has both sustainability and equity implications, especially from a Global South perspective (Prakash & Gupta, 1994; Malghan, 2010). In the seminal 'The Economics of the Steady State', Daly (**?**) discusses the urgent desirability of the steady state in the sense of a much-needed balanced relationship between the economy and the environment and speculates with the kind of institutions that may support it, namely population control through marketable birth quotas and resource control through state-determined depletion quotas.

Taking on Daly's call to advance the field of ecological macroeconomics, Heyes (2000) interestingly suggested a formalization of his notion of an environmental carry capacity supporting the optimal sustainable scale incorporating an 'ecological equilibrium' curve, defined by a constant physical stock of natural capital (Costanza & Daly, 1992), to the conventional textbook IS-LM model. However, the main insight of the model limits itself to the simple fact that higher levels of output have to be accompanied by higher levels of resource productivity and lower levels of waste in order to keep throughput constant (Rezai & Stagl, 2016). Moreover, the IS-LM framework bears important critics (Romer, 2000), starting by its own creator, John Hicks himself, and many also in the post-Keynesian tradition (Ferri & Minsky, 1989; Setterfield, 2009), which most notably highlight the incapacity of the framework to incorporate dynamics (Davidson, 1980): in this sense, the environmental macroeconomic equilibrium of the EE-IS-LM model is, in fact, not a naturally-occurring outcome: no natural forces ensure the automatic adjustment to the EE curve (Lawn, 2003).

While dynamics are treated explicitly by conventional models on the traditional macroeconomics of climate change, such as the canonical DICE model (Nordhaus, 1993, 2018), those are subject to the optimal control of welfare maximization, thus informing an anthropo-centric 'optimal scale' following the utilitarian trade-off between the costs of climate change and of its mitigation. A biospheric notion of optimal scale could be inferred if emissions could be considered a stylized measure of throughput, which may be overtly reductionistic within the scope of ecological economics. The nature of transitional dynamics between equilibria are generally not investigated explicitly in such models, which lack dynamical realism (Grubb et al., 2021). Their dynamical trajectories do not fundamentally differ much due to a general low parameter sensitivity, are generally monotonic, showing a maximum number of one optima, and do not necessarily reach the steady state when variables reach stationarity. Hackett and Moxnes extend the DICE model by including a defintion of natural capital (Hackett & Moxnes, 2015). Computational general equilibrium models on climate change mitigation are generally static, not dynamic (**?**).

In Rosser (2001), various complex dynamics in ecologic–economic systems are presented with an emphasis upon models of global warming dynamics and fishery dynamics. Chaotic and catastrophic dynamic patterns are shown to be possible, along with other complex dynamics arising from non-linearities in such combined systems.

In contrast to the neoclassical stylization of the individual as fundamentally utility-maximizing, classical political economy views each social class as following, overall, starkly different behavioral principles: workers' goal is not maximizing utility but securing basic survival, which they obtain exchanging their labor for a living wage. Instead, it is competitive profit-seeking capitalists that drive overall growth as they re-invest their profits, while rentiers are an unproductive, leisure class that exclusively lives straight off the surpluses generated. MALTHUS. REPRODUCTIVE RIGHTS - ECO-FEMINIST CRITIQUE

3. The Ricardian Model of Economic Growth under Limited Natural Resources

Ricardo, one of the wealthiest economists in history and one of the seminal authors in the tradition of classical political economy, developed his seminal 'corn model' as a political argument in the context of the heated debate taking place in Great Britain regarding the Corn Laws, tariffs on imported food and corn enforced between 1815 and 1846 that symbolized the mercantilist trade policy of the time. In a defense of free trade, Ricardo justified repealing such tariffs by explaining the secular decline in profitability, and thus economic growth, as a 'profit squeeze' due to increasing rent pressures, as an ever-increasing share of output

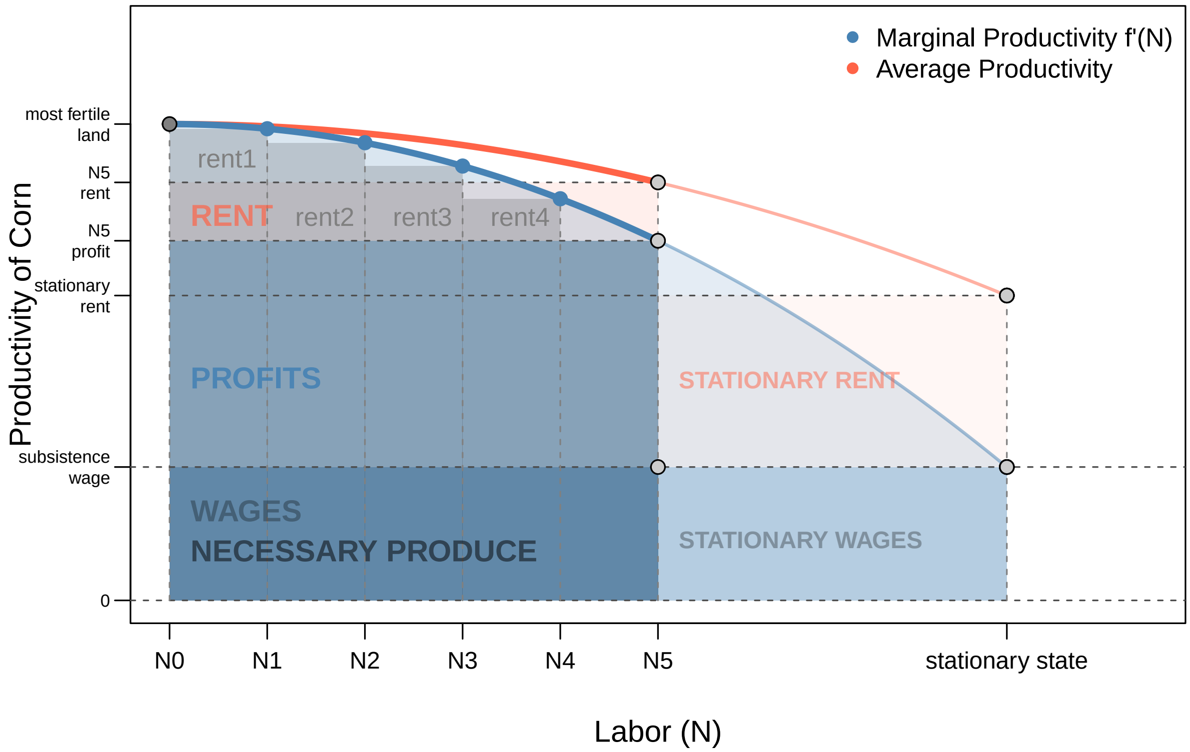

Figure 1: **Visualization of the Ricardian growth model**

devoted to the landlords in the form of economic rents as less and less fertile land is cultivated over time. In classical and neoclassical economics, economic growth is supply-led, driven by the profit-seeking investment by the owners of capital. In Ricardo's model, growth gradually dwindles over time as more and more output goes, instead of profit, as rent to the private owners of natural resources.

In this context, the interaction between economic growth and the distribution of income in wages, profits, and rent among workers, capitalists, and landlords was the "principal problem in political economy" (Ricardo, 1971). The underlying assumption of decreasing returns to scale due to declining fertility of land is critical in Ricardo's argument. For Kaldor (1955), Ricardian theory was based on two separate principles under the crucial assumption of diminishing returns: the "marginal principle", which applies to the productivity of natural resources and thus the rentier share of economic output, and the "surplus principle" that divides the residue between wages and profits. In this stylized context, land can be interpreted in a general, abstract way, that is, as 'natural resources' that are privately owned, limited, and exhaustible (Pearce & Turner, 1989): this can be oil, gas, or critical mineral resources such as lithium or magnesium, as well as water and, of course, land itself. Decreasing returns to scale is a general property of such limited natural resources: for instance, South African gold mining, leading the world after China surpassed it in 2009, has steadily seen its production costs rise in the last decades (**?**). In particular, diminishing returns apply to carbon-based energy sources such as oil, gas, and coal (as well as nuclear energy) as their useful energy inflation-adjusted costs have only increased since the 1960s, in stark contrast to the plummeting costs of renewable sources (Way et al., 2022). Some authors have suggested that the whole US economy had slightly decreasing returns to scale (Basu & Fernald, 1997).

Following the work of Kaldor (Kaldor, 1955), Pasinetti presents the highly simplified economic system that Ricardo discusses in the *Principles of Political Economy* (1971) in which only one commodity, corn, is produced, e.g. an aggregate, one-sector model. This paper follows the formulation of Bhaduri and Harris (1987).

Consider an economy where labor N is applied in fixed proportion to less and less fertile land as the margin of cultivation is extended in the process of capital accumulation. Accordingly, there exists a falling marginal product curve for labor with fixed "doses" of land, which decreases linearly. The linear decrease in marginal productivity is the most stylized simplification of the existence of hard limits of natural resources, subject to decreasing returns to scale.

In such a stylized theory, (corn) output Y is produced by labor N, working in fixed proportion on less and less productive land along the process of capital accumulation, which raises labor N and thus output Y over time:

$$Y = f(N) \tag{1}$$

with properties $f(0) \geq 0$, $f'(1) > w$, and $f''(N) < 0$. Following the marginal principle, (differential) rent R is the difference between average $AP = Y/N$ and the marginal product $MP = Y'$ of land,

$$R = N(AP - MP) = f(N) - Nf'(N) \tag{2}$$

Following the surplus principle, profits are the remainder of the output after subtracting differential rent and wages:

$$P = Y - R - W \tag{3}$$

where the wage bill W is

$$W = wN \tag{4}$$

at a constant wage rate w.

Bhaduri and Harris (1987) suggest the simplest functional form for the function f, which arises from

Class	Income	Share
Output	$Y = aN - 0.5bN^2$	$\iota = 1$
Rents	$R = 0.5bN^2$	$\rho = \frac{bN}{2a-bN}$
Wages	$W = wN$	$\omega = \frac{2w}{2a-bN}$
Profits	$P = (a-w)N - bN^2$	$\pi = \frac{2a-2w-2bN}{2a-bN}$

Table 1: **Functional Classes of Income and their Shares of Output**

considering a linear decrease for the marginal productivity of labor, with parameters a and b:

$$MP = f'(N) = a - bN \quad a > 0, \quad b > 0 \tag{5}$$

so that rent is

$$R = \frac{bN^2}{2} \tag{6}$$

and output follows a quadratic form:

$$Y = f(N) = aN - bN^2/2 \tag{7}$$

In the Ricardian model, economic growth is driven by profits. The dynamics of the wage bill capture the whole process of accumulation in this simple economy. Following classical principles, its time difference entirely comes from reinvestment of capitalist profits:

$$W_{t+1} - W_t = P_t \tag{8}$$

Using both marginal (2) and surplus principles (3) in addition to the assumption of a linear decrease in the productivity of labor (5),

$$W_{t+1} = P_t + W_t = Y_t - R_t = Y_t - Y_t + N\frac{dY}{N} = N\frac{dY}{N} = aN - bN^2 \tag{9}$$

yielding, after substituting the wage bill by employment times the wage rate, the discrete dynamic equation of motion:

$$N_{t+1} = \frac{a}{w}N_t - \frac{b}{w}N_t^2 = \frac{a}{w}N_t\left(1 - \frac{b}{a}N_t\right) \tag{10}$$

4. An Ecological Interpretation

Most significantly, equation (10) is the two-parameter version of the logistic growth equation that is much well-known in population ecology, but less discussed in economics until very recently (Galanis et al., 2024).

In the Ricardian growth model, the logistic equation models the growth of an economy N in an environment under limited natural resources, where the ratio between the technical parameter a over the social wage w

$$r = \frac{a}{w} \tag{11}$$

corresponds to the reproduction rate r of the economy and the ratio of technical parameters a and b, describing the decreasing linear slope of the marginal productivity curve (5),

$$K = \frac{a}{b} \tag{12}$$

corresponds to the *carrying capacity of the natural environment*, usually denoted by K (Chapman & Byron, 2018):

$$X_{t+1} = \underbrace{rX_t}_{\text{exponential term}} \underbrace{\left(1 - \frac{X_t}{K}\right)}_{\text{starvation term}} \tag{13}$$

Carrying capacity K implies a notion of hard natural bounds or biophysical limits to population growth imposed by the environment, for instance in the form of available food in population ecology or land in the Ricardian model. For this reason, the notion of environmental carrying capacity for human society is also widely discussed in ecological economics, for instance in the writings of Herman Daly (Daly, 1990a,b). When the population size is small relative to the carrying capacity, the population will increase exponentially without bounds, at a reproduction rate proportional to its own size, i.e. rX_t. However, when the population reaches the vicinity of the carrying capacity $X_t \sim K$, the starvation effect of the second term prevails, so that the growth rate decreases at a rate that depends on the carrying capacity and the economy stabilizes within the natural limits; growth becomes negative and the population contracts if $X_t > K$.

4.1. Ecological-Economic Equilibrium

Such biophysical limits of the environment impose a specific ecological scale K within which an economy can grow, which in the Ricardian model is determined by the technical parameters a and b (the intercept and slope of the linearly decreasing returns to scale) in critical interaction with the social wage w. In this simple dynamical discrete-time system, two fixed points (i.e. where no growth occurs) exist, a trivial one at $N^* = 0$ and another one at

$$N^* = \frac{a - w}{b} \tag{14}$$

or

$$X^* = K\left(1 - \frac{1}{r}\right) \tag{15}$$

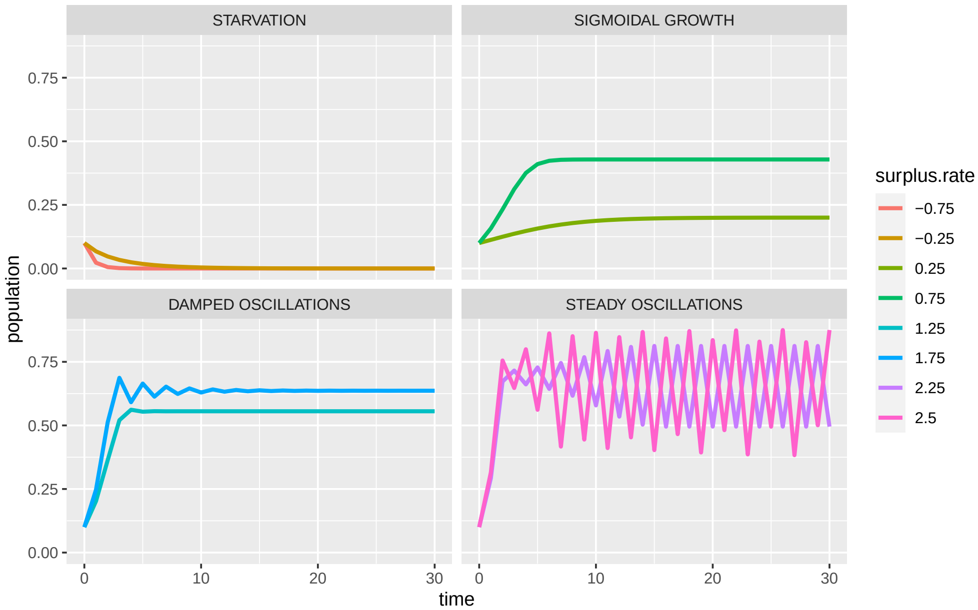

Figure 2: **Scenarios of Single-Parameter Logistic Growth**

In such ecological-economic equilibrium, the marginal productivity of labor MP^* is equal to the given real wage rate w, so that all profit disappears $P^* = 0$ due to a profit squeeze driven by increasing rents, as the whole surplus over the wage bill accrues to the landlords as rent – the canonical *Ricardian stationary state* of no growth. Hence, in the Ricardian model of growth under limited natural resources, the economic system will actually never grow exponentially indefinitely, but rather inevitably evolve towards such the steady state of an ecological scale K determined by how much economic-ecological surplus can be extracted at the expense of the social wage w in a situation of ecological-economic balance.

The two-parameter version of logistic growth can be further simplified if population size X is normalized by the carrying capacity K, i.e. $x \equiv X/K$, yielding:

$$x_t = rx_t(1 - x_t) \tag{16}$$

Likewise, a new variable n_t can be defined in the Ricardian model by dividing N_t by the carrying capacity $K = a/b$,

$$n_t \equiv \frac{bN_t}{a} \tag{17}$$

which lies between 0 and 1 as a measure of density. This allows to re-write the Ricardian model in simplified form under a single driving parameter:

$$n_{t+1} = \frac{a}{w} n_t(1 - n_t) \tag{18}$$

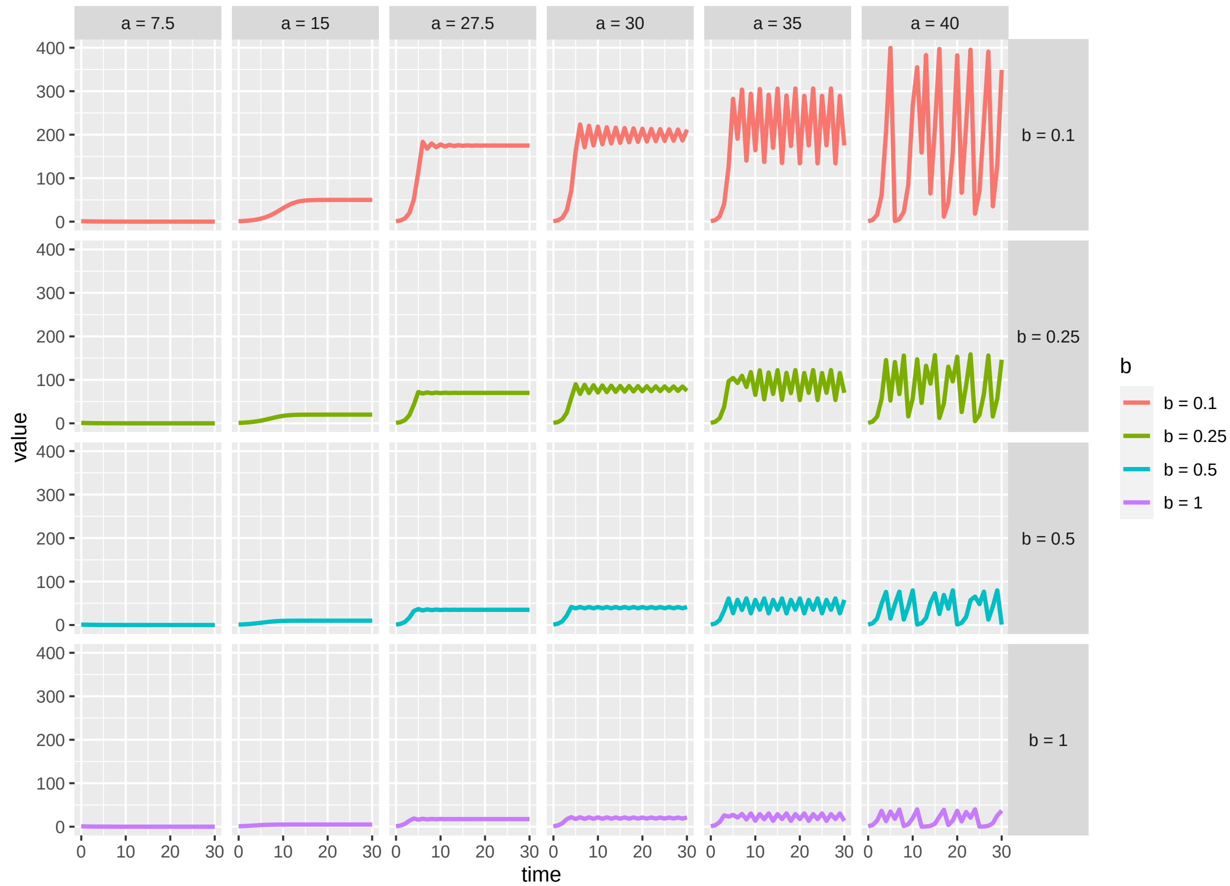

Figure 3: **Scenarios of 2-Parameter Logistic Growth** Wage rate is set at $w = 10$, the reproduction rate is thus $a/w = 0.1w$, and the carrying capacity is a/b.

with two fixed points, $n^* = 0$ and

$$n^* = 1 - \frac{w}{a} \tag{19}$$

or

$$x^* = 1 - \frac{1}{r} \tag{20}$$

4.2. Complex Dynamics

While the carrying capacity K determines the ecological scale imposed by limited natural resources, it is the reproduction rate r, which highlights the critical interaction between economic growth and distribution at the core of the Ricardian model, that determines how the economy dynamically converges to it, following very different transition regimes: starvation, sigmoidal growth, damped oscillations, steady oscillations, or even deterministic chaos. Bhaduri and Harris (1987) show that the single parameter $r \equiv \frac{a}{w}$ is associated to the maximum rate of exploitation of labor and nature (or ecological-economic surplus) at the initial state of the system $t = 0$, i.e. ϵ_0, something akin the classical notion of "primitive accumulation" in which common nature is initially privatized to set the course for capital accumulation (Robinson, 1969):

$$r \equiv \frac{a}{w} = \frac{a - w + w}{w} = 1 + \frac{a - w}{w} = 1 + \epsilon_0 \tag{21}$$

denoting the original proportion of economic-ecological surplus $a - w$ over the social wage rate w at time 0, so that equilibrium values become

$$n^* = 1 - \frac{1}{1 + \epsilon_0} = \frac{\epsilon_0}{1 + \epsilon_0} \tag{22}$$

and

$$N^* = \epsilon_0 \frac{w}{b} \tag{23}$$

As dynamical-systems theory shows, the ratio of ecological-economic surplus, $r = a/w = 1 + \epsilon_0$, critically regulates the dynamical behavior of logistic growth in a very well-known form in population ecology (see figures 2, 3). Despite its stylized simplicity, the logistic model is in fact able to yield very complex dynamics far beyond conventional sigmoidal growth depending on such critical parameter. While the economy evolves following a conventional logistic curve only for low values of the rate of economic surplus, logistic growth becomes oscillatory and eventually chaotic for high values of the rate of surplus (see figures 4, 5):

- *Starvation* With r between 0 and 1, the population will eventually die, independent of the initial population, as the economy is unable to generate a surplus over wages. The economy is not viable as the surplus rate is negative.

- *Sigmoidal Growth* With r between 1 and 2 (i.e. $0 < \epsilon_0 < 1$) , the economy is viable and will quickly approach the steady state (22) or (23) in logistic fashion. The economy smoothly stabilizes to its steady state without much difficulty in harmony with the natural environment. At the steady state under a zero surplus rate, all output goes to wages; as the surplus rate increases, more output goes to rents at the steady state. Transitory nonzero profits quickly dwindle to zero due to the profit squeeze by rents.

- *Damped Oscillations* With r between 2 and 3 (i.e. $1 < \epsilon_0 < 2$), the economy will also eventually approach the same value $1 - \frac{1}{r}$, but first will fluctuate around that value for some time, as it initially overshoots and undershoots beyond the carrying capacity of the environment. In that transitory phase, declining profits oscillate around zero as they drive the growth of the system.

- *Steady Oscillations* With r between 3 and $1 + \sqrt{6} \sim 3.44949$, from almost all initial conditions the population will approach permanent oscillations between two values, which depend on r. The reproduction rate is high enough so the economy constantly overshoots and undershoots beyond K, unable to eventually stabilize with the environment, fraught by booms and busts driven by the steady oscillations in profits around zero. Until $r = 3$, the bifurcation graphs (4 and 5) show the steady state of the system and its corresponding income shares. From then on, it shows the discrete states around which the system oscillates.

- *Period-Doubling Cascade* With r between 3.44949 and 3.54409 (approximately), from almost all initial conditions the population will approach permanent oscillations among four values. With r increasing beyond 3.54409, from almost all initial conditions the population will approach oscillations among 8 values, then 16, 32, ...: this behavior is the most well-known example of a period-doubling cascade, a very peculiar route to deterministic chaos (see the bifurcation graph 4, which features the period-doubling cascade as a sequential branching process).

- *Onset of Deterministic Chaos* At $r \sim 3.56995$ is the onset of chaos, at the end of the period-doubling cascade. From almost all initial conditions, we no longer see oscillations of finite period that is proportional to 2. Although the dynamical behavior is still deterministic, it becomes, paradoxically, highly unpredictable due to its high sensitivity to initial conditions: in the jargon of dynamical-systems theory, chaos sets in (Strogatz, 2014). From an ecological-economic point of view, the rate of extraction is so high that a proper balance is unfeasible: ecological collapse ensues quasi-periodically, unpredictably. In the bifurcation graph 4, graphing all the states visited by the system after $t = 20$ shows a myriad of points as no state visited by the system is exactly equal to any other. However, very specific islands of stability occur, where the system oscillates between only three specific states over time.

Such complex behavior with respect to the rate of ecological-economic exploitation $r = a/w$ illustrates the impact of the hard limits of the natural environment on economic growth, especially at high levels of natural-resource extraction without consideration for ecological balance, disrupting the natural cycles of the environment and degrading it in the process. Due to the oscillatory behavior beyond $r = 3$, there may be episodes of actual growth within specific time windows, but on average growth will always be zero. The higher the rate of ecological-economic surplus r, the more unstable the system is, and the more prone to extreme oscillatory behavior. Hence, such logistic dynamics illustrate the classical notion of the "metabolic rift" (Foster, 2000).

4.3. Technical Change or Degrowth?

Despite its simplicity, the ecological Ricardian growth model illustrates with clarity the potential impact of technical change in addressing the climate crisis. In this pressing context, there is an intense debate about whether there may exist a 'technological fix' as an alternative solution to climate change other than degrowth, for instance in the form of beliefs in technical innovation able to decouple emissions from economic

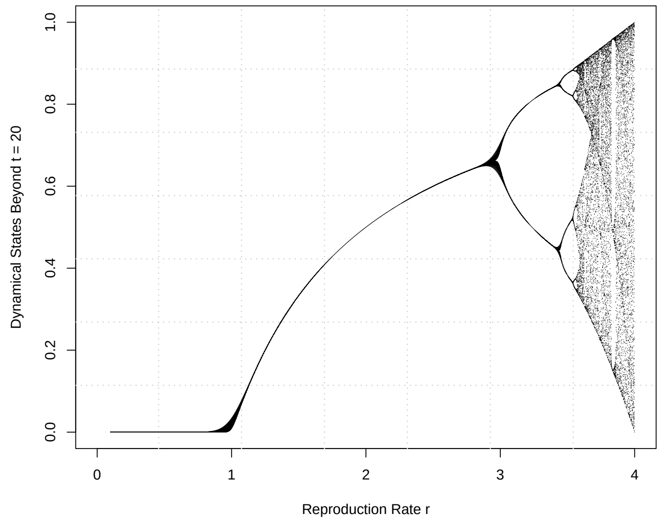

Figure 4: **Bifurcation Graph** For $0 < r < 3$, the bifurcation graph shows the steady state of the system with respect to r. From then on, it shows the states between which the system oscillates following a period-doubling cascade. Chaos sets in at $r \sim 3.56995$.

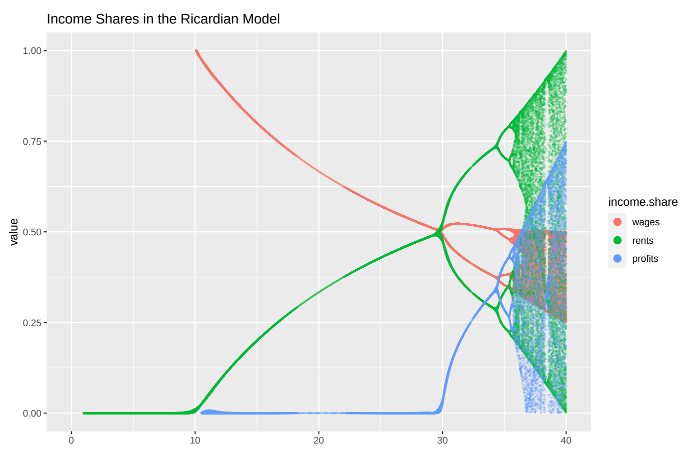

Figure 5: **Bifurcation Graph with Income Shares** Steady states of the income shares depending on technical parameter a given $w = 10$.

activity, such as carbon capture technologies (Anderson & Bows, 2011). Empirical evidence shows that such decoupling is very unlikely, a critical argument in the de-growth literature (Parrique et al., 2019).

As seen in figure 3, although the technical parameter a is linearly present in both terms, the rate of ecological-economic exploitation a/w, which corresponds to the reproduction rate r in population ecology, is independent of the carrying capacity of the natural environment a/b, e.g. the population and economic output it can support. Through a decrease of the technical parameter b, technical innovation may be very

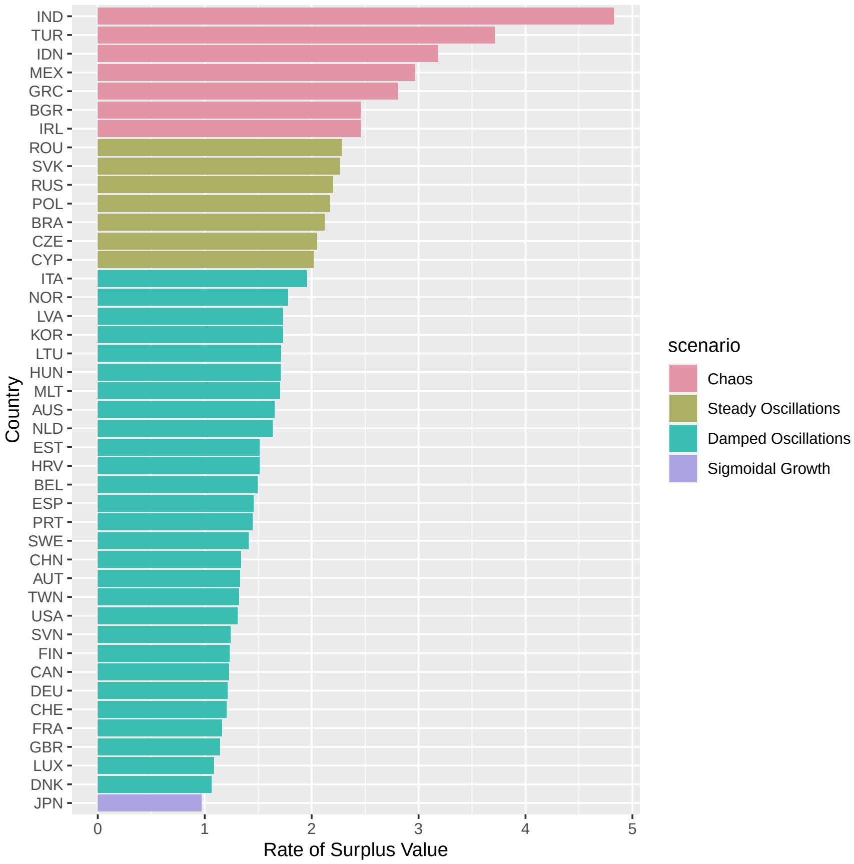

Figure 6: **Empirical Values of the Rate of Surplus Value** (Rotta & Kumar, 2024)

well able to increase the population and raise the living standards the environment and the economy can support, but this will have no impact on the actual dynamical behavior of the system, which critically depends on income distribution, in short, on how much both labor and nature are exploited: if the rate of ecological-economic surplus is high enough, it will always yield oscillations or chaos, irrespective of the carrying capacity. The only effect of technical change is to let the economy grow, on average, at the same pace the carrying capacity grows; if existing, oscillations will persist – it consists, in figure 3, of moving up vertically in the same column, decreasing the slope of the marginal productivity curve a/b (e.g. the carrying capacity) by reducing b but keeping the a coefficient constant. Malthusian accounts may desire to decrease the social wage w: however, if the social wage decreases *ceteris paribus*, the reproduction rate increases so that ecological-economic balance becomes much more fragile.

5. Empirics

Since the Ricardian model is highly stylized, the interpretation of its dynamical parameters is very abstract. However, three empirical measures for the reproduction rate can be tentatively suggested at the

Figure 7: **Empirical Values of the Rate of Energy Surplus Value**, own calculations based on the EORA database

country or region level: an energy rate of surplus (figure 7) by energy source, defined as the 2016 total production of energy divided by its household consumption following the EORA database (Lenzen et al., 2013); an ecological rate of surplus (figure 8) as the ratio of the ecological footprint to biocapacity (Global Footprint Network, 2024); or the labor rate of surplus (figure 6) following the Rotta-Kumar dataset (Rotta & Kumar, 2024).

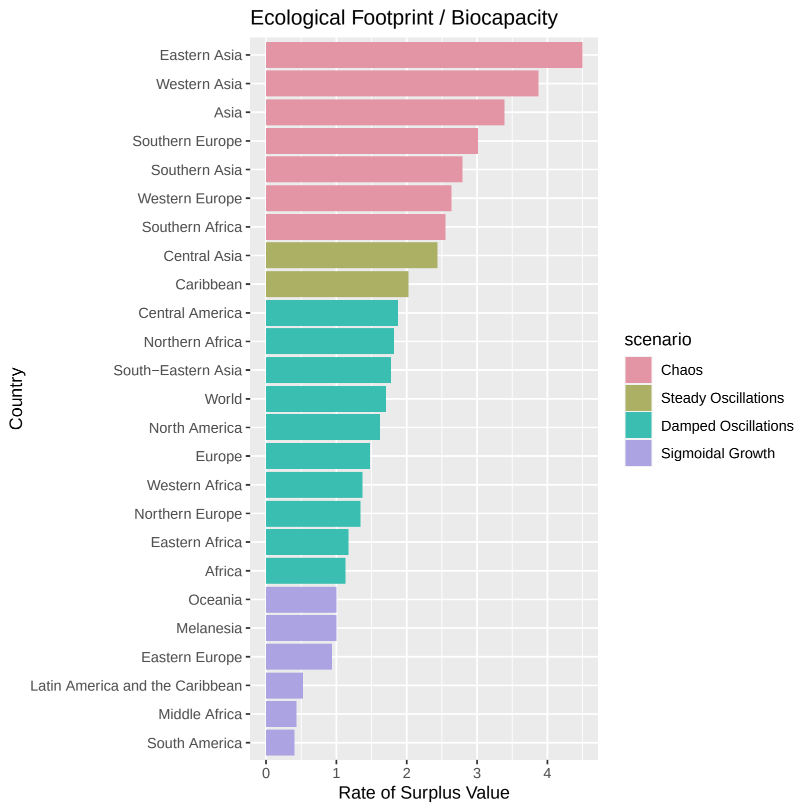

Figure 8: **Empirical Values of Ecological Footprint to Biocapacity Ratio** (Global Footprint Network, 2024)

6. Conclusions

Paraphrasing Kalecki's 'Political Aspects of Full Employment' (1943), addressing climate change is, like full employment, entirely feasible on paper; the problem, though, is of naked political power.

In the pressing context of the climate crisis, many academics call for a more diversified, more ambitious climate-policy portfolio including vigorous state support for green finance and green investment for energy and infrastructure. More skeptical voices in the tradition of de-growth consider instead that the uncoupling of carbon emissions to economic activity within such a limited time frame is straight unfeasible, hence favoring no growth so that the economy reaches a steady state within the carrying capacity of the environment. However, why would de-growth be more feasible than uncoupling?

References

References

Anderson, K., & Bows, A. (2011). Beyond 'dangerous' climate change: emission scenarios for a new world. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *369*, 20–44.

Ayres, R. U. (1998). Eco-thermodynamics: economics and the second law. *Ecological economics*, *26*, 189–209.

Basu, S., & Fernald, J. G. (1997). Returns to scale in us production: Estimates and implications. *Journal of political economy*, *105*, 249–283.

Bhaduri, A., & Harris, D. J. (1987). The complex dynamics of the simple ricardian system. *The Quarterly Journal of Economics*, *102*, 893–902.

Capstick, S., Thierry, A., Cox, E., Berglund, O., Westlake, S., & Steinberger, J. K. (2022). Civil disobedience by scientists helps press for urgent climate action. *Nature Climate Change*, *12*, 773–774.

Chapman, E. J., & Byron, C. J. (2018). The flexible application of carrying capacity in ecology. *Global ecology and conservation*, *13*, e00365.

Costanza, R., & Daly, H. E. (1992). Natural capital and sustainable development. *Conservation biology*, *6*, 37–46.

Daly, H. E. (1990a). Carrying capacity as a tool of development policy: the ecuadoran amazon and the paraguayan chaco. *Ecological Economics*, *2*, 187–195.

Daly, H. E. (1990b). Sustainable development: from concept and theory to operational principles. *Population and Development Review*, *16*, 25–43.

Daly, H. E. (1991). Towards an environmental macroeconomics. *Land economics*, *67*, 255–259.

Daly, H. E. (1992). Allocation, distribution, and scale: towards an economics that is efficient, just, and sustainable. *Ecological Economics*, *6*, 185–193.

Davidson, P. (1980). Causality in economics: a review. *Journal of Post Keynesian Economics*, *2*, 576–584.

Ferri, P., & Minsky, H. P. (1989). The breakdown of the is–lm synthesis: implications for post-keynesian economic theory. *Review of Political Economy*, *1*, 123–143.

Foster, J. B. (2000). *Marx's ecology: Materialism and nature*. NYU press.

Galanis, G., Koutny, C., & Weber, I. (2024). Systemic cycles of accumulation and chaos in the world capitalist system: a missing link. *Socio-Economic Review*, (p. mwae007).

Georgescu-Roegen, N. (1971). *The entropy law and the economic process*. Harvard University Press.

Global Footprint Network (2024). Ecological footprint. URL: `https://www.footprintnetwork.org/our-work/ecological-footprint/` accessed: 2024-06-30.

Grubb, M., Wieners, C., & Yang, P. (2021). Modeling myths: On dice and dynamic realism in integrated assessment models of climate change mitigation. *Wiley Interdisciplinary Reviews: Climate Change*, *12*, e698.

Hackett, S. B., & Moxnes, E. (2015). Natural capital in integrated assessment models of climate change. *Ecological Economics*, *116*, 354–361.

Hailemariam, A., Dzhumashev, R., & Shahbaz, M. (2020). Carbon emissions, income inequality and economic development. *Empirical Economics*, *59*, 1139–1159.

Hardt, L., & O'Neill, D. W. (2017). Ecological macroeconomic models: assessing current developments. *Ecological Economics*, *134*, 198–211.

Heyes, A. (2000). A proposal for the greening of textbook macro:'is-lm-ee'. *Ecological Economics*, *32*, 1–7.

Huber, M. T. (2022). *Climate change as class war: Building socialism on a warming planet*. Verso Books.

Kåberger, T., & Månsson, B. (2001). Entropy and economic processes—physics perspectives. *Ecological Economics*, *36*, 165–179.

Kaldor, N. (1955). Alternative theories of distribution. *Review of Economic Studies*, *23*, 83–100.

Kalecki, M. (1943). Political aspects of full employment. *The Political Quarterly*, *14*, 322–330.

Kartha, S., Kemp-Benedict, E., Ghosh, E., Nazareth, A., & Gore, T. (2020). The carbon inequality era: An assessment of the global distribution of consumption emissions among individuals from 1990 to 2015 and beyond, .

Lawn, P. A. (2003). Environmental macroeconomics: Extending the is–lm model to include an 'environmental equilibrium'curve. *Australian economic papers*, *42*, 118–134.

Lenzen, M., Moran, D., Kanemoto, K., & Geschke, A. (2013). Building eora: a global multi-region input–output database at high country and sector resolution. *Economic Systems Research*, *25*, 20–49.

Malghan, D. (2010). On the relationship between scale, allocation, and distribution. *Ecological Economics*, *69*, 2261–2270.

Malm, A. (2016). *Fossil capital: The rise of steam power and the roots of global warming*. Verso books.

Martinez-Alier, J. (1991). Ecology and the poor: A neglected dimension of latin american history. *Journal of Latin American Studies*, *23*, 621–639.

Martinez-Alier, J. (2003). *The Environmentalism of the poor: a study of ecological conflicts and valuation*. Edward Elgar Publishing.

Mendes, C., & Gross, T. (1989). *Fight for the forest. Chico Mendes in his own words.*. Inland Book Co.

Moore, J. W. (2015). *Capitalism in the Web of Life: Ecology and the Accumulation of Capital*. Verso.

Nordhaus, W. (2018). Evolution of modeling of the economics of global warming: changes in the DICE model, 1992–2017. *Climatic change*, *148*, 623–640.

Nordhaus, W. D. (1993). Optimal greenhouse-gas reductions and tax policy in the "DICE" model. *The American Economic Review*, *83*, 313–317.

Parrique, T., Barth, J., Briens, F., Kerschner, C., Kraus-Polk, A., Kuokkanen, A., & Spangenberg, J. H. (2019). Decoupling debunked. *Evidence and arguments against green growth as a sole strategy for sustainability. A study edited by the European Environment Bureau EEB*, .

Pasinetti, L. L. (1977). *Lectures on the Theory of Production*. Columbia University Press.

Pearce, D. W., & Turner, R. K. (1989). *Economics of natural resources and the environment*. Johns Hopkins University Press.

Prakash, A., & Gupta, A. K. (1994). Are efficiency, equity, and scale independent? *Ecological Economics*, *10*, 89–90.

Rezai, A., & Stagl, S. (2016). Ecological macroeconomics: Introduction and review. *Ecological Economics*, *121*, 181–185.

Ricardo, D. (1971). *Principles of political economy and taxation*. Harmondsworth: Penguin Books.

Robinson, J. (1969). *The Accumulation of Capital*. Palgrave Classics in Economics. Palgrave Macmillan, London.

Romer, D. (2000). Keynesian macroeconomics without the LM curve. *Journal of Economic Perspectives*, *14*, 149–170.

Rosser Jr, J. B. (2001). Complex ecologic–economic dynamics and environmental policy. *Ecological Economics*, *37*, 23–37.

Rotta, T. N., & Kumar, R. (2024). Was marx right? development and exploitation in 43 countries, 2000–2014. *Structural Change and Economic Dynamics*, *69*, 213–223.

Schwartzman, D. (2008). The limits to entropy: Continuing misuse of thermodynamics in environmental and marxist theory. *Science & Society*, *72*, 43–62.

Setterfield, M. (2009). Macroeconomics without the lm curve: an alternative view. *Cambridge Journal of Economics*, *33*, 273–293.

Stoddard, I., Anderson, K., Capstick, S., Carton, W., Depledge, J., Facer, K., Gough, C., Hache, F., Hoolohan, C., Hultman, M. et al. (2021). Three decades of climate mitigation: why haven't we bent the global emissions curve? *Annual Review of Environment and Resources*, *46*, 653–689.

Strogatz, S. H. (2014). *Nonlinear dynamics and chaos: with applications to physics, biology, chemistry, and engineering*. Westview press.

Taylor, L., Rezai, A., & Foley, D. K. (2016). An integrated approach to climate change, income distribution, employment, and economic growth. *Ecological Economics*, *121*, 196–205.

Way, R., Ives, M. C., Mealy, P., & Farmer, J. D. (2022). Empirically grounded technology forecasts and the energy transition. *Joule*, *6*, 2057–2082.