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Keywords: Economic growth; pollution concentration; labor productivity; functional Distribution of the social product.

JEL Codes: E11, O44, Q52.

Economic growth as a double-edged sword: The pollution-adjusted Kaldor-Verdoorn effect

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Abstract

There is evidence that pollution concentration impacts negatively on labor productivity, which has implications for the Kaldor-Verdoorn law. While the growth rate of labor productivity varies positively with the growth rate of output, the growth rate of pollution concentration also varies positively with the latter. As a result, an increase in pollution concentration leading to environmental degradation might offset the productivity-enhancing effect of a rise in the scale of output production. This paper explores such a double-edged sword feature of output growth in a demand-led macrodynamic framework having pollution concentration as a further influence on the class conflict over the functional distribution of the social product. The stability of the environment-economy system in the long run hinges on how output growth varies with the functional distribution of income. When output growth is positively related to the wage share, the balanced growth path is unstable. When output growth varies positively with the profit share, stability is a possibility, but the system undergoes fluctuations in the wage share and the ratio of capital to pollution concentration when converging to the balanced growth path. Environmental preservation and functional distribution and growth of the social product interact to each other in a complex way.

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1 Introduction

The importance of the Kaldor-Verdoorn law in output growth dynamics has been amply vindicated in the literature. The law states that, given the presence of dynamic increasing returns especially in the industrial sector, labor productivity growth varies positively with output growth. Although increases in industrial production primarily improve labor productivity in industry itself, the use of industrial products as capital goods in primary and tertiary sectors together with other technological spillover effects imply that product or process innovations in industry also boost the rate of technical progress in the overall economy. The empirical evidence has been considerably supportive of the Kaldor-Verdoorn law (Kaldor, 1966; McCombie et al., 2002; Wells and Thirlwall, 2003; Magacho and McCombie, 2018).

However, it is conceivable that economic or non-economic factors attenuate or even preclude the operation of the Kaldor-Verdoorn law, and this is arguably the case with climate change. In addition to significantly impacting on ecosystems, climate change represents a great threat to economic stability due to production activities becoming increasingly sensitive to variations in environmental quality. The mutual interaction between the environment and the economy becomes vivid: output growth expands environmental degradation and the latter may irreversibly reduce the capacity for generating output growth in the future (Arrow et al., 1995). Therefore, the operation of the Kaldor-Verdoorn law is also inevitably affected by the accompanying impact of the scale of output production on the level of environmental quality.

Several empirical studies have been contributing robust evidence on how and to what extent the environment impacts output production. Key evidence suggests that the rise in pollution concentration decreases labor productivity across a range of sectors, including agriculture, manufacturing, and the service sectors. Graff Zivin and Neidell (2012) find a causal relationship between variations in the atmosphere ozone concentration and the productivity of a sample of agricultural workers: a 10 ppb (parts per billion) decrease in ozone concentration increases labor productivity by 5.5 percent. Chang et al. (2016) find similar results for the effect of outdoor air pollution on the productivity of industrial workers, with increases in fine particulate matter, PM2.5, leading to significant decreases in productivity. Similar results have been found for high skilled and unskilled workers in the tertiary sector (Chang et al., 2019; Kahn and Li, 2019).

Under certain conditions, such evidence on the negative impact of pollution concentration on labor productivity has non-negligible theoretical and policy implications. Although an increase in the rate of growth of output boosts the rate of growth of labor productivity, such a rise in the rate of growth of the scale of production also raises the rate of growth of the gross flow of pollution as a negative side effect. If the concentration of pollution is sufficiently persistent and harmful to workers' overall health conditions (including their cognitive abilities), environmental degradation may then offset the forces of aggregate demand and dynamic increasing returns combining to enhance labor productivity. In principle, the net impact of output growth on productivity growth may be positive, null, or even negative, depending on the sensitivity of labor productivity to pollution concentration. We dub this augmented causal chain the *pollution-adjusted* Kaldor-Verdoorn effect.

This paper explores the operation of the *pollution-adjusted* Kaldor-Verdoorn effect within a Neo-Kaleckian analytical framework of the functional distribution and growth of the social product. The rate of growth of labor productivity varies positively with the rate of growth of output and negatively with the rate of growth of pollution concentration. Meanwhile, there is a positive relationship between the two growth rates that impact separately on the rate of growth of labor productivity. Thus, the dynamic behavior of the labor productivity component of the unit labor cost (and then of the wage share in the social output) arises from the double-edged sword feature of the output growth. As there is an inherent class conflict over the distribution of the social output between workers and capitalists, the *pollution-adjusted* Kaldor-Verdoorn effect becomes a further element influencing such a distributive conflict, which we explore using a modified version of the pioneering formulation by Rowthorn (1977). In fact, the dynamic behavior of the real wage as the other component of the unit labor cost and hence wage share in income is conditioned by the dynamics of the concentration of pollution as well. The reason is that the dynamic behavior of the pollution concentration impacts on the dynamic behavior of the nominal wage and the price level as workers and capitalists, respectively, respond to the resulting environmental degradation in a tentatively share-preserving way in the class conflict over the functional distribution of the social product.

Firms respond to the productivity-reducing (and hence cost-increasing) impact of the concentration of pollution by allocating a fraction of their mass of profits to pollution abatement. Thus, the flow of pollution reduces (net) profits through two separate channels: by raising the unit labor cost and by leading firms to spend a fraction of their gross profits on pollution abatement. Yet, firms' expenditures on such an abatement have only a mitigating impact on the gross flow of pollution, so that the net flow of pollution released in the environment as a by-product of output production is always positive. This is partially due (but playing a minor role) to the circumstance that pollution abatement requires the use of goods and services (and hence contributes to aggregate demand formation) the production of which is polluting as well. As pollution abatement is only effective in partially reducing the net flow of pollution, firms' expenditures on such an abatement are only partially effective as a profit-preserving device. In a further attempt to safeguard their net flow of profits, firms establish a desired price inflation which varies positively with the rate of growth of pollution concentration. In a broad sense, this specification of the price inflation is consistent with the empirical evidence on a pass-through of pollution costs to prices (Grainger and Kolstad, 2010; Fabra and Reguant, 2014).

Meanwhile, workers as a class bargain for (and succeed in obtaining) a desired nominal wage inflation which varies positively with the rate of growth of pollution concentration. Admittedly, an increase in the latter, with everything else remaining constant, by causing a lower (higher) rate of growth of labor productivity (unit labor cost), ends up raising the rate of growth of the wage share in the social product. Yet, a higher rate of growth of pollution concentration, with everything else held constant, by leading to a higher rate of price inflation, also causes a fall in the rate of growth of the real wage and hence in the rate of growth of the wage share in the social product. In addition to the detrimental effects of pollution on the general health conditions of workers recalled earlier, our specification of the nominal wage inflation as varying positively with the rate of growth of pollution concentration is also motivated by the related empirical evidence on the use of pollution compensation mechanisms in the form of wage premia (Cole et al., 2009; Chai et al., 2020). Therefore, one of the novelties of our analytical framework lies in the incorporation of the concentration of pollution as a key element affecting the conflict over the functional distribution of the social product between workers and capitalists. On Kaldorian lines, pollution concentration operates as another endogenous channel influencing the two-way relationship between aggregate demand growth and productivity growth.

The stability of the environment-economy system in the long run depends upon the functional distribution of the social product, which has a key influence on aggregate demand formation and hence output growth determination, and on the financing of pollution abatement. The environment-economy system is unstable when output growth varies positively with the wage share in the social product, with the experience of a climate crisis being a possibility. When output growth varies positively with the profit share in the social product, stability becomes a possibility, but the environment-economy system exhibits fluctuations in the wage share and the ratio of capital to pollution concentration when eventually converging to the balanced growth path. Both long-run configurations feature a complex trilemma involving output growth, pollution concentration growth, and the functional distribution of the social product.

Our analytical contribution in this paper is related to an emerging literature on ecological macroeconomics that has been addressing climate change policy issues (Taylor et al., 2016; Rezai et al., 2018); the interaction between the financial system and the environment (Fontana and Sawyer, 2016); and directed technical change (Naqvi and Stockhammer, 2018), all located in the Post-Keynesian tradition broadly defined. Meanwhile, the double-edged sword attribute of output growth as productivity-enhancing yet pollution-generating raised and explored in this paper brings a 21st century perspective to the Kaldor-Verdoorn law and relates more broadly to the extensive literature ignited by the seminal contribution of Kaldor on the macrodynamics of economic growth (Kaldor, 1966; Thirlwall, 1987).

The remainder of this paper is organized as follows. Section 2 lays down the building blocks of the model framework on which our analytical investigation is based and explores its short-run equilibrium configuration. Section 3 analyzes the behavior of the model framework in the long run, especially concerning the (in)stability properties of the balanced growth path. The final section summarizes the main results derived along the way and offers some final thoughts.

2 Growth, distribution and the environment

Consider a standard Neo-Kaleckian closed–economy model that produces a single good usable for consumption and investment. Output production is carried out under imperfect competition, with excess capacity being the normal state of affairs. The aggregate social product, X, is generated with the use of two homogeneous factors of production, capital, K, and labor, L, which are combined through a fixed–coefficient technology:

$$X = min(\rho K, aL), \tag{1}$$

where ρ stands for a technological coefficient, defined as the ratio of the potential output to capital stock, and normalized to 1, for simplicity, while a is the labor productivity.

The social activity of production also generates $b \in \mathbb{R}_+$ units of pollution as a joint product of X (Copeland and Taylor, 1994; Brock and Taylor, 2010). As there is no clean technical change, b is fixed. The amount of pollution released into the environment is lower than the amount produced as there is pollution abatement, A. Abatement is an in-house activity carried out by firms using internal funds as specified in section 2.1. It requires expenditures on the consumption of abatement equipment to prevent a certain level of emissions from being released into the environment. This equipment fully depreciate at the end of each production period.

The net flow of pollution, E, is thus given by:

$$E = bX - \psi A, \tag{2}$$

where ψ is an exogenously fixed measure of abatement efficiency. For simplicity, we innocuously assume that $\psi = 1$. Units of E, X, and A, are comparable through the transforming technical coefficients b and ψ. In order to focus on the most common real-world situation of a positive net flow of pollution, we further suppose that $bX > A$.

The rise in E increases the concentration of pollution, Ω. The net effect of E on Ω, however, depends on the magnitude of the rate at which natural pollution dissipation occurs, $\omega \subset (0,1) \in \mathbb{R}$, which is exogenous and constant. The rate of change of the pollution concentration is:

$$\frac{d\Omega}{dt} = E - \omega\Omega. \tag{3}$$

The current level of pollution concentration depends on the entire history of emissions up to that point in time. Even with a constant net flow of pollution E in the past which remains so in the future, Ω varies over time whenever the flow of pollution dissipation $\omega\Omega$ differs from E.

It is supposed that the concentration of pollution impacts negatively on labor productivity, which is supported by burgeoning empirical literature. Graff Zivin and Neidell (2012) provided early evidence on the causal relationship between variations in ozone concentration and labor productivity using a sample of agricultural workers in the Central Valley of California. The workers were paid via piece-rate for each unit of fruit they picked, a clean measure of productivity. Using emission and meteorological data from a nearby monitor, it is found that a 10 ppb (parts per billion) decrease in ozone concentration increases labor productivity by 5.5 percent.

Related evidence links pollution concentration with labor productivity in the industrial sector. A key distinction from the agricultural setting is that manufacturing activities typically occur in indoor environments. Chang et al. (2016) focus on workers at a pear-packing factory in the US. The study found that increases in fine particulate matter, PM2.5, leads to decreases in labor productivity. An estimation made by the authors suggests that positive labor productivity effects represented 25% of the total benefits obtained with improvements in air quality. He et al. (2019) obtained similar results for day-to-day fluctuations in labor productivity at two manufacturing cities in China. They also found significant, albeit relatively small, adverse labor productivity effects resulting from more prolonged exposure to pollution. More precisely, a substantial increase in PM2.5 sustained over 25 days would reduce daily productivity by 1%.

Zhang et al. (2018) further extended the relevance of the environment-productivity link to a larger number of firms. They employed detailed data from a half million Chinese manufacturing plants over 1998–2007 to estimate the effects of temperature variations on firm-level total factor productivity, factor inputs, and output. High temperatures are relevant because they can reduce labor productivity by causing fatigue and cognitive impairment in workers. They detected that one day with temperature above 90°F reduces manufacturing production by 0.45%. This result is similar across labor- and capital-intensive firms, thus suggesting that high temperatures may lower both labor and capital productivity. A simulation carried out by the authors obtained that if no additional adaptation or mitigation policies are implemented, by mid 21st century, climate change will reduce Chinese manufacturing output by 12% per year.

Robust evidence on the negative impact of the concentration of pollution on labor productivity has also been collected for the service sector. Chang et al. (2019) found that higher levels of PM2.5 concentration reduce labor productivity in two call centers in China. Kahn and Li (2019) provided evidence for the highest-skilled and well compensated workers of public sector in China. They examined decisions made by 135,924 judges in 9.7 million criminal and civil cases adjudicated from 2014 to 2016 and found that judges perform less efficiently during polluted days: a 1% increase in PM2.5 leads to a 19.8% increase in the case handling time. In these days judges also have trouble working on more complex cases and are more likely to make decisions that are appealed. Khanna et al. (2021) found that skilled workers emigrate more in response to pollution than the unskilled, which results in higher compensation to skill in regions away from which more educated workers migrate. They obtained that workers' sensitivity to pollution may explain a substantial portion of the productivity gap between regions in China.

Climate change may severely amplify these adverse effects that occur in different work settings, which suggests that in a not too distant a future the environment may operate as a new source of development trap (Oliveira and Lima, 2020). The channel through which labor productivity is negatively affected by pollution operates via observable and unobservable effects, such as health conditions, cognitive abilities, and effort on the job, changing according to the specific pollutant and its time horizon of influence (Graff Zivin and Neidell, 2013; Nauze and Severnini, 2021). For generality sake, the mechanism embedded in our model framework does not try to formalize any specific labor productivity effect arising from a particular pollutant.

Following the Kaldorian perspective, it is also supposed that the use of capital goods in the production process increases the rate of technical progress in the economy, positively impacting on labor productivity (Kaldor, 1966). The model thus balances both the positive effect of the capital stock and the negative effect of pollution concentration by focusing on the ratio of capital to pollution concentration, $\kappa = K/\Omega$, as the key endogenous determinant of labor productivity. The rate of growth of labor productivity, $\hat{a}$, can then be linearly decomposed as being positively affected by the rate of growth of the ratio of capital to pollution concentration, $\hat{\kappa} = \hat{K} - \hat{\Omega}$:

$$\hat{a} = \alpha_0 + \alpha_1 \hat{K} - \alpha_2 \hat{\Omega}, \tag{4}$$

in which $\hat{a} \equiv (da/dt)/a$, while $\alpha_i \in \mathbb{R}_+$ are parameters. The first and the second term of (4) constitute the standard specification of the Kaldor-Verdoorn law, according to which the rate of growth of labor productivity varies positively with the rate of capital accumulation (Kaldor, 1966). The Kaldor–Verdoorn law has been subject to extensive empirical testing, which in general supports its validity (Fingleton and McCombie, 1998; Magacho and McCombie, 2018; Chandra and Sandilands, 2021). However, if the concentration of pollution is growing relatively fast, potentially damaging workers' health conditions, pollution concentration may offset the aggregate demand forces enhancing labor productivity, and thus we have the third term in (4).

Kaldor does not seem to have explicitly addressed environmental pollution issues in his published works. When describing his two sector model, Kaldor (1975, 1976, 1986) sometimes refers broadly to land as "natural environment" (Thirlwall, 1986), albeit not necessarily in the current sense. But Kaldor seemed to be aware of and concerned with the possible limits to growth imposed by natural resources (broadly defined). In the analysis of his technical progress function, Kaldor (1957) recognizes that “the scarcity of natural resources would put increasing obstacles to the expansion of output, even when population is constant - in which case, given the rate of invention and innovation, the growth of productivity at any given rate of investment will be slowed” (p.616).

The labor productivity is a key measure determining the wage share in income, σ:

$$\sigma = \frac{W}{Pa}, \tag{5}$$

in which W stands for the nominal wage, while P stands for the price level. The price equation is given by a markup factor, $z > 1$, over the unit labor cost: $P = zWa^{-1}$. The existence of surplus labor ensures a sufficiently elastic labor supply and implies that a rise in Ω, which reduces a, will increase the unit labor cost, thus lowering the profit share in income, $\pi = 1 - \sigma$. We assume that σ is given in the short run, varying over time according to the rates of growth of the nominal wage, $\hat{W}$, the price level, $\hat{P}$, and labor productivity, $\hat{a}$:

$$\hat{\sigma} = \hat{W} - \hat{P} - \hat{a}. \tag{6}$$

The rates of growth of the price level and the nominal wage are determined within a modified framework of conflicting class claims on the social product drawing on the pioneering formulation by Rowthorn (1977). Following Lima et al. (2021), labor-selling workers and firm-owner capitalists have desired rates of growth of the nominal wage and the price level, respectively, which fully materialize into actual rates in the inherent conflict over the functional distribution of the available social product.

The negative effect of pollution concentration on labor productivity occurring through the *pollution-adjusted* Kaldor-Verdoorn effect, with its resulting rise in the unit labor cost, is *anticipated* by firms. In the absence of clean technological change, firms establish a desired price inflation which varies positively with the rate of growth of pollution concentration, $\hat{\Omega}$, in a preemptive attempt to protect their profitability.[1] Rezai et al. (2018) also suppose that pollution concentration impacts negatively on profitability, but in their model, the profit rate is linearly decomposed as a negative function of the pollution concentration. In our model, as described below, a further response of firms to the concentration of pollution is to allocate a fraction of their mass of profits to pollution abatement.

Accordingly, the price level, P, varies over time at a rate of growth which is equal to firms' desired rate of growth of the price level, $\hat{P}_f$, as given by:

$$\hat{P} = \hat{P}_f = \lambda\hat{\Omega}, \tag{7}$$

in which $\lambda \in \mathbb{R}_+$ is a parameter measuring the sensitivity of $\hat{P}_f$ to $\hat{\Omega}$. In a broad sense, this formulation is consistent with the empirical evidence on the pass-through of pollution costs to prices (Grainger and Kolstad, 2010; Fabra and Reguant, 2014).

Workers' desired nominal wage inflation also varies positively with the rate of growth of pollution concentration. At least two reasons motivate this reasonable response on the part of workers. First, workers *anticipate* that firms adjust $\hat{P}$ according to $\hat{\Omega}$ in order to protect their profitability, which exerts a downward pressure on the real wage and thereby in the wage share in the social product. The second reason is that workers conceivably seek to meet a sufficient level of security needs, such as good health conditions. Admittedly, an increase in $\hat{\Omega}$, with everything else remaining constant, by causing a lower (higher) rate of growth of labor productivity (unit labor costs), raises the rate of growth of the wage share in the social product. However, a higher rate of growth of pollution concentration also increases the detrimental effects of pollution on the general health conditions of workers. Therefore, an increase in $\hat{\Omega}$ leads workers to desire, bargain for and succeed in obtaining a higher rate of nominal wage inflation.

There is empirical evidence supporting such a pollution compensation mechanism. In China, some multinational companies have been designing pollution compensation mechanisms to maintain and attract the labor force to more polluted regions. For instance, Panasonic designed a "pollution allowance" program, while Coca-Cola introduced a "haze danger subsidy" (Chai et al., 2020). There have also been empirical attempts to measure the pollution wage premium compensation. Using a sample of 81 industrial classes and a range of pollution measures in the UK, Cole et al. (2009) estimate a positive wage premium associated with working in a dirty industry. The estimated average wage premium is about 0.5% of the weekly nominal wage, while for workers in one of the five dirtiest industries the wage premium rises to 15%.

Hence, our framework of conflicting claims on the social product features the nominal wage growing at a rate which is equal to workers' desired rate of growth of the nominal wage, $\hat{W}_l$:

$$\hat{W} = \hat{W}_l = \mu\hat{\Omega}, \tag{8}$$

in which $\mu \in \mathbb{R}_+$ is a parameter measuring the sensitivity of $\hat{W}_l$ to $\hat{\Omega}$. Both capitalists and workers are always able to have their desired inflation rate fully translated into the respective actual inflation rate (price inflation rate in the case of the former, wage inflation rate in the case of the latter) in the conflict over income shares. The variation of the wage share depends on the relative bargaining power of workers and capitalists alongside the behavior of the labor productivity, the behavior of the pollution concentration playing a central influencing role.

2.1 Pollution abatement and the short-run equilibrium

The short-run is defined as the period in which N, the labor supply, K, Ω, a, P, and W are all given. As intimated earlier, firms allocate a fraction, $\theta \subset (0, 1) \in \mathbb{R}$, of the mass of gross profits, $\Pi = (1 - \sigma)X$, to an in-house pollution abatement activity. For simplicity and tractability, θ is assumed to be an exogenously given constant. Formally:

$$A = \theta(1 - \sigma)X. \tag{9}$$

This financing scheme is consistent with the polluter-pays principle, according to which the polluter bears the expenses of carrying out the pollution prevention, but we abstract from explicitly modeling the government regulatory system enforcing the abatement rule followed by firms. This formulation is related to Taylor et al. (2016) and Rezai et al. (2018), which scale the spending on "mitigation" to the level of output. For simplicity and tractability, as in these related papers, the pollution abatement activity is not explicitly modeled.

Aggregate consumption is the sum of workers' consumption out of wage income and capitalists' consumption out of profit income net of firms' expenditures on pollution abatement,

$C = [c_l\sigma + c_f(1-\theta)(1-\sigma)]X$, where c_l and c_f are the propensities to consume out of wage and net profit income, respectively. Following Kaldor (1955), we assume that profit receivers have a lower propensity to consume than wage earners. For simplicity, we further assume that workers as a class spend all their wage income in consumption, so that $c_l = 1$, while capitalists as a class save all their net profit income, so that $c_f = 0$. As a result, aggregate consumption is represented by $C = \sigma X$.

The investment function is defined as $I = g^I K$. The desired rate of capital accumulation, g^I, is described by a modified Marglin and Bhaduri (1990) function. It is a convenient way to generalize a Robinson (1962) investment function by allowing each individual component of the profit rate to have an independent influence on investment plans. More precisely, g^I is linearly driven by an autonomous component, $\eta \in \mathbb{R}_+$, the rate of capacity utilization, $u \equiv \frac{X}{K}$, and the net profit share in income:

$$g^I = \eta + \eta_u u + \eta_\pi(1-\theta)(1-\sigma), \tag{10}$$

with $\eta_u, \eta_\pi \in \mathbb{R}_+$. This specification adds some intriguing insights to the model as shown later.

Substituting the consumption, investment and abatement functions in the supply-demand equilibrium condition for the goods market, $X = C + I + A$, and normalizing it by K, the short-run equilibrium rate of capacity utilization is:

$$u = \frac{\eta + \eta_\pi(1-\theta)(1-\sigma)}{(1-\theta)(1-\sigma) - \eta_u}, \tag{11}$$

in which the Keynesian stability condition, $(1-\theta)(1-\sigma) > \eta_u$, is supposed to hold, which also ensures that the equilibrium value in (11) is positive. The existence of surplus labor in combination with excess capital capacity implies that u is the variable which adjusts to clear the goods market. The effect of a higher fraction of profits spent in pollution abatement, θ, on aggregate effective demand and hence the short-run equilibrium capacity utilization is given by:

$$u_\theta \equiv \frac{\partial u}{\partial \theta} = \frac{(u - \eta_\pi)(1-\sigma)}{(1-\theta)(1-\sigma) - \eta_u} > 0, \tag{12}$$

which is positive. Given that expenditures on abatement constitute a source of aggregate effective demand, and capitalists save all their net profit income, such expenditures behave as forced dissaving. This facet of the model captures the idea that the production of abatement goods and the abatement activity itself can also be polluting (Brock and Taylor, 2010).

Differentiating the short-run equilibrium rate of capacity utilization with respect to the wage share yields:

$$u_\sigma \equiv \frac{\partial u}{\partial \sigma} = \frac{(u - \eta_\pi)(1-\theta)}{(1-\theta)(1-\sigma) - \eta_u} > 0, \tag{13}$$

which has the same sign as $u - \eta_\pi$, which can be checked to be positive.

Supposing away capital depreciation and using (11) in (10), the rate of capital accumulation in the short-run equilibrium, g, which is also the output growth rate in this economy producing a single good, is:

$$g = (1-\theta)(1-\sigma)\left[\frac{\eta + \eta_\pi(1-\theta)(1-\sigma)}{(1-\theta)(1-\sigma) - \eta_u}\right]. \tag{14}$$

By differentiating (14) with respect to the wage share, we have:

$$g_\sigma \equiv \frac{\partial g}{\partial \sigma} = (1-\theta)\left[\frac{\eta_u u - \eta_\pi(1-\theta)(1-\sigma)}{(1-\theta)(1-\sigma)-\eta_u}\right]. \tag{15}$$

Thus, the impact of a change in the wage share on the short-run equilibrium rate of capital accumulation is ambiguous, leading to the distinction between the so-called wage- and profit-led growth regimes. A profit-led growth regime obtains when $\eta_\pi(1-\theta)(1-\sigma) > \eta_u u$, which yields a negative sign in (15), whereas a wage-led growth regime arises when $\eta_\pi(1-\theta)(1-\sigma) < \eta_u u$. Note that, all else constant, the higher the fraction of gross profits spent on pollution abatement, the less likely it is that the profit-led growth regime obtains. The intuition is that expenditures on pollution abatement are covered out of profits.

Meanwhile, the effect of a change in θ on g is given by:

$$g_\theta \equiv \frac{\partial g}{\partial \theta} = \frac{(1-\sigma)[\eta_u u - \eta_\pi(1-\theta)(1-\sigma)]}{(1-\theta)(1-\sigma)-\eta_u}. \tag{16}$$

Intuitively, therefore, in a profit-led (wage-led) regime, a rise in the fraction of gross profits spent on pollution abatement lowers (raises) capital accumulation and hence output growth in the short-run equilibrium.

3 The behavior of the model in the long run

In the long run, the short-run equilibrium values of the variables are always attained, with the economy moving over time due to changes in K, N, a, P, W, and Ω. In order to focus on the relationship between pollution concentration, income distribution, and capital accumulation, our analytical framework innocuously supposes that the growth rate of the labor supply is determined endogenously as $\hat{N} = \hat{K} - \hat{a}$. This means that $\hat{N}$ adjusts to g and $\hat{a}$ by means of a continual re-creation of the reserve army according to the needs of capitalist production, a familiar view in neo-Marxian descriptions of the labor market (Marglin, 1984). As a result, the ratio of capital to labor supply in productivity units, $v \equiv K/Na$, remains constant, so that the employment rate, $e = \frac{L}{X}\frac{X}{K}\frac{K}{N} = uv$, always varies in the same direction as capacity utilization; if the latter becomes stationary in the long run, so does the former.

Using (2), (3), and (9), the rate of growth of pollution concentration is given by:

$$\hat{\Omega} = [b - \theta(1-\sigma)]u\kappa - \omega, \tag{17}$$

where $u\kappa \equiv \frac{X}{K}\frac{K}{\Omega}$. The impact of σ on $\hat{\Omega}$ is given by:

$$\frac{\partial \hat{\Omega}}{\partial \sigma} = \theta u\kappa + [b - \theta(1-\sigma)]u_\sigma\kappa > 0. \tag{18}$$

Recall from (13) that an increase in the wage share raises capacity utilization and hence the gross flow of pollution, while (9) implies that the flow of abatement per unit of output varies positively with the profit share. Yet we supposed earlier the real-world situation that the net flow of pollution is positive, which, using (2) and (9), implies that $b > \theta(1-\sigma)$ and thereby the positive sign in (18). Thus, no matter whether the output growth regime is wage-led or profit-led, the growth of pollution concentration is wage-led. As shown shortly, the character of the output growth regime nonetheless plays a central role in the (in)stability properties of the long-run equilibrium (or balanced growth path) of the environment-economy system.

As X is scaled by the size of the economy, which we measure by K, the ratio of capital to pollution concentration is a key variable participating in the feedback loops between pollution concentration and functional distribution and growth of the social product. Thus, κ is a state variable of our dynamic system, with (14) and (17) implying that its growth rate is:

$$\hat{\kappa} \equiv g - \hat{\Omega} = g - [b - \theta(1-\sigma)]u\kappa + \omega. \tag{19}$$

Given the structure of the model, the other state variable is the wage share. Using (4), (6), (7), (8), and (17), the rate of growth of σ is:

$$\hat{\sigma} \equiv \hat{W} - \hat{P} - \hat{a} = (\mu - \lambda + \alpha_2)[b - \theta(1-\sigma)]u\kappa - \alpha_1 g - \epsilon, \tag{20}$$

in which $\epsilon \equiv \alpha_0 + (\mu - \lambda + \alpha_2)\omega$.

The stability properties of the environment-economy dynamic system represented by (19) and (20) are explored in the appendices. A distinctive characteristic of such a system is that its asymptotic stability depends on the prevailing output growth regime. When output growth is wage-led, the balanced growth path with $\hat{\kappa} = \hat{\sigma} = 0$ is asymptotically (saddle-point) unstable. When output growth is profit-led, asymptotic stability becomes possible, but the system exhibits fluctuations in the wage share and the ratio of capital to pollution concentration when converging to the balanced growth path. The instability of a wage-led output growth regime arises from the three-way relationship between pollution concentration and the functional distribution and growth of the social product, in which the pollution abatement mechanism plays a key role. In fact, recall from (9) that the pollution abatement per unit of output is profit-led, as it varies positively with the profit share, while per (18) the growth rate of the concentration of pollution is wage-led, meaning that it varies positively with the wage share. These features also help to explain why a profit-led output growth regime is potentially asymptotically stable.

Hence, the behavior of the environment-economy dynamic system depends on the output growth regime, the *pollution-adjusted* Kaldor-Verdoorn effect and the class conflict over the functional distribution of the social product. For analytical tractability and clearness of the causality channels involved, we focus on a limit case of each output growth regime. This simplifying focus has no qualitative bearing on our results for the balanced growth path and is formally consistent with the short-run equilibrium analysis carried out in the preceding section.

We start by exploring the limit case of a wage-led output growth regime arising from setting $\eta_\pi = 0$ in (10), which yields a positive sign in (15). The values of κ and σ satisfying $\hat{\kappa} = \hat{\sigma} = 0$ are respectively:

$$\kappa^* = \frac{(1-\theta)(\alpha_0 + \gamma\omega)\eta_u}{b(1-\theta)(\alpha_0 - \gamma\eta) - \theta\alpha_0\eta_u}, \tag{21}$$

$$\sigma^* = 1 - \frac{\alpha_0\eta_u}{(1-\theta)(\alpha_0 - \gamma\eta)}, \tag{22}$$

where $\gamma \equiv \mu - \lambda + \alpha_2 - \alpha_1$. The requirement for $\sigma^* > 0$ in (22) is that $(1-\theta)(\alpha_0 - \gamma\eta) > \alpha_0\eta_u$, a necessary condition for which is that $\alpha_0 > \gamma\eta$, which guarantees that $\sigma^* < 1$. Meanwhile, the requirement for $\kappa^* > 0$ in (21) is that $b(1-\theta)(\alpha_0 - \gamma\eta) > \theta\alpha_0\eta_u$, a necessary condition for which is also that $\alpha_0 > \gamma\eta$. Substituting (22) into (11) with $\eta_\pi = 0$ yields the long-run equilibrium rate of capacity utilization:

$$u^* = \frac{\alpha_0 - \gamma\eta}{\eta_u \gamma}, \tag{23}$$

which depends on the parameters of the investment function in (11) simplified with $\eta_\pi = 0$, the parameters of the productivity growth in (4) and the parameters denoting the sensitivity of the rates of growth of the price level and the nominal wage to the rate of growth of pollution concentration in (7) and (8), respectively. Meanwhile, substituting (23) into (10) with $\eta_\pi = 0$ yields the long-run equilibrium output growth:

$$g^* = \frac{\alpha_0}{\mu - \lambda + \alpha_2 - \alpha_1}, \tag{24}$$

which depends on the same parameters as the long-run equilibrium rate of capacity utilization in (23) except the parameters of the simplified version of the investment function in (11). Recalling that the balanced growth path features a constant ratio of capital to pollution concentration, so that $g^* = \hat{\Omega}^*$, substituting (24) into (4) yields the productivity growth rate in the long-run equilibrium:

$$\hat{a}^* = \alpha_0 \left[1 - \frac{\alpha_2 - \alpha_1}{\mu - \lambda + \alpha_2 - \alpha_1}\right], \tag{25}$$

which depends on the same parameters as the long-run equilibrium rate of output growth in (24). A stylized fact about labor productivity is that it grows at a roughly constant rate over long periods of time (Kaldor, 1961), which is yielded by (25) when $\mu > \lambda$. A positive productivity growth rate in the balanced growth path requires that the nominal wage inflation be more responsive to changes in the growth rate of pollution concentration (which is equal to the growth rate of output) than the price inflation. Notice that the same condition given by $\mu > \lambda$ guarantees that the real wage grows at the same constant rate as labor productivity in a balanced growth path featuring a positive rate of growth of output (and hence of pollution concentration). This is in keeping with the stylized fact that the shares of the social product accruing to labor and capital are nearly constant over long periods of time (Kaldor, 1961). We focus on the most common real-world case of a positive long-run equilibrium output growth, so we further assume that $\mu - \lambda > \alpha_1 - \alpha_2$, which is automatically satisfied when $\alpha_1 \leq \alpha_2$ in (4).

As shown in Appendix A, the sign of the determinant of the Jacobian matrix of the system composed by (19) and (20), when evaluated at any economically relevant long-run equilibrium (κ^*, σ^*), ultimately depends on the prevailing output growth regime. As confirmed in Appendix B, the determinant of the Jacobian matrix for the considered limit case of a wage-led regime is negative, which identifies the respective balanced growth path as (saddle-point) unstable. For this reason, we abstain from exploring the impact of parametric shifts on the rates of capacity utilization, output growth, and productivity growth in (23)-(25), respectively.

This instability is portrayed in Figure 1, the details of which are in Appendix B. As we are exploring the most common real-world case of a positive net flow of pollution, J_{11} is negative. The growth rate of the ratio of capital to pollution concentration varies negatively with the level of this ratio, so that $\hat{\kappa}$ is positive (negative) below (above) the $\hat{\kappa} = 0$ isocline. Intuitively, therefore, the rate of growth of the wage share varies positively with the ratio of capital to pollution concentration, so that $J_{21} > 0$. Meanwhile, as σ increases, the concentration of pollution grows at a higher rate than the capital stock, so that the growth rate of κ undergoes a steady decrease, yielding $J_{12} < 0$. The concentration of pollution grows at a higher rate than the capital stock due to the fall in the flow of abatement, which is financed out of profits. It is also intuitive why J_{22} is positive, so that the growth rate of the wage share is negative (positive) to the left (right) of the $\hat{\sigma} = 0$ isocline. Thus, both isoclines are negatively sloped in the neighborhood of (κ^*, σ^*) in (21)-(22).

Figure 1 around here.

The unstable dynamic behavior arises from several feedback effects.As capacity utilization varies positively with the wage share, so does the gross flow of pollution per unit of capital. As the flow of expenditures on abatement per unit of output varies negatively with the wage share, the net flow of pollution per unit of output and the growth rate of pollution concentration vary positively with the wage share. The rates of capital accumulation and output growth are positively related to the wage share, while the growth rate of the wage share is the net result of the growth rate of the real wage, which varies positively with the growth rate of pollution concentration, and the growth rate of labor productivity, which varies positively with the growth rate of output and negatively with the growth rate of pollution concentration. In the balanced growth path, the growth rate of the real wage is equal to the growth rate of labor productivity, while the growth rate of pollution concentration is equal to the growth rate of output.

Rezai et al. (2018) develop a Kaleckian model of climate change and output growth, in which the abatement share is exogenously determined by the government as a proportion of aggregate income. Under certain conditions, such an abatement policy can avoid the occurrence of climate instability in the wage-led output growth regime explored in the model (the profit-led regime is not considered). In our model framework, meanwhile, pollution abatement is an activity voluntarily carried out by firms to protect their profitability. As the flow of abatement expenditures is a share of the mass of gross profits, pollution abatement contributes to unstabilize instead of stabilizing an environment-economy system featuring a wage-led output growth regime. The unique and unstable balanced growth path features the ratio of capital to pollution concentration varying positively with the share of gross profits devoted to pollution abatement (per (21)), but it also features the wage share varying negatively with the latter (per (22)).

Let us now explore the limit case of a profit-led output growth regime arising from setting $\eta_u = 0$ in (10), which yields a positive sign in (15). For simplicity, we also make the innocuous assumption that $\eta = 0$. The values of κ and σ satisfying $\hat{\kappa} = \hat{\sigma} = 0$ are respectively:

$$\kappa^* = \frac{(1-\theta)(\alpha_0 + \gamma\omega)}{\gamma b \eta_\pi (1-\theta) - \alpha_0 \theta}, \tag{26}$$

$$\sigma^* = 1 - \frac{\alpha_0}{\gamma \eta_\pi (1-\theta)}, \tag{27}$$

recalling that $\gamma \equiv \mu - \lambda + \alpha_2 - \alpha_1$. The requirement for $\sigma^* > 0$ in (27) is that $\eta_\pi(1-\theta) > \alpha_0/\gamma$, while the requirement that $\sigma^* < 1$ is automatically satisfied. As a result, a sufficient condition for $\kappa^* > 0$ in (26) is that $b \geq \theta$, but $\kappa^* > 0$ will also arise with $b < \theta$ depending on the relative size of the other parameters involved. Interestingly, substituting (26) into (14) with $\eta_u = \eta = 0$ yields the same value of the long-run equilibrium output growth as in (24), and hence the same value of the productivity growth in the long-run equilibrium as in (25). Yet, the assumption that $\eta_u = \eta = 0$ yields the following long-run equilibrium capacity utilization:

$$u^* = \eta_\pi. \tag{28}$$

In fact, substituting (27) into (10) with $\eta_u = \eta = 0$ yields the long-run equilibrium output growth in (24). Thus, the two limit cases of output growth regime under consideration feature the same long-run equilibrium output growth and productivity growth, but two different long-run equilibrium rates of capacity utilization, which per (19)-(20) contributes to explain why (κ^*, σ^*) also differs across growth regimes.^{2} As will be seen shortly, the stability of the balanced growth path of the system does not depend on its featuring rate of output growth per se, but on how such a rate varies with the distribution of the social product between wages and profits.

As confirmed in Appendix C, the determinant of the Jacobian matrix of the dynamic system composed by (19) and (20), when evaluated at the long-run equilibrium values (κ^*, σ^*) in (26)-(27), is positive. As a result, the balanced growth path of the considered limit case of a profit-led regime is asymptotically stable when the trace of the same Jacobian matrix is negative. This requires that the absolute magnitude of the negative response of the growth rate of the ratio of capital to pollution concentration to a change in the level of this ratio (which has a stabilizing effect) is greater than the magnitude of the positive response of the growth rate of the wage share to a change in this share (which has a destabilizing effect). This stability configuration is displayed in Figure 2, the details of which are in Appendix C. As in the limit case of wage-led regime explored earlier, the respective isoclines are negatively sloped in the neighborhood of the values (κ^*, σ^*) in (26)-(27), but now the $\hat{\kappa} = 0$ isocline is steeper than the $\hat{\sigma} = 0$ isocline.

Suppose that the system starts at point A. The rising wage share lowers capital accumulation and abatement expenditures. The net flow of pollution is increasing, and pollution concentration is growing at a higher rate than capital accumulation, so κ is falling. The rise in the wage share goes on while the *pollution-adjusted* Kaldor-Verdoorn effect on productivity growth is weaker than the real wage growth effect, but a reversal eventually occurs and region IV is entered. Now the falling wage share raises capital accumulation and abatement expenditures, but pollution concentration is still growing faster than the capital stock, so κ keeps falling. The effect of falling levels of σ and κ on capital accumulation and abatement expenditures is the system eventually entering region III, where σ keeps falling but κ is now growing due to the capital stock growing faster than the concentration of pollution. Even though the *pollution-adjusted* Kaldor-Verdoorn effect on productivity growth is still stronger than the real wage growth effect, another reversal eventually occurs and region II is entered. Now the *pollution-adjusted* Kaldor-Verdoorn effect on productivity growth is weaker than the real wage growth effect, so σ starts increasing and κ continues to rise, the result of which is that the system eventually re-enters region I. Thus, the system undergoes clockwise cyclical fluctuations when converging to the balanced growth path.

Figure 2 around here.

It is worth exploring how some key variables respond to parametric changes in the balanced growth path, especially in the limit case of a profit-led regime (for which, unlike the wage-led regime, a stable balanced growth path is possible). In both growth regimes, the common output growth in (24) and the common productivity growth in (25) vary positively with α_0 and α_1 (the Verdoorn coefficient) and negatively with α_2 (the pollution coefficient), the parameters of the endogenous productivity growth in (4). Output growth is positively (negatively) related to λ (resp. μ), which measures the sensitivity of price (wage) inflation to pollution concentration growth, while productivity growth is positively (negatively) related to the sensitivity of wage (price) inflation to pollution concentration growth. In the profit-led (wage-led) regime, therefore, the wage share featured in the balanced growth path expectedly responds to each of the above parameters in the opposite (same) direction as output growth. In fact, (22) and (27) show that, for example, while a higher Verdoorn coefficient (α_1) unambiguously yields higher output growth and productivity growth, the accompanying response of the wage share is positive (negative) in the wage-led (profit-led) growth regime.

Interestingly, there are parametric shifts that affect the wage share but not output or productivity growth in the balanced growth path. In the limit case of a profit-led regime, a higher sensitivity of endogenous capital accumulation to the net profit share in (10) (with $\eta = \eta_u = 0$), as measured by η_π, yields a higher wage share (and higher capacity utilization in (28)) but no change in the growth rates of output and productivity. In the limit case of a wage-led regime, a higher sensitivity of endogenous capital accumulation to capacity utilization in (10) (with $\eta_\pi = 0$), as measured by η_u, yields a lower wage share but no change in the growth rates of output and productivity (the same applies to the autonomous component in (10), η). Meanwhile, a higher share of gross profits allocated to pollution abatement, as measured by θ in (9), yields a lower wage share but no change in either capacity utilization or the growth rates of output and productivity in both growth regimes. Nevertheless, it can be checked from (21) and (26) that a higher θ raises the ratio of capital to pollution concentration (κ^*) in both growth regimes, so that the level of pollution concentration per unit of capital capacity is lower. The same expressions show that either a higher rate of natural pollution dissipation, ω, or a lower coefficient of gross pollution creation per unit of output, b, also raise κ^*, doing so without affecting the wage share in (22) and (27). Additionally, in the limit case of a profit-led regime, κ^* varies positively with λ, the sensitivity of price inflation to pollution concentration growth, and α_1, the Verdoorn coefficient, and negatively with μ, the sensitivity of wage inflation to pollution concentration growth, and α_2, the pollution coefficient in the productivity growth in (4). In the limit case of a wage-led regime, the impact of the same parametric shifts are all inverted.

4 Conclusions

From the perspective of the environment-economy system, economic growth can arguably be seen as a double-edged sword. While an increase in output growth boosts labor productivity growth, the resulting rise in the scale of output production also increases the flow of pollution. If the concentration of pollution is relatively persistent, environmental degradation may offset the aggregate demand forces enhancing labor productivity. Against this backdrop, we set forth an analytical framework to explore the operation and implications of such a double impact of economic growth, which leads to what we dub *pollution-adjusted* Kaldor-Verdoorn effect. This pollution-generating attribute of output production brings a 21st century perspective to the well-established empirical regularity known as Kaldor-Verdoorn law, thus contributing to the substantial literature inspired by Kaldor's seminal contributions on the macrodynamics of economic growth, as well as to the literature on ecological macromodels.

The *pollution–adjusted* Kaldor-Verdoorn effect becomes a further key factor in the inherent conflict over the functional distribution of the social product between wages and profits, with the concentration of pollution coming in as a new influencing factor. We explore such an inherent distributive conflict with a modified analytical framework of conflicting class claims on the social product drawing on the pioneering formulation by Rowthorn (1977). As an individual response to the productivity-reducing impact of the pollution concentration, in the absence of public environmental policies, firms attempt to safeguard their profitability by allocating a given portion of their profits to pollution abatement and adjusting the growth rate of the price level to the growth rate of pollution concentration. Meanwhile, workers successfully bargain for a rate of growth of the nominal wage aimed at preserving their real wage and thereby living standards (which also includes health conditions). The resulting conflicting class claims on the available social product placed by workers and capitalists play a significant role in the dynamic stability properties of the environment-economy system.

The dynamic stability of the balanced growth path of the environment-economy system does not depend on its featuring output growth rate per se, but on how such a rate varies with the functional distribution of output between wages and profits. This functional distribution plays a key role on aggregate demand formation and thus output growth determination, as well as on the covering of the expenditures incurred with pollution abatement. When output growth varies positively with the share of wages in the social product, which defines a wage-led growth regime, the balanced growth path is (saddle-point) unstable. Meanwhile, when output growth varies positively with the profit share in the social product, which characterizes a profit-led growth regime, stability is a possibility, but the system experiences fluctuations in the wage share and the ratio of capital to pollution concentration when converging to the balanced growth path.

Both long-run configurations feature a complex trilemma involving output growth, pollution concentration growth, and the functional distribution of the social product. When output growth varies positively with the wage share, a relatively high wage share in the long-run equilibrium is accompanied by a relatively high rate of growth of pollution concentration. Meanwhile, when output growth varies positively with the profit share, the system can stabilize in the long run with a relatively high wage share accompanied by a relatively low rate of growth of pollution concentration growth. The reason is that the long-run equilibrium features the rates of output growth and pollution concentration growth being equal to each other. The trilemma is therefore characterized by the impossibility of the system achieving more than two out of the following three outcomes in the long-run equilibrium: a higher share of wages in the social product, a higher growth rate of the social product, and a lower growth rate of pollution concentration.

The results derived from our model framework raise interesting questions worthy of further research. The mechanism of pollution abatement considered here, which is financed by firms out of profits, contributes to the instability of the system in the long run under a wage-led growth regime. An alternative or additional pollution-controlling mechanism should be considered in such a context, which might be a green tax on aggregate income directed to the achievement of a desirable emissions target. The choice of such an alternative or additional pollution-controlling mechanism should also take into consideration how it would impact the functional distribution and growth of the social product and how the reaction of these variables would feedback into the pollution dynamics. Besides, our considered mechanism of pollution abatement does not ensure the stabilization of the level of pollution concentration in the long-run equilibrium, as such a level grows at the same rate as the capital stock and the social product in that equilibrium. Different specifications of an environmental policy intended to achieve a sustainable level of pollution concentration in the long run should be explored, but also taking into due account how each considered policy would affect the functional distribution and growth of the social product and how the response of these variables would in turn feedback into the dynamics of the concentration of pollution. The interactions between the functional distribution and growth of the social product and the concentration of pollution explored in this paper are likely even more complex when the considered environmental policy involves providing incentives to firms to promote technical change leading to cleaner production of goods and services.

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Notes

[1] As aptly stressed by Rowthorn (1977, p.1): "We must begin by distinguishing between two concepts which are often confused but which are really quite distinct: expectation and anticipation. The former refers to a state of mind, whereas the latter refers to actual behaviour. To *expect* something means simply to believe with greater or less confidence that it will occur, whereas to *anticipate* something means both to expect it and to act upon this expectation." (Original emphasis).

[2] As we assumed earlier that the supply of labor grows endogenously as given by $\hat{N} = \hat{K} - \hat{a}$, both growth regimes feature $\hat{N}^* = \alpha_0(1-\mu+\lambda)/\gamma$ in the balanced growth path. Given that we also assumed that $\mu > \lambda$ and $\gamma > 0$, a positive $\hat{N}^*$ is ensured by the reasonable further assumption that $\mu - \lambda < 1$.

Appendix A: Qualitative properties of the dynamic system

The *Jacobian* matrix of partial derivatives of the dynamic system is:

$$J(\kappa, \sigma) = \begin{bmatrix} -[b-\theta(1-\sigma)]u & g_\sigma - \theta u\kappa - [b-\theta(1-\sigma)]u_\sigma\kappa \\ (\mu-\lambda+\alpha_2)[b-\theta(1-\sigma)]u & (\mu-\lambda+\alpha_2)[\theta u + [b-\theta(1-\sigma)]u_\sigma]\kappa - \alpha_1 g_\sigma \end{bmatrix},$$

the determinant of which is:

$$|J| = -\gamma[b-\theta(1-\sigma)]u g_\sigma. \tag{A1}$$

While a wage-led regime ($g_\sigma > 0$) features $|J| < 0$, a profit-led regime ($g_\sigma < 0$) features $|J| > 0$.

Appendix B: Local (in)stability analysis of a wage-led regime

Let us set (19) and (20) to zero under the assumption that $\eta_\pi = 0$ to get the respective isoclines, but we will of course confine attention to the economically relevant intervals given by $\kappa > 0$ and $0 < \sigma < 1$ for the state variables:

$$\kappa^\kappa = \frac{(1-\theta)(\eta+\omega)(1-\sigma) - \eta_u\omega}{\eta[b-\theta(1-\sigma)]}, \tag{B1}$$

$$\kappa^\sigma = \frac{(\alpha_0 + Z\omega + \alpha_1\eta)(1-\theta)(1-\sigma) - (\alpha_0 + Z\omega)\eta_u}{Z\eta[b-\theta(1-\sigma)]}, \tag{B2}$$

where $Z \equiv \mu - \lambda + \alpha_2 > 0$, the sign of which is given by our assumption in the text that $\mu > \lambda$ to ensure that productivity grows at a roughly constant rate over long periods of time. These isoclines are negatively sloped and their intercepts in the κ-axis are respectively:

$$\kappa^\kappa|_{\lim_{\sigma\to 0}} = \frac{(1-\theta)(\eta+\omega) - \eta_u\omega}{\eta(b-\theta)},$$
$$\kappa^\sigma|_{\lim_{\sigma\to 0}} = \frac{(\alpha_1\eta + Z\omega + \alpha_0)(1-\theta) - (\alpha_0 + Z\omega)\eta_u}{Z\eta(b-\theta)}.$$

In order to ensure that $0 < \kappa^\kappa|_{\lim_{\sigma\to 0}} < \kappa^\sigma|_{\lim_{\sigma\to 0}}$, which is the case portrayed in Figure 1, we assume that $(\gamma\eta - \alpha_0)(1-\theta) + \eta_u\alpha_0 < 0$, a necessary condition for which is that $\gamma\eta < \alpha_0$, as assumed in the text to yield an economically relevant value of the wage share in (22). These isoclines have intercepts in the σ-axis respectively given by:

$$\sigma^\kappa|_{\lim_{\kappa\to 0}} = 1 - \frac{\eta_u\omega}{(1-\theta)(\eta+\omega)},$$
$$\sigma^\sigma|_{\lim_{\kappa\to 0}} = 1 - \frac{(\alpha_0 + Z\omega)\eta_u}{(1-\theta)(\alpha_1\eta + Z\omega + \alpha_0)}.$$

The condition for $\sigma^\kappa|_{\lim_{\kappa\to 0}} > \sigma^\sigma|_{\lim_{\kappa\to 0}}$, which is also the case portrayed in Figure 1, is that

$\eta_u\eta(\gamma\omega+\alpha_0) > 0$, which is automatically satisfied. The respective Jacobian matrix with $\eta_\pi = 0$, when evaluated at the long-run equilibrium values in (21)-(22), is:

$$J_{11} = -\frac{b(1-\theta)(\alpha_0-\gamma\eta)-\theta\alpha_0\eta_u}{(1-\theta)\eta_u\gamma} < 0,$$
$$J_{12} = -\frac{(\alpha_0-\gamma\eta)[(1-\theta)(\eta+\omega)+\theta\eta\kappa^*]}{\eta_u\gamma\eta} < 0,$$
$$J_{21} = \frac{Z[b(1-\theta)(\alpha_0-\gamma\eta)-\theta\alpha_0\eta_u]}{(1-\theta)\eta_u\gamma} > 0,$$
$$J_{22} = \frac{(\alpha_0-\gamma\eta)[(1-\theta)[\alpha_0+Z(\eta+\omega)]+Z\theta\eta\kappa^*]}{\eta_u\gamma\eta} > 0.$$

The parametric restrictions imposed in the text to ensure economically relevant values for the long-run equilibrium represented by (21)-(22) explain the signs in J above, whose determinant is in fact negative: $|J| = -[(1-\theta)(\alpha_0-\gamma\eta)b-\theta\alpha_0\eta_u](\alpha_0-\gamma\eta)^2(\gamma^2\eta\eta_u)^{-1} < 0$.

Appendix C: Local (in)stability analysis of a profit-led regime

Let us set (19) and (20) to zero under the assumption that $\eta_u = \eta = 0$ to get the respective isoclines, again confining attention to the economically relevant intervals for the state variables:

$$\kappa^\kappa = \frac{\eta_\pi(1-\theta)(1-\sigma)+\omega}{\eta_\pi[b-\theta(1-\sigma)]}, \tag{C1}$$

$$\kappa^\sigma = \frac{\alpha_1\eta_\pi(1-\theta)(1-\sigma)+\epsilon}{Z\eta_\pi[b-\theta(1-\sigma)]}. \tag{C2}$$

These isoclines are negatively sloped and their intercepts in the κ-axis are respectively:

$$\kappa^\kappa|_{\lim_{\sigma\to 0}} = \frac{\eta_\pi(1-\theta)+\omega}{\eta_\pi(b-\theta)},$$
$$\kappa^\sigma|_{\lim_{\sigma\to 0}} = \frac{\alpha_1\eta_\pi(1-\theta)+\epsilon}{Z\eta_\pi(b-\theta)}.$$

To ensure that $\kappa^\kappa|_{\lim_{\sigma\to 0}} > \kappa^\sigma|_{\lim_{\sigma\to 0}} > 0$, which is the situation shown in Figure 2, we assume that $\gamma\eta_\pi(1-\theta) > \alpha_0$. These isoclines cross the σ-axis respectively at the points:

$$\sigma^\kappa|_{\lim_{\kappa\to 0}} = 1 + \frac{\omega}{\eta_\pi(1-\theta)},$$
$$\sigma^\sigma|_{\lim_{\kappa\to 0}} = 1 + \frac{\epsilon}{\alpha_1\eta_\pi(1-\theta)},$$

which are both greater than one and thus located outside the economically relevant domain of σ. The Jacobian matrix with $\eta_\pi = 0$, when evaluated at the stationary values in (26)-(27), is:

$$J_{11} = -b\eta_\pi + \frac{\theta\alpha_0}{\gamma(1-\theta)} < 0,$$
$$J_{12} = -[1-\theta(1-\kappa^*)]\eta_\pi < 0,$$
$$J_{21} = Zb\eta_\pi - \frac{Z\theta\alpha_0}{\gamma(1-\theta)} > 0,$$
$$J_{22} = [\alpha_1(1-\theta)+Z\theta\kappa^*]\eta_\pi > 0.$$

The parametric restrictions imposed to ensure economically relevant values for the long-run equilibrium given by (26)-(27) explain the signs of the partial derivatives above, in fact yielding a positive determinant, $|J| = \eta_\pi[\gamma b\eta_\pi(1-\theta)-\theta\alpha_0] > 0$, a necessary condition for (local) stability of the balanced growth path. The characteristic points of each isocline and the restrictions for a unique long-run equilibrium configuration define the balanced growth path as being locally stable. The formal analysis also requires that $J_{11} + J_{22}$ is negative. $J_{11} = \partial\hat{\kappa}/\partial\kappa$ is negative, so that variations in the net flow of pollution per unit of capital stock, $[b - \theta(1-\sigma)]u$, in the neighborhood of the balanced growth path, contributes to stability. Yet $J_{22} = \partial\hat{\sigma}/\partial\sigma$ being positive contributes to instability. $J_{22} > 0$ arises from a combination of destabilizing effects. In the neighborhood of the balanced growth path, a rise in σ, by lifting the growth rate of pollution concentration, raises the growth rate of the real wage and exerts a downward pressure on the productivity growth rate, such pressure being intensified by the accompanying fall in the output growth rate. The cyclical convergence to the balanced growth path shown in Figure 2 assumes that the stabilizing effect of $J_{11} < 0$ overcomes the destabilizing effect of $J_{22} > 0$.

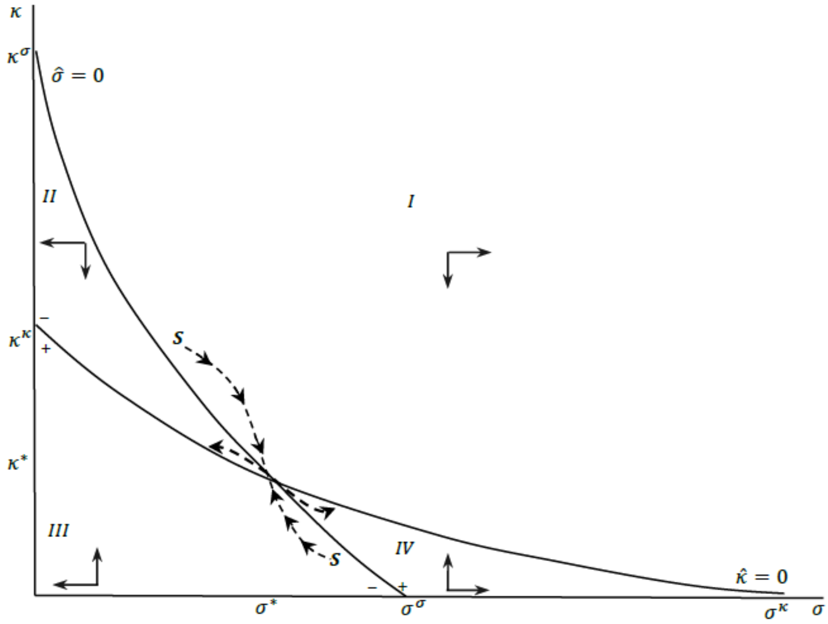

Figure 1: Saddle-point instability of the balanced growth path in a wage-led regime.

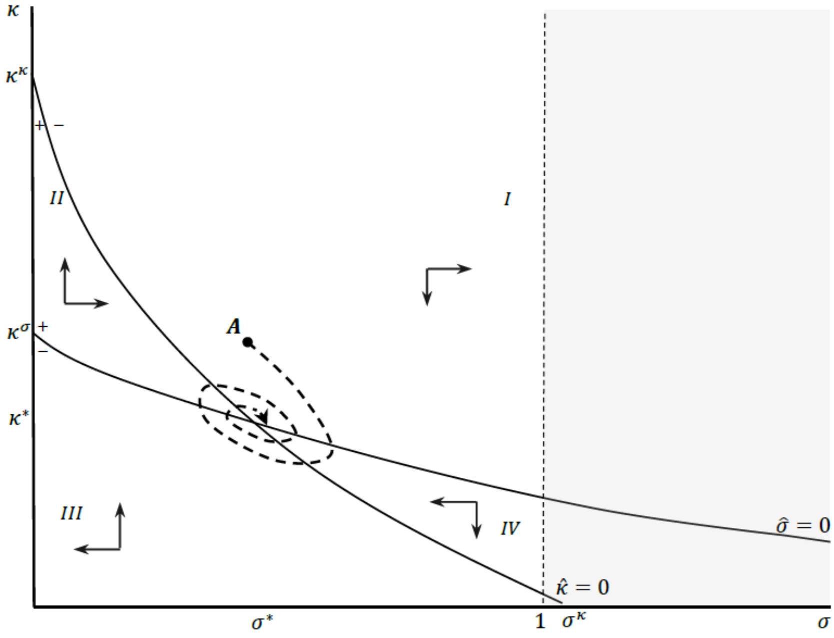

Figure 2: Balanced growth path as a locally stable focus in a profit-led regime.