Received: 1 May 2019 | Accepted: 29 July 2020

DOI: 10.1111/jpet.12466

ORIGINAL ARTICLE

JOURNAL OF PUBLIC ECONOMIC THEORY WILEY

Income inequality and technological progress: The effect of R&D incentives, integration, and spillovers

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Funding information
Spanish Ministry of Science and Innovation, Grant/Award Numbers: RTI2018-094733-B-100, PID2019-105982GB-I00; Portuguese Foundation for Science and Technology (FCT), Grant/Award Numbers: PTDC/MAT-NAN/6890/2014, PTDC/MAT-APL/31753/2017

Abstract

Recent years witnessed an increase in income inequality. Several explanations have been put forward. In the present paper, we consider a series of technologically related events that have been crucial for the increased income inequality, that is, public R&D incentives, increasing horizontal integration and spillover effects. We found that public R&D incentives and the increasing horizontal integration have biased the income distribution towards the top income group. In particular, the high-skilled workers involved in the R&D process have benefited enormously from this process. Similarly, capital owners have seen an increase in their profits, because of the reduction in product market competition and technological improvements in the production process. We found the effect of knowledge spillovers to be less clear-cut. We conclude discussing the implications of our results and suggesting possible solutions to the increasing income inequality. We call for the creation of supranational institutions, and for stricter legislation on competition and antitrust policy.

1 | INTRODUCTION

Recent decades have witnessed a persistent and general increase in income inequality and polarization (Piketty & Saez, 2006). The World Economic Forum's Inclusive Growth and Development Report (2015) shows that income distribution is favoring the top two quintiles worldwide (Samans, Blanke, Corrigan, & Drzeniek 2015). Simultaneously, there has been a clear and robust rise in the share of capital income and in the wealth inequality (Piketty, 2014; Piketty & Zucman, 2014). Referring to this issue, the former US President, Barack Obama, said that tackling inequality and wage stagnation is the United States' foremost challenge. In this context, we question what forces are driving the increasing income inequality and what can be done to reverse this process.

The answer to those questions is far from trivial, as it involves considerations from almost every field in economics, in particular macroeconomics. In this paper, we try to address these fundamental questions in a completely different way by offering a novel perspective from industrial organization and competitive markets.

In this context, we study how the increases in (a) public R&D incentives, (b) horizontal integration, and (c) knowledge spillovers have affected the firms' strategies, and consequently, the income distribution and inequality, by analyzing their impact on the top income (i.e., the capital and the high-skilled workers' income) and the bottom income (i.e., the low/medium-skilled workers' income).

To address these issues, we present a simple theoretical model with spillovers, in line with the d'Aspremont and Jacquemin (1988) model, but in which R&D cooperation cannot be disentangled from product market cooperation, as in López and Vives (2019).[1] The objective is to study how the aforementioned technologically related aspects affect different types of income in contexts in which firms strategically compete for consumers in terms of price and technological efficiency.

The model generates interesting trade-offs with implications for income distribution and inequality. In this context, we consider two income groups. The *top income* group, which consists of the *capital income* (i.e., the returns associated with the firms' profits) and the *high-skilled workers' income* (i.e., the returns associated with the firms' R&D process), and the *bottom income* group, which consists of the *low/medium-skilled workers' income* (i.e., the returns associated with the firms' manufacturing process).

Subsequently, we analyze the impact of increasing (a) public R&D incentives, (b) horizontal integration, and (c) knowledge spillovers on these different types of incomes and discuss its consequences in terms of income inequality.

In what follows, we summarized the obtained results.

(a) *Increasing public R&D incentives.*

According to the OECD, in the most developed countries, direct spending on R&D activities has been well above 3% of the gross domestic product (GDP) in 2015, and if we consider other indirect spending, such as education, then the involvement of governments in R&D is much higher. Similar reasoning applies to private R&D investments. Between 50% and 60% of private R&D expenses consist of high-skilled workers' salaries, which seem to have biased the job market in favor of high-skilled workers (Giandrea & Sprague, 2017; Lokshin & Mohnen, 2013; Wolff & Reinthaler, 2008). In this paper, we want to understand the income distribution and inequality implications of these large investments and mobilization of resources into the R&D activities.

[1]In an early influential work on R&D and market performance, Spence (1984) introduced a spillover parameter as a way of modeling the imperfect appropriability of R&D in competitive markets. Subsequently, a large body of literature has followed this approach, for example, M. Katz (1986), d'Aspremont and Jacquemin (1988), Kamien, Muller, and Zang (1992), Amir, Evstigneev, and Wooders (2003), or more recently Cosandier, De Feo, and Knauff (2017) and Amir, Liu, Machowska, and Resende (2019), just to mention a few.

In this context, we found that public R&D incentives have biased the income distribution towards the top income group, which has contributed to the increasing income inequality observed in recent decades. In particular, the high-skilled workers involved in the R&D process have benefited enormously from these policies. Simultaneously, despite the increasing competition, capital owners have also seen an increase in their profits. First, because part of the increase in R&D costs, in particular the costs with the high-skilled workers, were paid indirectly by public R&D incentives. Second, because the increase in product market competition was compensated by technological improvements in the production process, which have led to important cost reductions in the production process. The latter effect also explains why the low/medium-skilled workers' income has been decreasing in relative terms, and consequently, why income inequality has increased.

(b) *Increasing horizontal integration*.

In our context, horizontal integration includes mergers and acquisitions (M&As), R&D collaboration, minority and cross-shareholding, and other forms of integration that are widespread in most industries (Salop & O'Brien, 2000). Recent years have witnessed an impressive wave of M&As, strategic alliances, and partnerships. Many companies are being bought for their data, patents, licenses, market share, name brand, research staff, methods, customer base, or culture. Despite the antitrust concerns, if the alleged motive involves R&D benefits, these operations are often allowed by public and competition authorities (Lopéz & Vives, 2019).

In this context, we found that the increasing integration has reduced the product market competition but has strengthened the firms' focus on R&D activities, which has favored the high-skilled workers' income. Despite the higher R&D costs, capital income has increased because of the reduction in the product market competition and the R&D technological improvements in the production process, which have led to important cost reductions. In relative terms, the production process has become less relevant in the firms' strategies, which has led to a reduction in the low/medium-skilled workers' income, and consequently, to an increase in income inequality.

In both cases (i.e., public R&D incentives and horizontal integration), we found a strong positive relation between the income of the capital owners and the high-skilled workers. The reason is that profits depend crucially on R&D technology improvements, and vice versa. Consequently, higher the capital owners' incentives to reward the resources that are more important in this process, that is, the high-skilled workers, and vice versa.

(c) *Increasing knowledge spillovers*.

The impact of R&D on growth by means of spillovers has been a major topic of economic research over the last 30 years (Hall, 2006). Several studies agree on the importance of social returns over private returns in R&D (Bloom, Schankerman, & Van Reenen, 2013; Coe & Helpman, 1995; Griliches, 1992; Jones & Williams, 1998). However, the literature has systematically ignored the effects of spillovers on income distribution and inequality.

In this context, we found that the high-skilled workers' income does not seem to benefit from spillovers because—as knowledge spreads and becomes easier to assimilate—firms tend to free ride on the R&D efforts of other firms. Therefore, the demand for high-skilled workers decreases, with negative repercussions on their income. Consequently, the overall effect of the increasing spillovers on the top income group and on the income inequality depends on the size of the capital income gains. In this context, we found that if spillovers are sufficiently low, income inequality increases because the capital income gains are high. Otherwise, we observe the opposite. Nonetheless, we argue that capital income owners—either by means of patents and copyrights or by means of multiple forms of integration—have minimized the impact of spillovers on profits, which has not allowed reductions in income inequality to be anything other than temporary exceptions.[2] In this context, the relationship between R&D spillovers and income inequality is not as clear as the relationships between public R&D incentives and horizontal integration.

Thus, in line with our results, we argue in favor of legal restrictions on firms' integration and other similar strategic decisions. In particular, when performed by large corporations. We support the creation of an "industrial welfare state" with higher taxation on top corporations (based on their size and market power) and redistribution to entrepreneurs and Small and Medium-sized Enterprises (SMEs). In this context, we defend the creation of independent supranational institutions on competition and antitrust issues, with legal and enforcing power. The objective behind these policy recommendations is to reduce income inequality with minimum impact in terms of R&D incentives.

This paper is related to several strands of literature that proposes technology-related explanations for the increased income inequality. However, none of these studies focused on the details and implications of the public R&D incentives, horizontal integration, and knowledge spillovers on the income inequality and distribution. In theoretical terms—to the best of our knowledge—there is nothing done on this subject.

For instance, the skill-biased technical change empirical literature (Acemoglu, 2002; Aghion, 2002; Hornstein, Krusell, & Violante, 2005) claims that the increasing income inequality observed in recent decades is related to the high correlation between the wage share of skilled workers and the use of new technologies (L. Katz & Murphy, 1992).[3] While this literature has focused on the impact of technological progress in the qualitative distribution of tasks, in this paper, we focus on income inequality, not only among low/medium- and high-skilled workers, but also among capital owners.

This paper is also related with a large body of literature that attributes the increasing income inequality to the emergence of a new class of highly paid "superstars" (e.g., entrepreneurs, entertainers, sports stars, authors, top scientists, managers, etc.), as the result of the increasing globalization (Rosen, 1981).[4] For Piketty and Saez (2006), the big companies are giving their top executives excessively high payment packages. Compared with the 1950s, the pay ratio between the highest- and the lowest-paid workers has risen from about 20 to more than 200.[5]

[2]The strong capital owners lobby has demanded more protection and appropriation of their R&D investments (e.g., through patents, property rights, licenses, etc.). In this context, the public good property of R&D has been a major argument in favor of public R&D incentives and horizontal integration. This observation links together the three aforementioned technological related events in this paper.

[3]Autor, Levy, and Murnane (2003) show that since the 1970s, the labor requirements in nonroutine, analytical, and interactive tasks increased sharply compared with routine and manual tasks. Hémous and Olsen (2014) argue that the incentives to automate low-skilled tasks increase as the economy develops. According to Acemoglu and Autor (2012), this trend shifted the middle of the income distribution to the low and top ends which has led to higher income inequality.

[4]A branch of the literature argues that the increasing income inequality is the result of globalization (Antràs, de Gortari, & Itskhoki, 2017). In this paper, we acknowledge the importance of globalization. Spillovers are an inseparable part of globalization. Moreover, a large share of the increasing public R&D incentives and horizontal integration is justified by the firms (and countries) need to be competitive globally.

[5]Garicano and Rossi-Hansberg (2006) present a model where technology shapes the organizational structure and induces income inequality between the top and bottom level workers.

Other authors argue that most of the transformation in the labor market and inequality results from the complementarity between capital-embodied and skill-biased technological change (Hornstein et al., 2005). Aghion, Akcigit, Bergeaud, Blundell, and Hémous (2015) showed that innovation favors social mobility, but increases inequality, because the top incomes are earned by innovator capital owners. The increased correlation between the high-skilled workers and the capital owners' incomes has been a major factor in the increasing income inequality. Our results confirm this observation.

Lastly, our framework takes into account the shift in the income distribution of different types of workers and capital owners by linking (a) the low/medium-skilled workers with the production process, (b) the high-skilled workers with the R&D process, and (c) the capital owners with the firms' profits in competitive markets. These relations have never been studied before in the literature. In this context, we found that the gains and losses from technological progress are very unequally distributed among the different income groups, which has enormous implications in terms of income inequality.

This paper is organized as follows: Section 2 presents the theoretical framework, Sections 3, 4 and 5 analyze the effects of increasing (a) *public R&D incentives*, (b) *horizontal integration*, and (c) *knowledge spillovers*, respectively, in terms of income distribution and inequality, Section 6 discusses our results and offers some policy recommendations, and Section 7 concludes. The proofs are relegated to the appendix.

2 | MODEL AND INCOME MEASURES

We consider an economy with two firms competing with each other. In our simplified economy, low/medium-skilled workers are the only factor that enters into the production process, which can be made technologically more efficient by resorting to high-skilled workers.

In this context, we extend the celebrated d'Aspremont and Jacquemin (1988) two-stage model.[6] In the first stage, firms simultaneously choose their R&D levels. In the second stage, firms compete in the product market by simultaneously choosing their output levels. To capture the horizontal integration trend observed in the last decades, we allow firms to hold shareholder positions in their opponents as in López and Vives (2019).

Firms face a linear inverse demand function of the type

$$p = a - b(q_1 + q_2),$$

where a and b are the constant parameters, $q_i \geq 0$ is the output of firm $i = 1, 2$, and $p \geq 0$ is the market price.

The *production process* is costly, with marginal cost of production given by

$$c_i(x_1, x_2) = A - x_i - \beta x_{-i}$$

[6]d'Aspremont and Jacquemin (1988) compare the cases of R&D competition and R&D cooperation. One of their main results is that firms tend to prefer cooperation because they can internalize the R&D spillovers. This framework has the advantage of being tractable. However, as pointed out by Amir (2000) and Martin (2002) the d'Aspremont and Jacquemin model is more adequate to capture outgoing spillovers, while the Kamien et al. (1992) model is more adequate to capture incoming spillovers (Martin, 2002).

for $i = 1, 2$, where $A \in (0, a)$ is constant and $x_i \geq 0$ and $x_{-i} \geq 0$ denote firm i and the rival firm $-i$ R&D efforts, respectively. In other words, each firm can reduce the marginal cost of production by spending resources on R&D activities that can improve the production process. In our context, *technological progress* refers to improvements in the production process, that is, reductions in the marginal cost of production $c_i(x_1, x_2) \geq 0$.

The parameter $\beta \in [0, 1]$ captures the existence of *technological spillovers*.[7] Technological improvements result from the firm's own R&D efforts and the other firms R&D efforts in the proportion β. For instance, in the case $\beta = 0$ there is no dissemination of knowledge, while in the case $\beta = 1$ there is full dissemination of knowledge.

The *R&D process* is costly (strictly increasing and convex in the R&D effort x_i) and given by $\gamma x_i^2/2$ for $i = 1, 2$, where $\gamma > 0$ captures the cost of the R&D effort.

2.1 | Labor income

In our simple economy, the firms' costs are the labor income received by the workers:

$$tc_i = c_i(x_1, x_2)q_i + \gamma x_i^2/2 \tag{1}$$

for $i = 1, 2$.[8]

We distinguish between (a) the low/medium-skilled workers' income and (b) the high-skilled workers' income. (a) The first component on the right-hand side of Expression (1) is related to the production process, which typically employs low/medium-skilled and lower-paid workers (i.e., blue-collar workers and low/medium-skilled white-collar workers). Therefore, the *low/medium-skilled workers' income* is given by

$$\underline{w}_i = c_i(x_1, x_2)q_i \tag{2}$$

for $i = 1, 2$.

(b) The second component on the right-hand side of Expression (1) is related to the R&D process, which typically employs high-skilled and well-paid white-collar workers.[9] Therefore, the *high-skilled workers' income* is given by

$$\overline{w}_i = \gamma x_i^2/2 \tag{3}$$

for $i = 1, 2$.

[7]This paper considers exogenous outgoing spillovers. A large body of the literature endogenizes the spillovers process and the sender/receiver roles (e.g., Amir & Wooders, 2000; Amir et al., 2003).

[8]To abstract from other cost considerations, without loss of generality, and to be able to study the impact of the increasing public R&D incentives, horizontal integration, and spillovers on income inequality in a simple and tractable framework, we focus on labor costs, which are linked with the labor income received by the workers.

[9]There is not always a well-defined frontier between the production and the R&D processes. In both processes, there is a great diversity of labor skills and incomes. For instance, we can find high-skilled workers involved in the production process, as well as low/medium-skilled workers participating in the R&D process. Nonetheless, in our context, the proposed link between production and R&D processes, and low/medium- and high-skilled workers, respectively, is the most realist and general representation of the distribution of skills and incomes inside the firms.

Two comments are in order at this point. First, we have translated manufacturing costs and R&D investments into low/medium- and high-skilled workers' income, respectively. However, despite that production costs and R&D spending are in general more diverse and not exclusively composed of labor costs (e.g., taxes, raw materials, tools, and machinery, just to mention a few), the share of labor costs on the total costs is extremely large. For instance, Giandrea and Sprague (2017) estimate that the labor share is 58% of the total output, that is, the percentage of economic output that accrues to workers in the form of compensation. Similarly, the majority of the private R&D budgets consist of wages paid to highly qualified technicians, scientists, and engineers, among other skilled workers.

Second, we have intentionally kept the model simple, but without compromising its accuracy and reliability. Otherwise, it would have been difficult to study the effects of public R&D incentives, integration, and spillovers on income inequality in a unique and tractable framework.

2.2 | Capital income

Hence, each firm's profit is given by

$$\pi_i = pq_i - tc_i = (a - b(q_1 + q_2))q_i - (A - x_i - \beta x_{-i})q_i - \gamma x_i^2/2 \tag{4}$$

for $i = 1, 2$.

To capture the *horizontal integration* trend observed in the last decades, we follow López and Vives (2019) by allowing partial cross-ownership. In other words, firm 1 may hold a participation $\omega_{12} \in [0, 1]$ in firm 2, and firm 2 may hold a participation $\omega_{21} \in [0, 1]$ in firm 1. Therefore, R&D cooperation cannot be disentangled from product market cooperation. For simplicity and concreteness, we consider the case of symmetric cross-ownership between the firms in the economy, that is, $\omega_{21} = \omega_{12} = \omega \in [0, 1]$.

Therefore, the *capital income* of shareholder i is the sum of the net profit obtained in firm i (i.e., after the financial interest of shareholder $-i$ has been paid), plus the financial interest received from the shareholder's position in the opponent firm $-i$:

$$k_i = (1 - \omega)\pi_i + \omega\pi_{-i} \tag{5}$$

for $i = 1, 2$.[10] The shareholder i chooses the quantity q_i and the R&D effort x_i that maximizes their own capital income.

To summarize, we distinguish between three different types of income: low/medium-skilled workers income $\underline{w}_i$, high-skilled workers income $\overline{w}_i$, and capital owners income k_i.

Lastly, as it is commonly assumed in the literature, we consider that $a = b = 1$. Subsequently, to reduce the number of parameters and to obtain tractable equilibrium expressions that depend exclusively on the parameters γ, ω, and β (i.e., the parameters that are going to be linked to the three hypotheses regarding income inequality: public R&D incentives, horizontal

[10]In our model, we consider the capital income that is obtained from business and manufacturing activities. Clearly, there are other forms of capital income (e.g., monetary flows from physical capital, such as real estate and factories, intangible capital returns, such as brands and patents, and financial capital returns, such as stocks, bonds, etc.).

integration, and technological spillovers, respectively), we set $A = 1/4$. These assumptions have no relevant implications for the results.

2.3 | The Gini coefficient

To measure income inequality, we consider the Gini coefficient. The Gini coefficient is justified because it is the most well-known and consensual measure of inequality in economics, but also in other social sciences.

The Gini coefficient is defined as the ratio of the area between the line of the uniform income distribution and the Lorenz curve, divided by the total area under the line of the uniform income distribution. A value of 0 corresponds to perfect income equality (i.e., everybody holds the same income) and a value of 1 corresponds to perfect income inequality (i.e., one person holds all income). For a general population with n incomes y_i, indexed in nondecreasing order (i.e., $y_i \leq y_{i+1}$), the Gini coefficient is given by

$$G = \left(n + 1 - 2\sum_{i=1}^{n}(n + 1 - i)y_i/\sum_{i=1}^{n}y_i\right)/n. \tag{6}$$

Following the skill-biased technological change and the "superstars" theories, and because of the great correlation between capital and high-skilled workers' incomes (see Section 1), we consider two income groups:

(i) The *top income* group that includes the capital owners and the high-skilled workers' incomes, that is,

$$\overline{y} = k_i + \overline{w}_i, \tag{7}$$

according to Expressions (5) and (3), respectively.[11] The aggregation adds together the population groups with highest earnings in our model, and does not entail a loss of information, because throughout the paper we distinguish between the effects on the capital owners and high-skilled workers incomes, and how these effects feedback into income inequality.

(ii) The *bottom income* group that is composed exclusively of low/medium-skilled workers' income, that is,

$$\underline{y} = \underline{w}_i,$$

according to Expression (2), which captures the income of the population that typically has the lowest earnings in the society.[12]

[11] Since the model is symmetric, in equilibrium we must have $\underline{w}_1 = \underline{w}_2$, $\overline{w}_1 = \overline{w}_2$, and $k_1 = k_2$. For that reason, and without loss of generality, the incomes $\overline{y}$ and $\underline{y}$ are denoted without the subindex i. Therefore, workers and capital owners must be seen as representative workers and capital owners.

[12] The model provides information about the income of each group, but not about the size of each group. Typically, the population size of low/medium-skilled workers is larger than the capital owners and high-skilled workers populations. However, with only two different income groups the mass of individuals earning top and floor incomes is irrelevant, which allows us to study income inequality effects without concerning about changes in the size of these two groups.

Note that with only two different income groups, the Gini coefficient simplifies, and the income inequality analysis could dispense with it. Nonetheless, we consider it because it is the main reference in the literature regarding income inequality.

3 | PUBLIC R&D INCENTIVES

In this section, we consider the impact of the public R&D incentives on income inequality. Even though some empirical evidence suggests that public R&D investment may crowd out private R&D investment, there is a general agreement about the desirability of subsidizing R&D (David, Hall, & Toole, 2000). Consequently, government-supported R&D policies have been at the center of most countries competitiveness strategy. For instance, in the most developed countries, direct spending on R&D activities has been well above 3% of the GDP (OECD, 2015), but if we consider other indirect expenses (e.g., education), then public involvement in R&D is even larger. A similar investment and spending intensity have been observed in private R&D.

In our context, we want to understand the influence that these large amounts of resources transferred into R&D activities had on income inequality.

The majority of the private R&D expenses consist of the salaries of high-skilled workers (e.g., technicians, scientists, and engineers, among other skilled workers). Goolsbee (1998) found that the majority of public R&D spending goes directly to higher wages, which bias the labor market in favor of high-skilled workers. Lokshin and Mohnen (2013) and Wolff and Reinthaler (2008) report qualitatively similar results.

At this point, to be objective, we abstract from the specificities associated with each potential policy instrument.[13] Consequently, we consider that the mechanism by which the public R&D policy influences firms' innovation is by reducing their R&D costs (i.e., in our context, a reduction in the parameter γ), thereby increasing R&D activities and hopefully innovation outputs. This transmission mechanism captures, to a great extent, the observed reality because, in one way or another, most public R&D incentives end up reducing the firms' R&D costs.[14]

The following result summarizes our findings regarding the effects of public R&D incentives on income distribution and inequality (for details see the appendix).

Proposition 1. *The increasing public R&D incentives (i.e., a decrease in γ):*

(a) *increases top income:*
  ($a1$) *increases capital income for $\gamma > 8(2-\beta)^2(1+\beta)/(27\beta)$, and the opposite otherwise,*
  ($a2$) *increases high-skilled income,*
(b) *decreases bottom income,*
(c) *increases income inequality.*

[13]The public R&D policy can be very diverse and employ different instruments, for example, R&D cooperation between institutions, support to university research and to high-skilled human capital formation, as well as R&D subsidies and tax incentives (see Becker, 2015) for a review of the literature).

[14]The partial equilibrium analysis in this paper does not consider explicitly government budget restrictions. We are also not concerned about the effectiveness of the public R&D policy, because we want to focus on understanding how public R&D spending affects firms' decisions and how it feedbacks into income inequality.

Our results show a robust tendency for an increase in top incomes (Part (a) of Proposition 1), and a decrease in bottom incomes (Part (b) of Proposition 1), as a consequence of the increasing public R&D incentives. Consequently, income inequality increases (Part (c) of Proposition 1).

Intuitively, the increase in public R&D incentives bias the income distribution in favor of the top income earners: Capital owners obtain higher profits and the high-skilled workers—who are the central actors of these policies—obtain higher wages. These results reproduce and give consistency to the empirical reality.

In our model, public R&D incentives increase competition in the product market and in R&D. We observe a consistent and simultaneous increase in the quantities produced, and in the R&D levels, which explains why the high-skilled workers' income has increased. However, despite the higher intensity of competition, capital income has also increased. The reason is twofold. First, part of the additional R&D costs with high-skilled workers (x) is paid for by public R&D incentives (note that public R&D incentives imply a reduction in γ). Second, the increase in market competition is compensated for by technological gains in the production process, which has caused a reduction in the marginal cost of production (c) and explains why the low/medium-skilled workers' income has decreased.

The only situation in which capital income may decrease occurs when the spillover effects (β) and the R&D costs parameter of the high-skilled workers (γ) are sufficiently low, because in this case the competition intensity effect is particularly strong, which has negative implications for the firms' profits.[15]

3.1 | Discussion

The increasing spending on public R&D activities observed in the recent decades is the result from a worldwide political and governmental obsession with the technological competitiveness and excellence of the national industries. Consequently, a large amount of resources and public spending has been applied directly or indirectly into R&D. In most developed countries, industrial policy focuses almost exclusively on this objective. There is a sense that any other competitive goal is secondary or that can be easily achieved once technological excellence is established.

We do not claim that such a strategy is wrong or inadequate, but simply highlight that such a strategy may have contributed to greater income inequality. Actually, in terms of welfare, in recent decades, consumers seem to have benefited enormously from those policies, which have led to higher consumption and variety at lower prices. These observations are consistent with the idea that welfare and income inequality have been increasing during recent decades.

Lastly, even though the low/medium-skilled workers have benefited from social policies and the welfare state more than ever before, our results seem to suggest that the solution to the income inequality may pass through a further adjustment in the redistributive policy. In line with this argument, Piketty (2014) defends more taxation at the top income levels and redistribution at the bottom income levels. In Section 6, we will discuss these and other possible solutions in more detail.

[15] *Technical note*: The relevant range of parameters is given by the equilibrium existence condition (A4) and the assumption $0 \leq \underline{y} \leq \bar{y}$ (see the appendix). The condition (A4) establishes that $\gamma \in [1.78, \infty)$ for $\beta \in [0, 1]$. One implication is that the inequality in Part (a1) of Proposition 1 is in general satisfied.

4 | HORIZONTAL INTEGRATION

The firms' success depends crucially on the ability to differentiate and develop independently in competitive markets. In this context, shareholders reward highly the resources that allow them to achieve this objective. These resources are top managers, researchers and other high-skilled workers who, in one way or another, make the difference. However, differentiation and innovation in competitive contexts are not always easy to achieve. Consequently, capital owners have searched for alternative ways to protect their interests.

One of those ways has been an increasing worldwide trend towards the integration of activities within the same firm (e.g., the localization of production or the centralization of the R&D process) and between different firms (e.g., horizontal and vertical M&A, minority and cross-shareholding, partnerships, strategic alliances, and knowledge exchange with rival firms, among other types of behavior). See Hagedoorn, Link, and Vonortas (2000) for a review survey on R&D cooperation across institutions.

Many companies are being bought for their patents, licenses, data, market share, name brand, research staff, methods, customer base, or culture. Despite antitrust concerns (i.e., less competition intensity and more market power), if the alleged motive involves R&D cooperation these operations are often allowed by public authorities. However, cooperation in R&D easily extends to the product market, which reduces competition (Lopéz & Vives, 2019; Salop & O'Brien, 2000).

These events are also related to the increasing globalization trend, which has benefited from technological improvements in telecommunications and transportation.

In this section, we are interested in the implications in terms of income inequality and distribution of the increasing integration observed in recent decades. Since integration is a multiple-dimensional and complex phenomenon, we focus on horizontal integration because it is the most salient and intuitive form of integration, and because it is easier to analyze.

In our context, horizontal integration is captured by an increase in ω (i.e., the shareholding position that firms hold on each other).

The following result sums up our findings regarding the effects of horizontal integration on income distribution and inequality (for details see the appendix).

Proposition 2. *The increasing horizontal integration (i.e., an increase in* ω*):*

(a) *increases top income:*
  ($a1$) *increases capital income,*
  ($a2$) *increases high-skilled income,*
(b) *decreases bottom income,*
(c) *increases income inequality.*

The intuition for the obtained results is straightforward. Higher levels of integration tend to reduce competition in the product market, but increase competition in R&D, which favors the high-skilled workers income (Part (a2) of Proposition 2).[16] Similarly, capital returns in the form of profits

[16]*Technical note*: Product market competition (measured by produced quantities) always decreases for $\beta \in [0, 0.95)$ or $\gamma \in (1.89, \infty)$. Outside these cases, competition may increase if $\gamma > 5(1+\beta)^2/9$ with $\gamma \in [1.78, 1.89]$ and $\beta \in [0.95, 1]$ (see Footnote 15 and the appendix). Therefore, an increase in product market competition requires spillovers of unlikely magnitude. For that reason, we do not discuss this possibility in detail. Moreover, there might be some concerns regarding the validity of the d'Aspremont and Jacquemin model for large spillover values (Amir, 2000).

also increase because of the product market competition reduction effect (Part (a1) of Proposition 2). The latter observation is not surprising, since the ultimate goal of horizontal integration is the search for higher profit. Consequently, top income increases (Part (a) of Proposition 2).

Note that capital and high-skilled workers' incomes seem to be complementary and positively correlated. A similar result appears in Hornstein et al. (2005). In other words, the higher the capital returns, the higher the reward that shareholders offer to the high-skilled workers that are crucial for their high returns, and vice versa.

Note also that the increase in R&D efforts increases the R&D costs faced by firms. Consequently, the increase in capital income is explained (simultaneously) by the overall reduction in the intensity of competition and by the technological improvements achieved in the production process.

In relative terms, the production process and the role played by the low/medium-skilled workers (i.e., the workers that are more closely related to the production process) becomes less relevant for the firm strategy, which is reflected by a reduction in their income (Part (b) of Proposition 2). Consequently, income inequality tends to increase (Part (c) of Proposition 2).

4.1 | Discussion

Integration allows firms to focus on R&D activities by reducing product market competition. This observation is in line with the argument that less competitive market structures may favor innovation. The reason is that innovators appropriate the innovation benefits more easily, which incentivizes R&D activities and investments. This argument is usually given in support of horizontal integration. However, to reduce income inequality, we may need more competition in the product market. In Section 6, we will discuss possible solutions to this problem.

Another consequence of the trend towards the greater integration observed in recent decades is an increase in the firms' size, market power and a growing gap between small and large companies. In our model, we capture these effects by an increase in the horizontal integration between firms. The result is an increase in the income inequality. In line with our results, Greg Ip, WSJ chief economics commentator, points out that the prime driver of wage inequality is the growing gap between the most and the least-profitable companies.[17]

In this context, we think that competition policy should play a more important role in narrowing the gap between the highest- and the lowest-paid workers, and in reducing the firms' differences in terms of size and power. This objective may be achieved through adequate protection and discriminatory R&D incentives in favor of entrepreneurs and SMEs. In our perspective, this type of policies may be more effective than the exclusive taxation of top incomes as defended by Piketty (2014).

5 | KNOWLEDGE SPILLOVERS

Knowledge spillovers are technological developments, by a particular firm, that stimulates further technological developments, by other firms—and by the society in general—through the processes of technological diffusion and absorption.

[17] Ip, Greg "Behind Rising Inequality: More Unequal Companies," The Wall Street Journal, November 4, 2015, http://www.wsj.com.

The impact of R&D on growth as a result of spillovers has been a major topic of economic research over the last 30 years. Several studies coincide on the importance of R&D spillovers, and on the importance of the society returns being higher than the private returns from R&D (Bloom et al., 2013; Coe & Helpman, 1995; Griliches, 1992; Jones & Williams, 1998). Empirically, spillover effects are difficult to measure and quantify.

Nonetheless, there is a general agreement in the literature that the impact and influence of spillovers depends crucially on the capacity of firms to assimilate and apply new technologies, which has been increasing in recent decades. For instance, technological competition between rival firms has increased the diffusion and the absorption rates (Aghion, Bloom, Blundell, Griffth, & Howitt, 2005). Consequently, in recent decades, spillover effects have become an increasingly important component of technological progress, and thus, an important source of wealth and economic growth (Hall, 2006). However, the literature has systematically ignored the effects of spillovers on income distribution and inequality.

The objective of this section is to shed some light on these issues.

The following result summarizes our findings regarding the effects of spillovers on income distribution and inequality (for details see the appendix).

Proposition 3. *The increasing technological spillovers (i.e., an increase in β):*

(a) *increases top income for $\beta < 1/2$, and the opposite otherwise:*
  (*a*1) *increases capital income for $\gamma > 2(2-\beta)^3/(27(1-\beta))$, and the opposite otherwise,*
  (*a*2) *decreases high-skilled income,*
(b) *increases bottom income for $\beta > 1/2$, and the opposite otherwise,*
(c) *increases income inequality for $\beta < 1/2$, and the opposite otherwise.*

In our context, we found that spillovers reduce the R&D incentives because of free-riding effects, which translates into a reduction in the demand for high-skilled workers, and consequently, in a decrease in their income (Part (a2) of Proposition 3). This conclusion is particularly robust. Consequently, the reduction in the R&D costs explains the increase in profits and in the capital owners' income (Part (a1) of Proposition 3).[18]

The overall effect of spillovers on top income depends crucially on the magnitude of the increase in capital income with respect to the reduction in the high-skilled workers' income. We have two cases:

(i) In the case that knowledge spillovers are low ($\beta < 1/2$), the top income increases (Part (a) of Proposition 3), but not the bottom income (Part (b) of Proposition 3). Consequently, income inequality increases (Part (c) of Proposition 3). Intuitively, lower spillovers imply lower free-riding behavior. Consequently, the R&D competition is higher, which is materialized by larger investments in R&D. However, as we consider higher spillovers, the R&D competition is replaced by product market competition. In this case, the increase in production does not compensate for the R&D improvements in the production process, which leads to a reduction in the low/medium-skilled workers' income and to an increase in

[18]*Technical note*: The increase in capital income is true in general. Under condition (A4) (see the appendix), the inequality in Part (a1) of Proposition 3 is always true for $\beta \in [0, 0.95)$ and $\gamma \in [1.82, \infty)$, see Footnote 15. Therefore, a reduction in capital income requires spillovers of unlikely magnitude. For that reason, we do not discuss this possibility in detail.

income inequality. This result is compatible with the observation that in recent years an increasing number of low/medium-skilled jobs are being automated and replaced by robots, and consequently, are being negatively affected by technological developments (Acemoglu & Autor, 2012; Hémous & Olsen, 2014).

(ii) In the case that knowledge spillovers are high ($\beta > 1/2$), we observe the opposite scenario, that is, a decrease in the income inequality.[19] In this case, the R&D free-riding effects are stronger. Consequently, the R&D incentives and the associated technological developments in the production process are weak, which sustain an increase in the low/medium-skilled workers' income. Simultaneously, the top income decreases because the high-skilled workers' income is affected by the low R&D investment incentives due to free-riding effects, which cancels out the potential gains in terms of capital income.[20]

5.1 | Discussion

As a general conclusion, the effect of spillovers on income inequality depends on their intensity and magnitude. Consequently, we cannot state unequivocally that spillovers have contributed to the income inequality observed in recent decades because we do not know their intensity and magnitude, which could have oscillated with the time.

Nonetheless, we believe that the periods of high knowledge spillovers, which could have resulted in reductions in income inequality, are likely to have been temporary exceptions in the process of technology development (e.g., fundamental discoveries and breakthroughs). The reason is that to contradict the negative effects of spillovers on their income, the capital owners lobby has continually searched for appropriation mechanisms—for instance, by means of patents and copyright, but also by means of other multiple strategic and integration decisions. For instance, the increasing horizontal integration trend observed in recent decades (see Section 4) can also be seen as the capital owners attempt to limit and control spillover effects.

Simultaneously, the public good property of innovation (i.e., nonexcludable and nonrivalrous), which is linked with the existence of spillovers effects, has been a major argument in favor of public R&D incentives. The R&D investments are not profitable if not sufficiently appropriated. In this context, the capital income lobby has been demanding increasing amounts of public R&D incentives. This observation may help explain the increasing public R&D trend observed in recent decades (see Section 3).

On the other hand, the low/medium-skilled workers lobby (i.e., trade unions, political parties, and other social mechanisms) may have not been able to counterbalance this situation. This failure is in part justified by a technology-induced change in the labor market institutions and the deunionization trend observed in recent decades.

Therefore, in our perspective, to decrease income inequality, policymakers must limit the influence and power of the capital income lobby, either by means of new and better institutions

[19]The case of large spillovers is particularly sensitive. For instance, Amir (2000) expresses some concerns regarding the validity of the d'Aspremont and Jacquemin approach in dealing with large spillover values, while Chalioti (2019) argues that when the R&D decisions are strategic complements, larger spillovers may foster innovation.

[20]In this paper, we analyze public R&D incentives, horizontal integration, and spillovers effects independently of each other. However, in reality, they occur simultaneously, and they are largely interconnected, which strengthens even more our argument that income inequality is strongly related to undesirable side effects inherent to technological progress. Consequently, if we consider all these events simultaneously, it is likely that income inequality increases even in the presence of strong spillover effects.

or by means of the redistributive policy.[21] Considerations of this kind may have motivated direct taxation of top income, as defended by Piketty (2014), as a form of balancing a system that might be unbalanced and perhaps unsustainable.

6 | DISCUSSION AND POLICY CONSIDERATIONS

In this section, we further discuss our results and suggest possible solutions to the income inequality problem. In particular, we focus on the aspects that are most closely related to this paper.

Regarding horizontal integration (understood in a wider sense, ranging from M&A, concentration strategies or business alliances to other dissimulated strategic movements), in our perspective government and competition agencies should be stricter and play a more active role. For instance, in recent years, Alphabet (Google) has acquired more than 200 companies. Other technology giants, such as Facebook, Microsoft, Oracle, SAP, Apple, IBM, Salesforce, Twitter, or Yahoo, just to mention just a few, have followed similar strategies. The world seems to be moving towards an economy owned by a small group of individuals and firms with increasing bargaining and institutional power, which tends to perpetuate income and wealth inequality.

Simultaneously, contrary to the common perception, entrepreneurship and startup success is becoming increasingly difficult. The failure rate of new businesses is high, and the average economic impact of successful entrepreneurship is low (Shane, 2008). Nowadays, the firms' competitive capacity depends crucially on innovation. In this context, many entrepreneurs and small firms seem to accept that they cannot compete with large firms for long periods of time. Consequently, they do not have long-term goals other than being acquired by a large company. On the other hand, large companies seem to face no long-term threats—as they can avoid competition by acquiring raising small-size potential competitors and their technologies (Phillips & Zhdanov, 2013). In our perspective, some of these acquisitions are passing unnoticed by public authorities and competition agencies, which seem to be more concerned with operations between large corporations. The implication might be the extinction of the "middle-class" of capital owners, which strengthens income and wealth inequality.

These observations seem to support the idea that income inequality is associated with differences between firms in terms of capacity.

Our results seem to suggest restrictions on horizontal and vertical integration and other similar strategic decisions by large corporations. In our perspective, public authorities and competition agencies should enact new legislation on M&A and antitrust behavior, and should focus on removing and weakening anticompetitive obstacles. Moreover, since most strategic decisions involve considerations with implications in several markets, which are supervised by different countries and competition agencies, we may need independent supranational institutions on competition and antitrust issues with sufficient legal and enforcement power.[22]

We support an "industry welfare state" with progressive taxation of large corporations (based on their size and market power), and lower taxation to entrepreneurs and SMEs. This

[21]The negative effect of lobbies in the process of technology diffusion and adoption is shown in Comin and Hobijn (2009). Aghion et al. (2015) show the negative effect of lobbies in entrepreneurship, and social mobility.

[22]Political and economic institutions may play a more important role in explaining the patterns of income inequality than other economic factors. Comin and Hobijn (2009) show the negative effects of lobbies, political and institutional barriers in the process of technological progress.

type of taxation may require more precise measures of market power, the creation of new institutions and the reinforcement of the existing ones.

In our perspective, public R&D incentives should be directed to entrepreneurs and SMEs, to support the establishment and survival of efficient firms, and stimulate growth and welfare.[23] Nonetheless, a bias in public R&D incentives towards entrepreneurs and SMEs may not be enough to solve the income inequality problem in markets that are already dominated by large corporations. Consequently, we may need to consider alternative and complementary policy instruments. In this context, we believe that taxation can play an important role in reducing income inequality, in particular taxation on wealth. We acknowledge Piketty's (2014) proposal of a global tax on wealth with progressive taxation of top incomes and redistribution at the bottom incomes (see Aghion et al., 2015; Auerbach & Hassett, 2015 for alternative solutions).[24]

7 | CONCLUSION

In this paper, we consider the effect of public R&D incentives, horizontal integration, and spillovers on income distribution and inequality. The goal is to study how these technologically related aspects impact on different types of income in contexts in which firms strategically compete for consumers in the product market and in R&D.

The approach and the results obtained are novel in the context of the existing literature. Altogether, we address a series of relevant issues for income inequality that have not been studied by the industrial organization and microeconomics literature. This paper attempts to close this gap.

Our results suggest that the increasing public R&D incentives and horizontal integration may have played an important role in the increasing income inequality observed in recent decades. As explained in this paper, the mechanisms are different, but the implications are similar. The effect of spillovers on income inequality is less clear-cut, as it depends on their intensity.

Our approach and findings are novel in the industrial organization and microeconomics context, but they are also consistent with the existing macroeconomic explanations and theories (see Section 1), for example, the globalization, the firms scale, and the skill-biased technical change theories. Our results are also consistent with the existence of correlation between the high-skilled and capital incomes (Hornstein et al., 2005), and that a large portion of top income is earned by innovators and capital owners (Aghion et al., 2015). Our results are also in line with the increasing trend towards automation and robotization of many low/medium-skilled tasks and the fall on the returns of these workers (Acemoglu & Autor, 2012; Hémous & Olsen, 2014).

The main conclusion of this paper is that R&D and technology are key elements for the growth and the progress of our society. Technological progress is desirable and should be potentiated, but to reduce the effects of technology and R&D on income inequality, we should take adequate policies in terms of income redistribution. In this context, we should be attentive to undesirable side effects and search for remedies to the income inequality that do not affect

[23]This is a particularly sensitive issue in the actual context in which different countries offer different R&D incentives to their industries. The world harmonization of the public R&D policy seems to be an objective difficult to achieve in the short-run.

[24]The risk of overtaxing capital income is a reduction in the investment and R&D incentives, and consequently, a slow down on the overall economic activity. A global tax rate also involves nontrivial considerations regarding tax havens and unequal taxation among countries. From our perspective, taxation is a complementary policy instrument and cannot solve the income inequality problem alone, without removing incentives and affecting growth.

the virtuous process of technological progress.[25] This seems to be the greatest challenge of public policy.

Finally, we expect that our results and policy recommendations will help decision-makers designing and implementing more effective competition and income inequality policies with minimum impact on the firms' R&D incentives and on economic growth.

ACKNOWLEDGMENTS

Support from the GRODE Spanish Ministry of Science and Innovation, Generalitat de Catalunya and the Spanish Ministerio of Ciencia y Innovación projects RTI2018-094733-B-100 (AEI/FEDER, UE) and PID2019-105982GB-I00, and the Portuguese Foundation for Science and Technology (FCT) projects PTDC/MAT-NAN/6890/2014 and PTDC/MAT-APL/31753/2017 are gratefully acknowledged. We would like to thank Ricardo Ribeiro, Juan Pablo Rincón-Zapatero, Peter Thompson, and Dirk Van de Gaer, as well as the participants in several seminars and congresses for their helpful comments and discussions. All remaining errors are ours.

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[25]Most of the issues raised in this paper can be the subject of further research. For instance, we can consider human capital and wages specific aspects, as well as other income groups, different forms of integration and public R&D incentives. Considerations of this kind can be added at the cost of more complexity, but they are unlikely to affect our main conclusions. Regarding this aspect, we found our results particularly robust. From an empirical perspective, we can consider new measures and hypotheses about the effects of the public R&D incentives, horizontal integration, and spillovers on income distribution and inequality. There seems to be plenty of work to be done in this direction.

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How to cite this article: Osório A, Pinto A. Income inequality and technological progress: The effect of R&D incentives, integration, and spillovers. *J Public Econ Theory*. 2020;22:1943–1964. https://doi.org/10.1111/jpet.12466

APPENDIX A: PROOFS OF THE PROPOSITIONS

Proof of Propositions 1, 2, and 3. To prove our results, we must first obtain the equilibrium of the model and then the expressions for k_i, $\underline{w}_i$, $\overline{w}_i$, $\overline{y} = k_i + \overline{w}_i$, $\underline{y} = \underline{w}_i$, and G. Start by replacing (4) in the objective function (5). Then, by backward induction, differentiate Expression (5) with respect to q_i for $i = 1, 2$, to obtain the system of first-order conditions:

$$(1-\omega)(3+4(x_i+\beta x_{-i}))/4 - 2(1-\omega)q_i - q_{-i} = 0 \tag{A1}$$

for $i = 1, 2$. The second-order condition is trivially satisfied. Subsequently, solve this system of two equations and two unknowns with respect to q_1 and q_2. Then, replace the obtained quantities q_1 and q_2 back into the objective function (5) to obtain k_i for $i = 1, 2$, as a function of x_1 and x_2 only. Subsequently, obtain the new set of first-order conditions by differentiating the objective function with respect to x_i for $i = 1, 2$. The second-order condition for a maximum is satisfied if $\gamma \geq 2(2-\beta)^2/9$ for $\omega \downarrow 0$. Note that after differentiating the expressions associated with the parameters γ, ω, and β, we let $\omega \downarrow 0$. This technical assumption is made to reduce the size and the number of parameters and to make the expressions obtained more tractable. The symmetric solution of the associated system of two equations and two unknowns is given by

$$x_i = \frac{3(2(2-\beta)-(1-\beta)\omega(5-2\omega))}{4(\gamma(3-2\omega)^2-(1+\beta)(2(2-\beta)-(1-\beta)\omega(5-2\omega)))} \tag{A2}$$

for $i = 1, 2$. Then, replace the equilibrium expressions in q_i for $i = 1, 2$, obtained from the system (A1) to obtain the equilibrium quantities:

$$q_i = \frac{3\gamma(1-\omega)(3-2\omega)}{4(\gamma(3-2\omega)^2-(1+\beta)(2(2-\beta)-(1-\beta)\omega(5-2\omega)))} \tag{A3}$$

for $i = 1, 2$. Now, the capital income expression is obtained by replacing (A2) and (A3) in (5):

$$k_i = \frac{9\gamma(2\gamma(3-2\omega)^2(1-\omega) - (2(2-\beta) - (1-\beta)\omega(5-2\omega))^2)}{32(\gamma(3-2\omega)^2 - (1+\beta)(2(2-\beta) - (1-\beta)\omega(5-2\omega)))^2}$$

for $i = 1, 2$. Similarly, to obtain the low/medium-skilled labor income, the high-skilled labor income, and the top-level income, respectively, simply replace (A2) and (A3) into (2), (3) and (7), to obtain

$$\underline{y} = \underline{w}_i = \frac{3\gamma(1-\omega)(3-2\omega)(\gamma(3-2\omega)^2 - 4(2(2-\beta) - (1-\beta)\omega(5-2\omega))^2)}{16(\gamma(3-2\omega)^2 - (1+\beta)(2(2-\beta) - (1-\beta)\omega(5-2\omega)))^2},$$
$$\overline{w}_i = \frac{9\gamma(2(2-\beta) - (1-\beta)\omega(5-2\omega))^2}{32(\gamma(3-2\omega)^2 - (1+\beta)(2(2-\beta) - (1-\beta)\omega(5-2\omega)))^2},$$

and

$$\overline{y} = \frac{9\gamma^2(1-\omega)(3-2\omega)}{16(\gamma(3-2\omega)^2 - (1+\beta)(2(2-\beta) - (1-\beta)\omega(5-2\omega)))^2}$$

for $i = 1, 2$, respectively, with $0 \le \underline{y} \le \overline{y}$ guaranteeing that the top income mass is larger than the bottom income mass. Finally, the Gini coefficient in (6) becomes

$$G = \frac{1}{2}\left(\frac{\gamma(9-6\omega)}{\gamma(3-\omega)(3-2\omega) - (1+\beta)(2(2-\beta) - (1-\beta)\omega(5-2\omega))} - 1\right).$$

Note that for $\omega \downarrow 0$ the denominator in x_i and q_i is nonnegative for $\gamma \ge 2(1+\beta)(2-\beta)/9$ (as well as $\overline{w}_i \ge 0$ and $c_i(x_1, x_2) \ge 0$), and $\underline{y} \ge 0$ for

$$\gamma \ge 8(2-\beta)(1+\beta)/9 \in [1.78, 2] \tag{A4}$$

for $\beta \in [0, 1]$. Inequality (A4) establishes the relevant range of parameters because it guarantees in simultaneous that $x_i, q_i, k_i \ge 0$, that $0 \le \underline{y} \le \overline{y}$ for $i = 1, 2$, and that the obtained equilibrium corresponds to a maximum. Any $\gamma \ge 2$ satisfies all these conditions and any $\gamma < 1.78$ fails some of these conditions. Therefore, in what follows, we assume that condition (A4), which implies that the denominator of the following expressions is positive, therefore, the sign of each derivative is given by the sign of the numerator.

To show Part (a) of Propositions 1, 2, and 3, we differentiate $\overline{y}$ with respect to γ, ω, and β, respectively, evaluated at $\omega \downarrow 0$, which is given by

$$\partial\overline{y}/\partial\gamma = -81\gamma(2-\beta)(1+\beta)/(4(9\gamma - 2(2-\beta)(1+\beta))^3),$$
$$\partial\overline{y}/\partial\omega = 27\gamma^2(9\gamma - 2(1-8\beta)(1+\beta))/(16(9\gamma - 2(2-\beta)(1+\beta))^3),$$

and

$$\partial\overline{y}/\partial\beta = 81\gamma^2(1-2\beta)/(4(9\gamma - 2(2-\beta)(1+\beta))^3),$$

respectively. Since $\beta \in [0, 1]$, the expression of the first derivative is negative, while the expression of the second derivative is positive by condition (A4). The expression of the third derivative is positive only if $\beta < 1/2$.

To show Part (a1) of Propositions 1, 2, and 3, we differentiate k_i with respect to γ, ω, and β, respectively, evaluated at $\omega \downarrow 0$, which is given by

$$\partial k_i/\partial\gamma = 9(2-\beta)(2(2-\beta)^2(1+\beta) - 27\beta\gamma)/(8(9\gamma - 2(2-\beta)(1+\beta))^3),$$
$$\partial k_i/\partial\omega = 81\gamma^2(3\gamma - 2 - 2\beta(2-5\beta))/(16(9\gamma - 2(2-\beta)(1+\beta))^3),$$

and

$$\partial k_i/\partial\beta = 9\gamma(27\gamma(1-\beta) - 2(2-\beta)^3)/(4(9\gamma - 2(2-\beta)(1+\beta))^3),$$

respectively. The first derivative is negative under condition $\gamma > 8(2-\beta)^2(1+\beta)/(27\beta)$, which by condition (A4) is true for $\beta > 1/2$ or $\gamma > 2$. The second derivative is positive always under condition (A4). The third derivative is positive under condition $\gamma > 2(2-\beta)^3/(27(1-\beta))$, which by condition (A4) is true for $\beta < 2(1+3\sqrt{3})/13$ (approximately $\beta < 0.95$) or $\gamma > 16(14+3\sqrt{3})/169$ (approximately $\gamma > 1.82$).

To show Part (a2) of Propositions 1, 2, and 3, we differentiate $\overline{w}_i$ with respect to γ, ω, and β, respectively, evaluated at $\omega \downarrow 0$, which is given by

$$\partial\overline{w}_i/\partial\gamma = -9(2-\beta)^2(9\gamma + 2(2-\beta)(1+\beta))/(8(9\gamma - 2(2-\beta)(1+\beta))^3),$$
$$\partial\overline{w}_i/\partial\omega = 27\gamma^2(2-\beta)(1+7\beta)/(8(9\gamma - 2(2-\beta)(1+\beta))^3),$$

and

$$\partial\overline{w}_i/\partial\beta = -9\gamma(2-\beta)(9\gamma - 2(2-\beta)^2)/(4(9\gamma - 2(2-\beta)(1+\beta))^3),$$

respectively. It is easy to see that the expression of the first derivative is always negative while the expression of the second derivative is always positive. The expression of the third derivative is always negative by condition (A4).

To show Part (b) of Propositions 1, 2, and 3, we differentiate $\underline{y}$ with respect to γ, ω, and β, respectively, evaluated at $\omega \downarrow 0$, which is given by

$$\partial\underline{y}/\partial\gamma = 9(2-\beta)(1+\beta)(9\gamma + 4(2-\beta)(1+\beta))/(4(9\gamma - 2(2-\beta)(1+\beta))^3),$$
$$\partial\underline{y}/\partial\omega = -3\gamma(81\gamma^2 + 40(2-\beta)(1+\beta)^3 - 54\gamma(3-\beta-4\beta^2))/(16(9\gamma - 2(2-\beta)(1+\beta))^3),$$

and

$$\partial\underline{y}/\partial\beta = 9\gamma(2\beta - 1)(9\gamma + 4(2-\beta)(1+\beta))/(4(9\gamma - 2(2-\beta)(1+\beta))^3),$$

respectively. The expression of the first derivative is trivially positive. The expression of the second derivative is always negative under condition (A4). The expression of the third derivative is positive if $\beta > 1/2$.

To show Part (c) of Propositions 1, 2, and 3, we differentiate G with respect to γ, ω, and β, respectively, evaluated at $\omega \downarrow 0$, which is given by

$$\partial G/\partial \gamma = -18(2-\beta)(1+\beta)/(9\gamma - 4(2-\beta)(1+\beta))^2,$$
$$\partial G/\partial \omega = 3\gamma(9\gamma - 2(7-11\beta)(1+\beta))/(2(9\gamma - 4(2-\beta)(1+\beta))^2),$$

and

$$\partial G/\partial \beta = 18\gamma(1-2\beta)/(9\gamma - 4(2-\beta)(1+\beta))^2,$$

respectively. The expression of the first derivative is trivially negative. The expression of the second derivative is positive under condition (A4). The expression of the third derivative is positive for $\beta < 1/2$. □