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Scale Effects, An Error of Aggregation Not Specification:

Empirical Evidence

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Abstract

In a set of influential papers, Charles Jones (1995a, 1995b, 1999) argued that R&D based endogenous growth models are inconsistent with the data. He showed, in a very striking manner, that the scale effects prediction of early endogenous growth models (e.g. Romer, 1986 and 1990, Grossman and Helpman, 1991, and Aghion and Howitt, 1992) is not borne out in the data. Standard endogenous growth models attribute constant or increasing returns in the stock of knowledge or technology to the aggregate level of resources. This assumption leads to the counterfactual prediction that the rate of productivity growth should be increasing in the aggregate amount of resources devoted to accumulating knowledge. This paper presents empirical evidence in support of R&D based endogenous growth models without scale effects (e.g. Young, 1998, Howitt, 1999, Thompson, 2001, and Peretto and Smulders, 2002). In these models the *average* level of workers or R&D workers per firm drives growth as opposed to the aggregate level and do not share the scale effects property in the limit. Using data for the US covering 1964-2001, we show that when the number of employees or scientists/engineers are scaled down on a per establishment basis, the empirics support the latter version of endogenous growth models. Specifically, the long-run size of establishments is stable, neither declining or growing in the long-run, where size is measured in two ways: by workers per establishment and R&D workers per establishment. Second, we demonstrate a positive effect running from average establishment size to productivity growth as predicted by the theories.

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1 Introduction

In an important set of articles, Charles Jones (1995a, 1995b, 1999) critiques the "scale effect" prediction of endogenous growth models (e.g Romer, 1990, Grossman and Helpman, 1991a, 1991b, 1991c, and Aghion and Howitt, 1992). The scale effect suggests that increases in the labor endowment of an economy should lead to higher productivity growth rates. Jones clearly demonstrates that this prediction is inconsistent with the data. We share this view. However, Jones goes on to contend that there must therefore be decreasing returns to scale in knowledge accumulation in order to avoid the scale effects prediction. The most recent study of the aggregate knowledge production function by Porter and Stern (2000), in contrast, cannot reject constant returns.

In the basic endogenous growth models cited above, constant returns in knowledge production are ascribed to the *aggregate* level. Instead, models of firm-based knowlege production, such as Young (1998), Howitt (1999), and Peretto (1999), posit non-decreasing returns to knowledge production at the firm level and do not have scale effects predictions. Employment $per\ firm$ drives growth, not the aggregate level of employment. Higher employment per firm increases the rate of growth of the knowledge stock. Entry by firms into new product lines also contributes to growth. An increase in the level of employment does allow firms to increase their size, but simultaneously it induces entry of new firms which draw labor away from incumbents leaving the average size stable in the long run.

Jones (1999) criticizes this latter set of models for essentially requiring a "knife-edge" condition where the relationship between the size of the workforce and the number of firms is proportional. Specifically, in the absence of policy shocks, long-run average firm size should be stable. If this fails to hold, either average firm size grows leading to explosive growth or average firm size falls leading to a model with decreasing returns in knowledge production. Within the models, this "knife-edge" relationship follows from an arbitrage condition that equalizes the rate of return between R&D conducted by incumbent firms and the returns to establishing firms selling new varieties.

Here we look specifically at this prediction using data on employment, R&D personnel, and the number of establishments in the US. For the available data from 1964 to 2001, the prediction of long-run stable size appears quite reasonable and we cannot reject the proportionality hypothesis.

While previous studies have looked at the basic implications of earlier endogenous growth models (e.g. Jones 1995a, 1995b, Dinopolous and Thompson, 1999), no one has looked directly at the basic implications of models that distinguish the firm level knowledge production function from the aggregate. Our main contribution lies in undertaking this task. While for the US the total number of R&D workers undoubtedly increases with no apparent matching change in the long-run trend in productivity, R&D personnel on a per establishment basis exhibits remarkable stability. Moreover, in all of the models of this class, average firm size is positively related to growth rates. We present results of some basic time series tests consistent with this prediction.

We present our argument below first by briefly reviewing various approaches to the scale effects in section 2. Section 3 provides a simplified version of the R&D based growth models without scale effects and looks empirically at two basic results of these models. Section 4 extends the analysis by showing the trend in average establishment size across sectors of the US economy and briefly presents available international data. Section 5 concludes.

2 Scale Effects in Endogenous Growth Models

2.1 Constant Returns in the Knowledge Production Function

Consider a simplified model where Y is output, A is productivity, L_Y is labor used in producing output, L_A is labor engaged in R&D, and δ is a parameter governing R&D productivity:

$$Y = AL_Y \tag{1}$$

$$\frac{\dot{A}}{A} = \delta L_A \tag{2}$$

and

$$L_Y + L_A = \bar{L}. \tag{3}$$

The first equation is the aggregate production function; the second is the knowledge production function; and the third is the labor resource constraint.

In equilibrium, both activities employ some fraction of labor. With an increase in the size of the workforce, $\bar{L}$, the shares of the workforce devoted to each activity remains the same in the new equilibrium. But the increase in the level of workers engaged in R&D causes the growth rate to rise permanently. Denote the share of the workforce in R&D as s. Then the growth rate of per capita income is:

$$g_y = \delta s L. \tag{4}$$

Therefore, doubling the level of the workforce yields a doubling of the growth rate. It is this prediction that cannot be reconciled with the data, except, perhaps, in very broad historical terms (See Kremer, 1993, and the discussion in Dinopolous and Thompson, 1999). Figure 1 plots the natural log of the 1960 population levels against the real GDP per capita growth rates between 1960 and 2000 for 107 countries.[1] There is no obvious relationship between the two variables as documented in other studies (e.g. Backus, Kehoe, and Kehoe, 1992 and Dinopoulos and Thompson, 1999).

One could argue that endogenous growth models are not well-suited to developing nations because standard neo-classical dynamics of factor accumulation are more appropriate (See Young, 1995, for example) in countries where little R&D takes place. If we look only at the OECD countries (excluding the new member transition economies), no clear relationship emerges as shown in Figure 2.[2] Studies such as Backus, Kehoe, and Kehoe (1992) which look more carefully for evidence of scale effects provide very little supportive evidence. In that study using cross-country

[1] The source is the Penn World Tables 6.1. For Germany, 1970 is the starting point as the 1960 values not included in the Penn World Tables.

[2] Data are from 1960-2000. For some countries the data start at a later date. The source is the Penn World Tables 6.1.

data, the authors fail to find evidence that the scale of the economy, R&D levels, or the size of the scientific and engineering workforce is significantly related to GDP per capita. They do find, however, that the scale of the manufacturing sector is positively and significantly related to the growth rate of manufacturing output per worker. However, their analysis is cross-country making interpretation of the coefficient on the scale of the manufacturing sector difficult due to potentially ommitted variables.

An alternative approach to the question of whether the scale effect exists or not has been to compare growth rates over a long time horizon. Romer (1986) and Jones (1995a) take this approach finding higher growth rates in the post World War II era than before the inter-War period. Even more convincingly, Ben-David and Papell (1995) allow for endogenously determined structural breaks. They find growth rates increased in the Post-World War I era for most countries, and after the Great Depression for most others. While the evidence suggests some increase in growth rates of per capita GDP over a long-time horizon, the tests do not provide any information on the source or sources of higher growth rates. Ben-David and Papell point out that the structural breaks in the time series represent periods of upheaval when strong coalitions can be broken leading to a more efficient allocation of resources. Increases in the trade could just as easily explain the change in growth rates. Thus, while rising growth rates over time are consistent with models with scale effects, many potential explanations are possible.

Rather than appeal to the cross-country evidence, focusing on the time series behavior for the US alone reveals the problem. Figures 3 and 4 show US data only. Figure 3 graphs the total amount of employment in the US economy from 1964 to 2000 taken from County Business Patterns and contrasts this with the growth rate of the Private Business Productivity Index (PBP) reported by the Bureau of Labor Statistics (BLS). Clearly PBP growth shows no significant upward or downward trend while the total amount of employment in the economy over that period is growing at an average annual rate of 2.54%. Figure 4 shows the same productivity measure against the total number of R&D personnel over the same time period, where the total number of personnel devoted to research grew at an annual rate of 2.38%. The basic story is clear. As in Jones (1995b), there is an increasing trend in the number of personnel and R&D personnel, although productivity shows no obvious increases as predicted by models with scale effects.

If the scale effects prediction is not consistent with the data, but we wish to retain the appealing feature of these models that productivity growth is endogenous, then where exactly does the scale effects problem lie? One argument contends that the constant returns to scale assumption in (2) drives the result and the function is mis-specified. The solution is to re-introduce diminishing returns to the knowledge production function. A different approach observes that equation (2) implies that if there are, say, one million scientists and engineers in the economy, then allocating them to one million firms or piling all of them into just one single firm will have no effect on the growth rate of the economy. But if there are increasing returns in knowledge creation at the firm level, then each firm's contribution to the stock of knowledge depends on its size. Therefore, the scale effects problem follows from failing to account for how the economy allocates its resources across productive units. We now turn to discussing the implications of these two theoretical arguments.

2.2 Decreasing Returns in Knowledge Production Function

The theoretical literature provides two approaches for removing the scale effects in endogenous growth models.[3] One approach assumes R&D becomes more difficult over time (Jones, 1995b, Kortum, 1997, and Segerstrom, 1998). These models predict that policy has no impact on long-run growth rates, only affecting the transition path. The second approach retains the policy implications of the early endogenous growth models, but spreads the resources of the economy into a greater number of varieties or firms (Young, 1998, Howitt, 1999, and Peretto & Smulders, 2002).[4] These models predict that average firm size is stable; the so-called "knife-edge" condition

[3] Dinopolous and Thompson (1999) discuss the implications of both extensively.

[4] An important exception here is Young (1998) which eliminates the scale effect, but also removes the effectiveness of policy to alter the long-run growth rate. In that model constant returns to scale on both the intensive (R&D by incumbents) and extensive (entry into new products) margins imply that entry will instantly dissipate any gains

mentioned in the introductory section.

Following Jones (1999) we can see the implications of these two groups of models in a reduced form. For the former (2) becomes:

$$\dot{A} = \delta L_A A^{\phi} \tag{5}$$

where $\phi < 1$. Innovations building on past discoveries becomes progressively harder, i.e. the knowledge production function of the economy exhibits decreasing returns. Thus, productivity growth is given by:

$$\frac{\dot{A}}{A} = \delta L_A A^{\phi - 1} \tag{6}$$

and along the balanced growth path we have:

$$g = \frac{n}{1 - \phi} \tag{7}$$

where n is the growth rate of the population. The model implies a proportional relationship between population growth and productivity growth. Now higher population *growth rates* lead to higher output per capita growth rates. Figure 5 plots population growth rates against real GDP per capita growth again using the Penn World Tables. Figure 6 looks at the relationship for OECD countries only. As in Figure 1, no obvious relationship emerges, though basic trend lines show the opposite result.

The model sketched above produces a different relationship between growth and the size of the population. The *level* of the population does not affect the long-run growth rate, but the growth *rate* of the population should be proportional to growth. However, the level of the population conducting research, sL, does affect the level of per capita income in a manner similar to the Solow growth model. Looking at the transition to steady-state, the model implies the per capita income at time t is given by:

$$y^*(t) = (1 - s) \left(\frac{\delta(1 - \phi)}{n} sL(t) \right)^{1/(1-\phi)} . \tag{8}$$

from policies that attempt to increase R&D incentives, such as a subsidy. In contrast, Howitt (1999) shows that with decreasing returns to incumbent R&D, the long-run growth rate will respond to policy.

Taking logs and derivatives, we find that

$$\frac{\dot{y^*}}{y} = \frac{1}{1-\phi}\left(n - \frac{\dot{n}}{n}\right) \tag{9}$$

which implies per capita income growth is positively related to the rate of growth in the population, but negatively related to the rate of change in the rate of growth in the population.

The appendix reports some simple results from testing equations (7) and (9) directly on the OECD data. While endogeneity problems persist, the results imply that the value of $1/(1-\phi)$ is approximately -0.2 which, in turn, implies $\phi \approx 6$, well outside of $0 < \phi < 1$. If we allow for a generalization of the production function, such that $Y = A^\sigma L_Y$, (7) becomes

$$g = \frac{\sigma n}{1-\phi}. \tag{10}$$

Now ϕ can take on values less than one when $\sigma/(1-\phi) = -0.2$. However, it generates the counterfactual prediction of $\sigma < 0$ which means that resources devoted to knowledge accumulation *lower* the productivity of the economy because increases in A now make workers less productive.

Beyond those suggestive results, however, we can turn to the huge body of empirical work by economists and demographers alike on the relationship between growth and population to ask if the evidence support the basic result that population growth and per capita growth are positively correlated. The answer is no. In fact, Kelley and Schmidt (2003) begin their survey of economic and demographic change by quite clearly stating that, "No empirical finding has been more important to conditioning the 'population debate' than the widely-obtained statistical result showing a general *lack* of correlation between the growth rates of population and per capita output."[5] After reviewing the latest work in the area, they go on to conclude that more recent empirical work demonstrates a net negative impact of rapid population growth on per capita standards of living. However, they repeatedly caution that drawing any strong conclusion based on the latest empirical work at this point is premature.

[5] Emphasis in the original.

Other empirical cast doubt on this class of models. First, Porter and Stern (2000) use international patent data to construct both global and country level knowledge production functions to estimate ϕ. They cannot reject $\phi = 1$ which creates immediate problems for the theory. If those estimates are correct, then growth according to the theory would explode.

In addition, one of the key implications of this class of models is that policy changes have only level effects on GDP per capita not growth effects. Thus, the term "semi-endogenous" growth is applied, since the models incorporate the production of A explicitly but find that governments have no control over its long-run growth rate. Kocherlakota and Yi (1997) devise a test between exogenous and endogenous growth models by examining the time series behavior for the US and UK separately rather than appealing to cross-country regressions. They look at the effect of taxation and public expenditure on the long-run growth rates. If policy has no effect then the sum of the coefficients on the policy variables should be zero. However, they find that both coefficients are significant and the sum is significantly different from zero. They interpret these findings to mean that policy does indeed have long-run effects on growth rates in contrast to the model discussed in this section.

Recall that in the earlier endogenous growth models, the problem was that doubling L led to a doubling of the growth rates. Now a doubling of the growth rate should double the per capita output growth rate. Neither of these predictions, based on alternative specifications of the knowledge production function shows up clearly in the data. The models in the next section, in contrast, predict that a doubling of the workforce should coincide with a doubling of the number of firms and firm size is positively related to per capita growth rates. To the best of our knowledge, no one has looked directly at these implications to date.

3 Firm Specific Knowledge Production Function with Non-Decreasing Returns

3.1 A Reduced Form Representation

The second approach to eliminating the scale effects allows for expansion in the number of firms (or varieties of products). As the size of the workforce grows so does the number of firms. Productivity growth depends on the R&D intensity at the firm level because each productive unit has fixed costs creating increasing returns to scale at the firm level consistent with the literature reviewed in Baldwin and Scott (1987) and Cohen and Levin (1989). More resources per firm allows firms to move down their average cost curves and increase their individual rates of knowledge accumulation. On the other hand, increases in the number of firms (varieties), draws labor away from incumbents driving them up their average cost curves. Thus, the scale effect vanishes in the limit as the number of firms grows.

We present this exposition by borrowing notation used elsewhere in the literature (See Jones, 1999, and 2003). This "reduced form" representation aids in focusing attention on the key implications of the theory, however it masks a great deal of subtlety behind the results.

Assume there are B firms (the upper limit in the integral of a Dixit-Stiglitz function) which grows with the economy and denote the elasticity of substitution between varieties by θ. Aggregate consumption, using symmetry, is given by $C = B^{\theta}Y$. We use the same form for the knowledge production function as in (2), but rewrite it as:[6]

$$\dot{A}_i = \delta L_{Ai} A_i \tag{11}$$

where i refers to each firm. Thus, the same functional form appears but the relevant unit of analysis is entirely different. Each firm's stock of knowledge contributes to the pool of general knowledge allowing the entire economy to grow through spillovers.[7] On the balanced growth

[6] Supporting evidence for the firm based knowledge production function can be found in Griliches (Chapter 3, 1998). He uses a sample of large firms only in R&D intensive industries, but finds a positive and significant relationship between average employment levels in manufacturing establishments and value added.

[7] The spillover mechanism varies across models, but the result is the same. In Peretto (1999) there are no

path, growth rates in per capita consumption and output are equal and given by:

$$g = \theta g_B + g_A. \tag{12}$$

g_B is growth from expansion of varieties and g_A is growth from improved technology in existing sectors. As the scale of the economy grows, the contribution to growth from additional varieties falls to zero in the limit, i.e $g_B \to 0$. Contributions to the public stock of knowledge, which depend on average firm size, drive long-run economic growth rates.

How is average firm size determined? In the models, average firm size is endogenous. However, to focus attention on a key prediction of this class of models regarding resource allocation, we simplify this relationship. Let B represent the number of firms (or products) and L remains the size of the workforce. One way of writing the relationship between B and L is

$$B = \frac{1}{\eta} L^{\beta} \tag{13}$$

where β and η are positive parameters for the moment. The number of firms will be increasing, decreasing, or proportional to the size of the workforce depending on the value of β. Define average firm size as N which is given by:

$$N \equiv \frac{L}{B} = \eta^{1/\beta} B^{(1-\beta)/\beta}. \tag{14}$$

Taking logs and derivatives of the relationship between B and L:

$$\frac{\dot{B}}{B} \equiv \beta \frac{\dot{L}}{L} \tag{15}$$

The debate here is on the value of β. When $\beta = 1$, all the predictions of this class of models go through. When that condition holds, the long-run firm size is equal to η. If $\beta < 1$, then scale effects return as the size of each firm grows since the relationship implies $g_B = \beta n$. Workforce growth leads to larger firms, and consequently a faster accumulation of the stock of

spillovers between firms, but new entrants benefit from being able to enter at the current average level; in Dinopoulos and Thompson (1998) spillovers depend on average knowledge; and in Young (1998) and Howitt (1999) spillovers depend on the knowledge level of the frontier firms.

public knowledge. If $\beta > 1$, each firm becomes progressively smaller because population growth outstrips growth in the number of firms resulting in a negative scale effect. Furthermore, if $\beta > 1$, the models generate decreasing returns to scale since as the economy grows larger R&D becomes more difficult, as in the models of the previous section.

We look at the possibility that η is constant, i.e. $\beta = 1$, in the following subsection. Let us emphasize that $\beta = 1$ is *not* an assumption in the literature. Only in this reduced form representation does it appear as a parameter assumption akin to ϕ in the knowledge production function. That $\beta = 1$ follows from arbitrage between allocating resources to incumbent R&D and new entrants.[8] Hence, a test of $\beta = 1$ is a test of a prediction, not an assumption.

This class of models makes another prediction. Substitute (14) back into (11) to get:

$$g_c = \theta g_B + \delta N. \tag{16}$$

Since $\delta > 0$ growth is positively related to the average firm size in the economy. Thus, the key equation for the theories relates growth directly to firm size. We turn our attention to this prediction in section 3.3.

To summarize, early endogenous growth models predicted scale effects on the growth rate of per capita income. A larger workforce should imply a higher growth rate. This prediction is very difficult to reconcile with the data. We have two theoretical approaches to correcting this problem. The first posits decreasing returns to scale in the knowledge production function. Now growth rates of the workforce, not its level, influence the economic growth rates. As mentioned at the outset, the most recent study by Porter and Stern (2000) cannot reject constant returns. Moreover, it leads to a positive relationship between population growth and economic growth which is also difficult to reconcile with the data. The second solution eliminates the scale effects with the prediction that long-run average firm size is constant. In addition, it implies that

[8] We spare the readers the details here. See, for example, the appendix in Peretto and Smulders (2002) and Howitt (1999) for detailed discussions.

increases in average firm size should be associated with higher growth rates. We now turn to these two implications.[9]

3.2 Is Long-Run Average Firm Size Constant?

In evaluating this prediction, there is a key question of what is the appropriate unit of analysis. The theories divide the economy into varieties of goods or production lines with one product corresponding to a single firm. The micro-level knowledge production then corresponds to both an individual product and an individual firm. How should we treat multi-product firms? In addition, what about multi-plant firms? Two alternative measures are possible: 1) the number of firms; and 2) the number of establishments.

Unfortunately, we have not located a sufficiently long time series of the number of firms suited to this study. However, we do not believe the firm is the appropriate unit of analysis. Firms, as defined by the U.S. Census Bureau are a "business organization under a single management and may include one or more establishments." Establishments, in contrast, refer to a physical locations. Thus, when thinking about the models which separate each individual product line, establishments correspond better to varieties in the sense of either producing different products or the same product but for different geographic markets. Furthermore, strong micro-level evidence suggests that productivity and R&D only weakly correspond to firm size once plant and business unit levels are taken into account. Adams and Jaffe (1996) provide evidence that R&D per plant, not the firm, drives productivity growth. They find that productivity increases from R&D at the firm level are diluted once the number of plants are included in the regression. Similarly, Cohen and Klepper (1996) find that the relationship between R&D and firm size weakens significantly when controlling for business unit size.[10]

[9] Another implication of this class of models that differentiates is from models with decreasing returns is the behavior of innovations per researcher over time. The firm-based models predict the flow of innovations per worker is constant while the latter models predict it is decreasing. Dinopolous and Thompson (1999) look at this data, but are confounded by the well known problems of interpreting patent data. They conclude that the patent statistics do not provide evidence in favor of one group of models over the other.

[10] While we believe that the establishment level is, in fact, the appropriate unit of analysis for the current study, we are seeking a comparably long firm level series to compare and contrast with the results presented here.

Recalling the implications of Figures 3 and 4, there is an increasing trend in the number of employees and R&D personnel, although productivity shows no obvious increases as predicted by models with scale effects. Those picture changes dramatically when the variables are scaled down on a per establishment basis. Figure 7 shows total employees, population, total R&D researchers, and total number of establishments.[11] All four series grow over time at comparable rates. Figure 8 displays both employees per enterprise and R&D researchers per establishment. Neither variable displays any significant trend to the naked eye though both fluctuate. Note that the stability of the per enterprise variables contrastswith the sharp increase in the participation rate for the entire population and the fall in population per establishment. Interestingly, those latter two changes offset any large movements in the per establishment variables.

Figure 8b looks at the per enterprise variables more closely. Cursory inspection suggests several possibile interpretations for the long-run behavior of employees and R&D personnel per establishment. First, employees and R&D personnel per establishment do exhibit a positive growth trend and the events of the 1970s were a mere aberration and increased growth will continue. That would correspond to $\beta < 1$ from above. Under this scenario, employees per establishment will continue to grow in the coming decades exceeding the peak levels of the mid-1960s. Alternatively, the series fluctuate around their long-run steady state and the fluctuations correspond to various business cycle or exogenous policy shocks. Thus, following the sharp negative shocks of the 1970s, the amount of personnel employed per establishment slowly returned to its steady-state level. The second interpretation is consistent with the firm-based theories discussed above where $\beta = 1$. Moreover, the possibility that $\beta > 1$ does not appear reasonable. Recall that in the case of $\beta > 1$, the models of firm-specific knowledge production predict falling firm size which generates implications akin to the models with decreasing returns to scale in the knowledge production function.

Specifically, we are inquiring about the availability of annual firm level information in the Longitudinal Business Database.

[11] Total establishments in the economy and employees are from County Business Patterns and cover 1964-2000. R&D personnel data are from the National Science Foundation.

If neither employees per enterprise or R&D personnel per establishment are showing any significant trend, that would be consistent with the firm-based theories. Table 1 below shows the results from simple time trend tests on employees per enterprise and R&D workers per enterprise.

TABLE 1: Tests of Trends in Employees/Enterprise and R&D Personnel/Enterprise.

		Coefficient	Standard Error	Test-Statistic
1	Time Trend (Employees/Enterprise)	0.01085	0.012121	0.895
2	Augmented Dickey-Fuller Test	-0.389		-2.890
3	Time Trend (R&D Personnel/Enterprise)	1.52E-07	2.21E-07	0.687
4	Augmented Dickey-Fuller Test	-0.228089		-1.542

The tests show no evidence of a time trend in the employee per enterprise variable. The ADF test (2) rejects the unit root at the 10% level, but not quite at the 5% level.[12] For the R&D personnel per enterprise, however, we cannot reject a unit root, though the time trend test is not significant at the standard levels.[13] Both variables appear quite stable and exhibit little evidence of a trend in either direction, although data for the next few decades should help clarify whether there is a trend or not.

We also test for cointegration among employees, establishments, and R&D workers. Cointegration would suggest that the three time series are growing together at the same rate, i.e. $\beta = 1$. Table 2 provides the results of three different possibilities using the Johansen Cointegration test.

TABLE 2: Tests for Cointegration between Employees, Enterprises and R&D Personnel.

[12] The ADF critical value for the 10% level is -2.6105; for the 5% level it is -2.9446 and for the 1% level it is -3.6228.

[13] Both ADF tests were conducted with a constant only and no time trend. Adding a time trend in test (4) does not alter the results.

Test	Variables	Likelihood Ratio	5% Critical Value	Co-integrating Equations
1	Employees and Enterprises	6.27	15.41	0
	Employees and Enterprises	0.263	3.76	1
2	R&D Personnel and Enterprises	14.41	15.41	0
	R&D Personnel and Enterprises	0.46	3.76	1
3	All Three	28.00	29.68	0
	All Three	6.04	15.41	1
	All Three	1.00	3.76	2

In none of the cases above, can the null hypothesis of a cointegrating relationship between the variables be rejected. Thus, the possibility that long-run average establishment size is constant cannot be rejected.

3.3 Is Average Firm Size Positively Related to Growth?

The R&D based growth models discussed above predict a relationship between the average resources devoted to R&D per firm and productivity growth. Specifically, they predict that an increase in average size leads to a temporary increase in the growth rate as firms move down their average cost curves. Over time, entry draws labor away from incumbent firms and the economy returns to equilibrium at the original growth rate.

Using the same time series tests as in Jones (1995a) we examine the question of interest.[14] The estimation technique takes the following form:[15]

$$g_t = A(L)g_{t-1} + B(1)rpf_t + C(L)\Delta rpf_t + \epsilon_t \tag{17}$$

$$c_k = -\sum_{i=k+1}^{p} b_i, \text{ where } k = 1, ..., p-1.$$

[14] That paper found changes in the investment share of GDP had no significant impact on growth rates, and negative in at least some cases, contrary to the predictions of AK models (e.g. Romer 1990).

[15] The derivation of this specification is presented in the appendix for clarification.

g_t is a measure of growth. Below we use both productivity growth and real per capita GDP growth as dependent variables. By writing the estimation in this manner, we can test directly the significance of the long-run effect. $A(L)$ is a distributed lag and $B(1)$ captures the long-run effect of a change in resources per firm, rpf_t. The test of the theories boils down to whether $B(1) > 0$.

The appropriate right-hand side variable depends on the interpretation of the models. As explanatory variables, resources per firm at time t we look at both employees per establishment, l_t, and R&D workers per establishment, rd_t. The models predict that increases in rpf should raise the rate of productivity growth.

One major drawback of this approach is the potential for reverse causality. It could be that firms increase their size in anticipation of higher economic growth rates. Thus, the results in this section look for the correlation, if it exists, and its sign but cannot make a strong statement regarding causality. However, Pagano and Schivardi (2003) use a cross-country regression and explicitly test for reverse causality but find no evidence for it. Their data utilize cross-country variation in employment shares across industrial sectors in a way that cannot be done here. However, if their results are correct that the direction of causality runs from firm size to GDP growth rates, that lends additional support to the theories and the results described here.

Since it is not clear how long it will take growth to respond to changes in resources per firm, and the theories provide little in the way of predicting the timing of the impact of changes in average size, we avoid imposing a strong interpretation on the individual lags. To determine the number of lags, we employ the Schwartz Information Criterion (SIC). Table 3 below shows the specification preferred by the SIC.[16] Testing for an effect of employees per establishment (l_t) on productivity growth, the SIC selects two lags and no lags when the right-hand side variable is R&D workers per establishment (rd_t).

TABLE 3: Effects of Resources per Firm on Private Business Productivity Growth.

[16] The SIC is more efficient than other specification tests. However, Geweke and Messe (1981) show that in small samples, the SIC tends to predict too few lags. Appendix III shows the estimates after adding 1 and 2 additional lags respectively. None of the key results are changed when considering alternative specifications.

Dependent Variable = pg_t	l_t, Employees/Enterprise	rd_t, R&D Workers/Enterprise
Variable	Coefficient (t-stats)	Coefficient (t-stats)
pg_{t-1}	0.003940 (0.0239)	0.185681 (0.9836)
rpf_t	0.000624 (2.9809)***	0.054037 (1.8732)**
Δrpf_{t-1}	-0.001539 (-0.3394)	-
Δrpf_{t-2}	-0.010851 (-2.4146)**	-
Number of Observations	34	30
SIC	-5.110135	-4.890288

* Significant at the 10% level; ** 5% level; *** 1% level.

For the US economy, the long-run effect of employment per establishment is positive and significant at the standard levels. The first column implies that a doubling of workers per establishment (from the mean of the sample, approximately 15.1) leads to a 0.94 percentage point increase in productivity growth. The second column for R&D workers per establishment also shows a positive, significant effect. A doubling of R&D workers per establishment evaluated at the mean, leads to an increase of 0.79 percentage points in productivity growth.

Table 4 below presents the same test, but uses real GDP per capita growth as the right-hand side variable.[17]

TABLE 4: Effects of Resources per Firm on GDP Per Capita Growth.

[17] Per capita growth rates are from the US Bureaua of Economic Analysis.

Dependent Variable = g_t	Employees/Enterprise	R&D Workers/Enterprise
Variable	Coefficient (t-stats)	Coefficient (t-stats)
g_{t-1}	0.102385 (0.6040)	0.1803 (1.0201)
rpf_t	0.001247 (3.911342)***	0.1352 (3.3980)***
Δrpf_{t-1}	0.008244 (1.4536)	-
Δrpf_{t-2}	-0.001835 (-0.3220)	-
Δrpf_{t-3}	-0.014760 (-2.7345)**	-
Number of Observations	33	30
SIC	-4.676179	-4.588155

* Significant at the 10% level; ** 5% level; *** 1% level.

The results are basically the same. The long-run effect is positive and statistically significant at the 1% level in both cases. The SIC chooses a lag length of three in the regression using l_t rather than two as in Table 3. The magnitude of the coefficients implies an even stronger relationship. In terms of workers per establishment, a doubling implies real GDP growth rate of 1.88 percentage points higher. For R&D workers per establishment, a doubling raises growth by 1.98 percentage points. More plausibly, a one standard deviation in workers and R&D workers per establishment is associated with real per capita GDP growth rate increases of 0.13 and 0.33 percentage point increases, respectively.

Appendix IV provides some alternative specifications to correct for two additional problems with the data. First, the data on employees and enterprises is collected in March and the growth variables are end of the year. Hence, the first lag is not a full year. To check that we are not introducing endogeneity, we re-run the specifications, but using one lag further back. Second, the data for researchers is also end of the year, but the denominator, enterprises, corresponds to the preceeding March. To account for this data mismatch, adjusted rd_t uses the R&D workers aggregate numbers from the previous year, such that the timing gap is only three months as opposed to nine. Neither of these modifications alter the results in any significant way.

Thus, using data on the US, the evidence presented here suggests a positive and significant relationship between average establishment size, R&D workers per firm and growth in GDP per capita. These results in this section are, at best, suggestive, but by no means conclusive. We have not controlled for a variety of factors nor attempted a direct structural estimation of the models. As such we leave it to future research to investigate stronger tests of the hypothesis that larger firm or establishment size is associated with higher growth rates. The major limitation to such studies is lack of available data. As mentioned above, Pagano and Schivardi (2003) looking at European data for the 1990s and find a positive relationship between firm size and growth. However, they fix the size distribution at one point in time and are unable to explore how changes in average size affect growth over time. The evidence here, however, does suggest that changes in the average size are positively correlated with per capita growth rates.

4 Other Considerations: Sectoral Changes and International Data

The data examined in the previous section show both predictions of the firm-based theories cannot be rejected. Here we look a little closer at the data. First, the CBP data allows us to break the US economy into broadly defined sectors to see more closely what is behind the apparent stability of establishment size. Second, we briefly look at international data from the OECD to see if the establishment size series for the US is typical or an anomaly. The latter data are extremely limited and little can be said.

4.1 Sectoral Changes in the US Economy

Figures 9 and 10 show the change in composition of economic activity, in terms of employment, in the US between 1964 and 2001. Manufacturing as a share of total employment declined from 37% to 14%. Services (including finance, insurance, and real estate) in contrast rose from 22% to 58% while the other larger sector, retail trade, declined from 19% to 13%. The broad category of "others" includes agriculture, mining, construction, transportation, communications, and other nonclassifiable establishments. None of these individual sectors accounted for more than 8% of employment over this period. The share of this catchall sector declined, dropping from 22% to 15% in the 37 year period.

Clearly the past few decades witnessed a shift in the allocation of labor across economic activities, from manufacturing to services. The average size of the establishments in each sector also changed, as shown in Figure 11. In manufacturing average employees per establishment declined from 57.1 to 45.2 between 1964 and 2001, a decline of 26.3%. At the same time, the average size for service establishments nearly doubled from 8.3 to 16.0. Between the changing shares of employment and average sizes, the overall average remained stable as documented in Section 3.

One possible objection to the firm-based theories would contend that R&D is concentrated in the manufacturing sector and therefore, the prediction of a constant average establishment size should apply to that sector alone. However, that line of reasoning requires a narrow view of the source of productivity improvements, essentially restricting them to formal or reported R&D activities. It is true that the manufacturing sector accounts for the lion's share of reported expenditures on R&D. According to the OECD data, manufacturing accounted for 76% of reported R&D conducted by business enterprises in 1996. However, as Dinopolous and Thompson (1999) point out, several studies indicate the difficulty in measuring productivity growth, particularly in the services sector. Studies such as Baily and Gordon (1988) indicate that mismeasurement of the services sector can account for as much as a 20% understatement of productivity gains.

4.2 International Comparison

Available international data are, unfortunately, quite limited. In Table 7, we present the available time series from the OECD Firm-Level Project. The project includes 10 OECD countries including those shown plus West Germany (for which data were not available). The coverage in terms of years varies by economy. The data contain employees and numbers of firms excluding single-person businesses. In addition, the data take the firm as the unit of analysis, except for Germany where only establishment level data are available, and Finland where data are reported at the firm and establishment level. Unfortunately, the data are at the firm level, with little available at the establishment level. Based on our arguments regarding the appropriate unit of analysis, establishments would be preferable.[18]

Because of the limited time period, it is difficult to say much about the stability of the average firm size over time. However, most countries appear to have fairly stable firm size with two potential exceptions. Both Portugal and the UK exhibit significant declines in average firm size. Clearly though, the striking feature is the large disparity across nations which raises many interrelated questions such as: Why the large disparity? What is the connection between these differences and economic growth? The latter question is the subject of Pagano and Schivardi (2003) which investigates this aspect using Eurostat data. They find that average firm size is positively correlated with growth even after controlling for potential reverse causality running from growth to firm size. However, their study can only examine the 1990s because of data limitations.

5 Conclusions

The debate over which endogenous growth models provide a more accurate description of the economy is an important one. Scale effects do not appear consistent with the data. Whether the error is one of specification in the knowledge production function or an error in aggregating productive units across the economy matters, because the competing classes of models make very different statements about the ability of policy to affect long-run growth rates.

In this paper, we showed that the basic predictions of the models that rely upon firm-based knowledge accumulation are consistent with the data. First, they predict that average establish-

[18] There is a missing observation for the UK in 1992. Note also that the data show a sudden spike for the US in 1992 in terms of employment and employment per firm. The data reported imply an increase in employment of 24.6% from 1991 to 1992 followed by a fall in employment of 18.0%. Clearly, 1992 data must be entered incorrectly.

ment size will be stable in the absence of shocks directly affecting the firm size distribution. The data appear quite consistent with this prediction. We do not find time trends for either employees or R&D workers per enterprise and we cannot reject that they are cointegrated. Second, the key variable in these models, average size, is positively and significantly related to growth. In contrast, the basic predictions of the early endogenous growth models and those which exhibit decreasing returns to scale appear at odds with the data.

While the data and simple econometric tests presented here are consistent with the firm-based theories, they are far from conclusive evidence. Longer data sets and more careful tests are needed to verify (falsify) the points made here. Moreover, the majority of the data examined here are only for the United States. Future work, along the lines of Pagano and Schivardi (2003) should include examining the behavior of average firm and establishment size across countries for a longer time horizon. In addition, the empirical work of Porter and Stern, using the OECD or Eurostat data to control for average firm or establishment size, would lead to a better test of the theories that emphasize firm specifics.

If the evidence presented here withstands more rigorous testing, it suggests that further progress in understanding the sources of growth and the policies that might affect it would benefit from paying greater attention to modeling R&D performing firms and the environment in which those firms make decisions. The models of firm-based knowledge accumulation make a strong statement about the first moment of the firm size distribution, i.e. average firm size. More attention to the connections between the other moments of the firm size distribution and growth would seem a fruitful avenue for further theoretical exploration. Recent work by Klette and Kortum (2001), Thompson (2001), and Aghion, Harris, Howitt, and Vickers (2001) moves in this direction.

6 Appendix

6.1 Appendix I: Data

Data on number of establishments and employees for the United States was gathered from County Business Patterns various years. An establishment is defined as a "single physical location at which business is conducted or services or industrial operations are performed." They exclude self-employed persons, employees of private households, railroad employees, agricultural production workers, and most government employees (but do include those working in wholesale or retail liquor establishments, Federally-chartered savings institutions and credit unions, and hospitals).

We use the Bureau of Labor Statistics measure of Private Business Productivity Productivity. US GDP growth is from Bureau of Economic Analysis website.

Total Number of R&D personnel from 1950-1988 was taken from Charles I. Jones website and the remaining data for 1989-2000 was collected from various issues of Statistical Abstracts of the United States and the National Science Foundation website. R&D workers in industry was taken from the IRIS website.

The data on international growth and population is from the Penn World Tables 6.1. The countries used in figure 1 include: Argentina, Australia, Austria, Burundi, Belgium, Benin, Burkina Faso, Bangladesh, Bolivia, Brazil, Barbados, Botswana, Canada, Switzerland, Chile, China, Cote d'Ivoire, Cameroon, Republic of Congo, Colombia, Comoros, Cape Verde, Costa Rica, Denmark, Dominican Republic, Algeria, Ecuador, Egypt, Spain, Ethiopia, Finland, France, Gabon, United Kingdom, Ghana, Guinea, The Gambia, Guinea-Bissau, Equatorial Guinea, Greece, Guatemala, Guyana, Hong Kong, Honduras, Indonesia, India, Ireland, Iran, Israel, Iceland, Italy, Jamaica, Jordan, Japan, Kenya, Republic of Korea, Sri Lanka, Lesotho, Luxembourg, Morocco, Madagascar, Mexico, Mali, Mozambique, Mauritania, Mauritius, Malawi, Malaysia, Namibia, Niger, Nigeria, Nicaragua, Netherlands, Norway, Nepal, New Zealand, Pakistan, Panama, Philippines, Papua New Guinea, Portugal, Paraguay, Romania, Rwanda, Senegal, Singapore, Sierra Leone, El Salvador, Sweden, Swaziland, Seychelles, Syria, Chad, Togo, Thailand, Trinidad & Tobago, Turkey, Tanzania, Uganda, Uruguay, USA, Venezuela, South Africa, Zimbabwe, and Zambia.

The countries used in figure 2 include: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, UK, and US.

Data on average firm size was taken from OECD Firm-Level Project on the OECD website.

6.2 Appendix II: Tests on the Population Growth Rate Equation

Using data from the Penn World Tables 6.1 on GDP per capita and population, we use data on 10-year periods for the OECD countries where data are available from 1950 forward. The countries included are Australia, Austria, Canada, Denmark, Finland, France, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Portugal, Spain, Switzerland, Turkey, UK, and USA. Population growth rates are constructed for each decade starting from 1950-1960 and the rates of change in the population growth rates are constructed from those. The 10-year intervals smooth out fluctuations that might be caused by business cycles and allow us to focus on the long-run. A similar approach has been taken in numerous studies (e.g. Barro and Sala-i-Martin, 1995). With five decades of data for each country we have 4 data points each for a total of 80 observations in a pooled sample. For equation (9) we have:

$$\frac{\dot{y}^*}{y} = \frac{1}{1-\phi}\left(n - \frac{\dot{n}}{n}\right) \tag{9}$$

where n is workforce growth rate. However, the endogeneity of workforce and per capita income growth appears obvious. Expectations of rising (or falling) income could induce changes in labor participation. Here, we use the actual population growth rate and changes therein to instrument for workforce growth rates. The growth rate of the population itself could certainly respond to expected changes in income per capita, through immigration or having more/less children, for example. Nonetheless, the endogeneity should be far less severe since the decision to move countries is more complex and costly than the decision to work or not and the decision to "consume" more children probably responds slowly to changes in income and the impact on the workforce takes more than a decade.

The following are the results where we allow for a constant in the equation:

Dependent Variable $= g$	n only	n and $\dot{n}/n$
n	-0.207 (-1.532)	-0.231^{*} (-1.672)
$\dot{n}/n$	-	0.163 (0.844)
Constant	0.279 (14.926)	0.282 (14.647)
R^2	0.028	0.037
Implied Value of ϕ	5.84	5.33
Lower Bound on ϕ	3.11	2.98
Upper Bound on ϕ	-15.21	-21.79

The $t-stats$ are in parentheses. The only significant variable at standard levels is n in the second specification. The signs and magnitudes of the coefficients are not what the theory would predict. We would expect a positive coefficient on n and a negative one on $\dot{n}/n$. Moreover, the expected magnitude should be greater than one to yield a value of $\phi < 1$. The results are quite different. Interestingly, we cannot reject that the magnitude of the coeffecients is equal and opposite, although the signs are wrong in the second specification.

When n is the only right-hand side variable, OLS gives us a point estimate for $1/(1-\phi)$ of -0.207. This value implies that ϕ is 5.84. Since the coefficient is negative, larger negative values for the point estimate will lower the value of ϕ. For example, if the point estimate were -2, that would imply $\phi = 1.5$, asymptotically approaching one as $1/(1-\phi) \to -\infty$. Moving in the opposite direction as the coefficient approaches zero, ϕ approaches $+\infty$. When the point estimate is positive, but less than one, it implies a negative value for ϕ. Only when the point estimate is larger than one is ϕ both positive and less than one. The 95% confidence intervals around the coefficient on n in the first regression above is $\{-0.475, 0.0612\}$ which yields the values in the last two rows in column one. For the second regression the associated 95% confidence interval is $\{-0.506, 0.044\}$. Thus, within the confidence interval, we either have $\phi < 0$ or $\phi > 1$.

The above tests of the theory could be substantially improved using more control variables, finding a better instrument, or attempting to account for growth through accumulation of productive factors which might be especially important in the post-war era for the European countries. Thus, the results need to be treated with a great deal of caution. Nonetheless, the results cast some doubt on the theories since the key relationship fails rather dramatically much like tests on the earlier endogenous growth models.

The implied values for ϕ can be made to fall within the $(0, 1)$ interval with a simple generalization the production function to $Y = A^{\sigma} L_Y$ where $\sigma > 0$. Now our coefficients above correspond to $\sigma/(1-\phi)$ instead of $1/(1-\phi)$. We have no prior on the value of σ other than it must be positive to make sense in the production function. However, if we take the point estimates above, the fact that they are negative implies that if $\phi \in (0, 1)$, then $\sigma < 0$. Hence, increases in the stock of knowledge lowers productivity of output.

6.3 Appendix III: Alternative Lag Choices

Because the SIC tends to choose too few lags in small samples, this appendix presents the results of adding one and two more lags to the specifications presented in Tables 3 and 4. None of the key results listed above are affected.

Table A1: Employees per Enterprise on Private Business Productivity Growth.

Dependent Variable = pg_t	1 extra lag	2 extra lags
Variable	Coefficient (t-stats)	Coefficient (t-stats)
pg_{t-1}	0.040742 (0.2122)	0.068202 (0.3590)
l_t	0.000603 (2.663)**	0.000552 (2.4392)**
$\Delta \mathrm{l}_{t-1}$	-0.001452 (-0.3036)	-0.003282 (-0.6783)
$\Delta \mathrm{l}_{t-2}$	-0.010551 (-2.2510)**	–0.012241 (-2.5797)***
$\Delta \mathrm{l}_{t-3}$	0.001661 (0.3239)	-0.001153 (0.2277)
$\Delta \mathrm{l}_{t-4}$		-0.001501 (-0.3259)
Number of Observations	33	32
SIC	-4.972083	-4.925813

* Significant at the 10% level; ** 5% level; *** 1% level.

Table A2: R&D Workers per Enterprise on Private Business Productivity Growth.

Dependent Variable = pg_t	1 extra lag	2 extra lags
Variable	Coefficient (t-stats)	Coefficient (t-stats)
pg_{t-1}	0.085419 (0.4122)	0.103019 (0.4922)
rd_t	0.056869 (1.7643)*	0.053168 (1.7038)*
Δrd_{t-1}	0.531713 (0.9609)	0.450401 (0.8413)
Δrd_{t-2}	-	–0.865317 (-1.5871)
Number of Observations	24	23
SIC	-4.702173	-4.684232

* Significant at the 10% level; ** 5% level; *** 1% level.

Table A3: Employees per Enterprise on Real GDP Growth Per Capita.

Dependent Variable = g_t	1 extra lag	2 extra lags
Variable	Coefficient (t-stats)	Coefficient (t-stats)
g_{t-1}	0.106763 (0.5345)	0.134739 (0.6628)
l_t	0.001262 (3.4950)***	0.001190 (3.1906)***
Δl_{t-1}	0.008773 (1.4796)	0.007278 (1.1939)
Δl_{t-2}	-0.001128 (-0.1858)	-0.003270 (-0.5158)
Δl_{t-3}	-0.014582 (-2.5964)**	-0.016168 (-2.7800)**
Δl_{t-4}	-0.000877 (-0.1396)	-0.001345 (-0.2112)
Δl_{t-5}		-0.001407 (-0.2498)
Number of Observations	32	31
SIC	-4.537226	-4.446244

* Significant at the 10% level; ** 5% level; *** 1% level.

Table A4: R&D Workers per Enterprise on Real GDP Growth Per Capita.

Dependent Variable = g_t	1 extra lag	2 extra lags
Variable	Coefficient (t-stats)	Coefficient (t-stats)
g_{t-1}	0.172634 (0.7933)	0.154872 (0.6945)
l_t	0.135951 (2.6205)**	0.129400 (2.4568)**
Δl_{t-1}	-0.1283 (-0.1836)	-0.101740 (-0.1436)
Δl_{t-2}	-	0.6205 (0.8812)
Number of Observations	24	23
SIC	-4.246927	-4.138523

* Significant at the 10% level; ** 5% level; *** 1% level.

6.4 Appendix IV: Derivation of the Time Series Equation

Derivation of Times Series Equation:

Let g_t be a function of i_t such that:

$$g_t = c + b i_{t-1} + \mu_t$$

Then:

$$\begin{aligned} g_t - g_{t-1} &= (c - c) + b(i_{t-1} - i_{t-2}) + \mu_t \\ g_t &= g_{t-1} + b(i_{t-1} - i_{t-2}) + \mu_t \end{aligned}$$

Generalizing the lag structure we have:

$$g_t = A(L)g_{t-1} + B(L)i_t + \epsilon_t$$

The lag polynomial of $B(L)$ is of the p^{th} order. For exposition purposes let $p = 3$. Then we can write the above specification as:

$$g_t = A(L)g_{t-1} + b_1 i_{t-1} + b_2 i_{t-2} + b_3 i_{t-3} + \epsilon_t$$

Now add and subtract $b_2 i_{t-1}$:

$$g_t = A(L)g_{t-1} + b_1 i_{t-1} + (b_2 i_{t-1} - b_2 i_{t-1}) + b_2 i_{t-2} + b_3 i_{t-3} + \epsilon_t$$

Rearrange to get:

$$g_t = A(L)g_{t-1} + (b_1 + b_2)\, i_{t-1} - b_2 i_{t-1} + b_2 i_{t-2} + b_3 i_{t-3} + \epsilon_t$$

Add and subtract again with $b_3 i_{t-1}$

$$\begin{aligned} g_t &= A(L)g_{t-1} + (b_1 + b_2)\, i_{t-1} - b_2 i_{t-1} \\ &\quad + (b_3 i_{t-1} - b_3 i_{t-1}) + b_2 i_{t-2} + b_3 i_{t-3} + \epsilon_t \end{aligned}$$

Rearrange:

$$\begin{aligned} g_t &= A(L)g_{t-1} + (b_1 + b_2 + b_3)\, i_{t-1} + b_2\,(i_{t-2} - i_{t-1}) \\ &\quad - b_3 i_{t-1} + b_2 i_{t-2} + b_3 i_{t-3} + \epsilon_t \end{aligned}$$

One more time add and subtract $b_3 i_{t-2}$

$$
\begin{aligned}
g_t &= A(L)g_{t-1} + (b_1 + b_2 + b_3)\, i_{t-1} + b_2\, (i_{t-2} - i_{t-1}) \\
&\quad + (b_3 i_{t-2} - b_3 i_{t-2}) - b_3 i_{t-1} + b_2 i_{t-2} + b_3 i_{t-3} + \epsilon_t
\end{aligned}
$$

And rearrange to get:

$$
\begin{aligned}
g_t &= A(L)g_{t-1} + (b_1 + b_2 + b_3)\, i_{t-1} + (b_2 + b_3)\, (i_{t-2} - i_{t-1}) \\
&\quad + b_3\, (i_{t-3} - i_{t-2}) + \epsilon_t
\end{aligned}
$$

or:

$$
\begin{aligned}
g_t &= A(L)g_{t-1} + (b_1 + b_2 + b_3)\, i_{t-1} - (b_2 + b_3)\, (i_{t-1} - i_{t-2}) \\
&\quad - b_3\, (i_{t-2} - i_{t-3}) + \epsilon_t
\end{aligned}
$$

which can be written more compactly as:

$$
g_t = A(L)g_{t-1} + B(1)i_{t-1} - C(L)\Delta i_t + \epsilon_t \tag{16}
$$

where:

$$
c_k = -\sum_{i=k+1}^{p} b_i, \text{ where } k = 1, ..., p-1.
$$

6.5 Appendix V

Here we turn to two possible problems with the data in Section 3.3. First, the data on employees and enterprises is collected in March and the growth variables are end of the year. Hence, the first lag is not a full year. To check that we are not introducing endogeneity, we re-run the specifications, but using one lag further back. Those estimates correspond to the first two columns in Tables 5 and 6.

Second, the data for researchers is also end of the year, but the denominator, enterprises, corresponds to the preceeding March. To account for this data mismatch, adjusted rd_t uses the R&D workers aggregate numbers from the previous year, such that the timing gap is only three months as opposed to nine. These estimates are in the third column of Tables 5 and 6.

TABLE 5: Resources per Firm dropping contemporaneous lag.

Dependent Variable = pg_t	l_t	rd_t	Adjusted rd_t
Variable	Coefficient (t-stats)	Coefficient (t-stats)	Coefficient (t-stats)
pg_{t-1}	0.004313 (0.0267)	0.089967 (0.5064)	0.134301 (0.7197)
rpf_t	NA	NA	0.050769 (0.0813)*
rpf_{t-1}	0.000612 (2.964)***	0.068340 (2.6096)**	NA
Δrpf_{t-2}	-0.010629 (-2.4051)**	-	-
Number of Observations	34	30	29
SIC	-5.203315	-4.979762	-4.904740

* Significant at the 10% level; ** 5% level; *** 1% level.

TABLE 6: Resources per Firm dropping contemporaneous lag.

Dependent Variable = g_t	l_t	rd_t	Adjusted rd_t
Variable	Coefficient (t-stats)	Coefficient (t-stats)	Coefficient (t-stats)
g_{t-1}	0.172476 (1.0322)	0.237831 (1.232007)	0.179332 (0.1783)
rpf_t	NA	NA	0.134361 (2.4880)**
rpf_{t-1}	0.001180 (3.6590)***	0.117236 (2.7220)**	NA
Δrpf_{t-2}	-0.003312 (-0.5767)	-	-
Δrpf_{t-3}	-0.014408 (-2.6114)**	-	-
Number of Observations	33	30	29
SIC	-4.700527	-4.509142	-4.571420

* Significant at the 10% level; ** 5% level; *** 1% level.

The key variables remain significant and positive. The adjusted R&D workers per enterprise is now only significant at the 10% level in the first, but remains significant at the 5% level in the second specification. The only other noticeable difference is the SIC prefers only one lag for workers per firm when private business productivity growth is the dependent variable.

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Figure 1: GDP per capita growth rates and Ln 1960 population

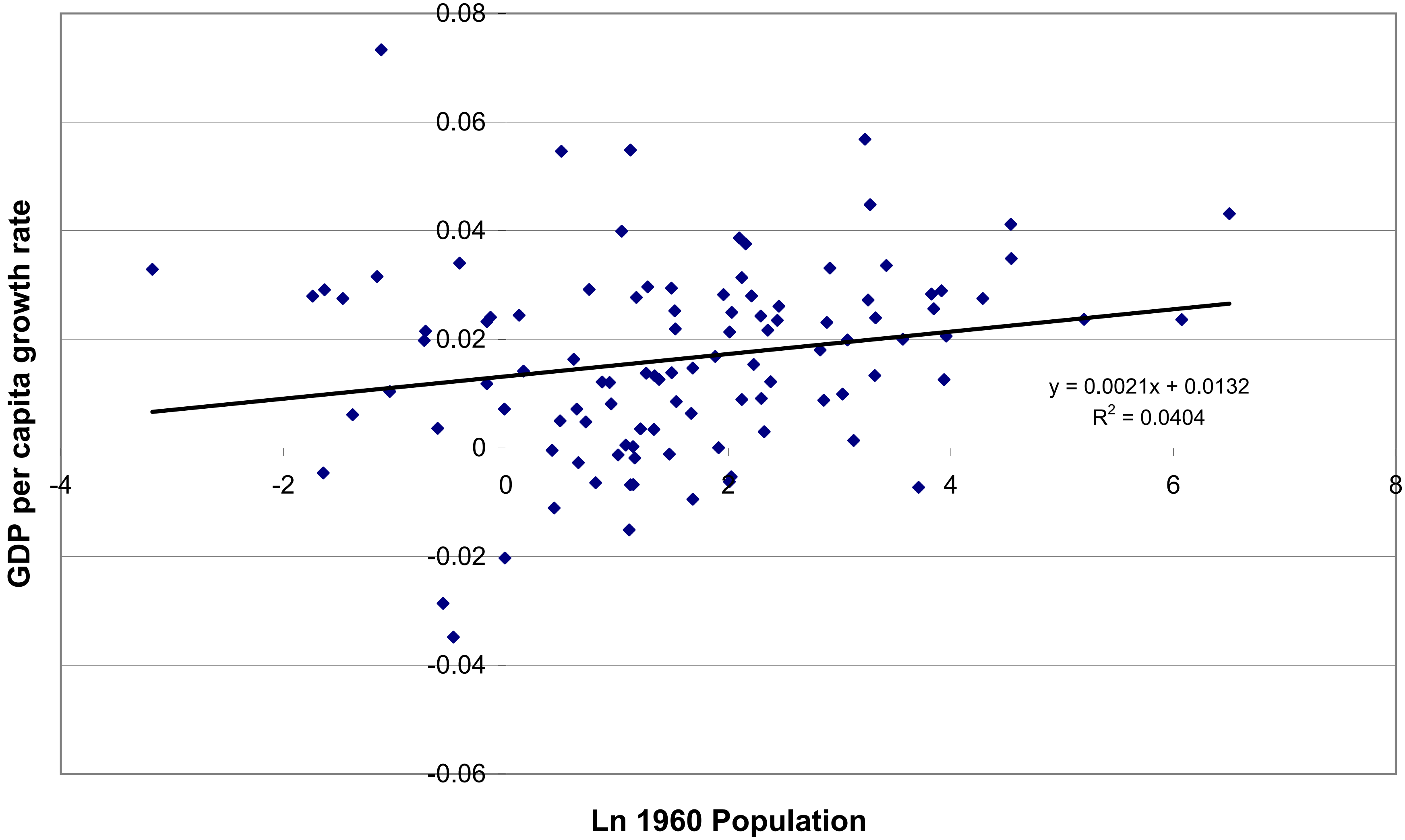


Figure 2: Ln of Population 1960 and GDP per capita growth rates (1960-2000), OECD

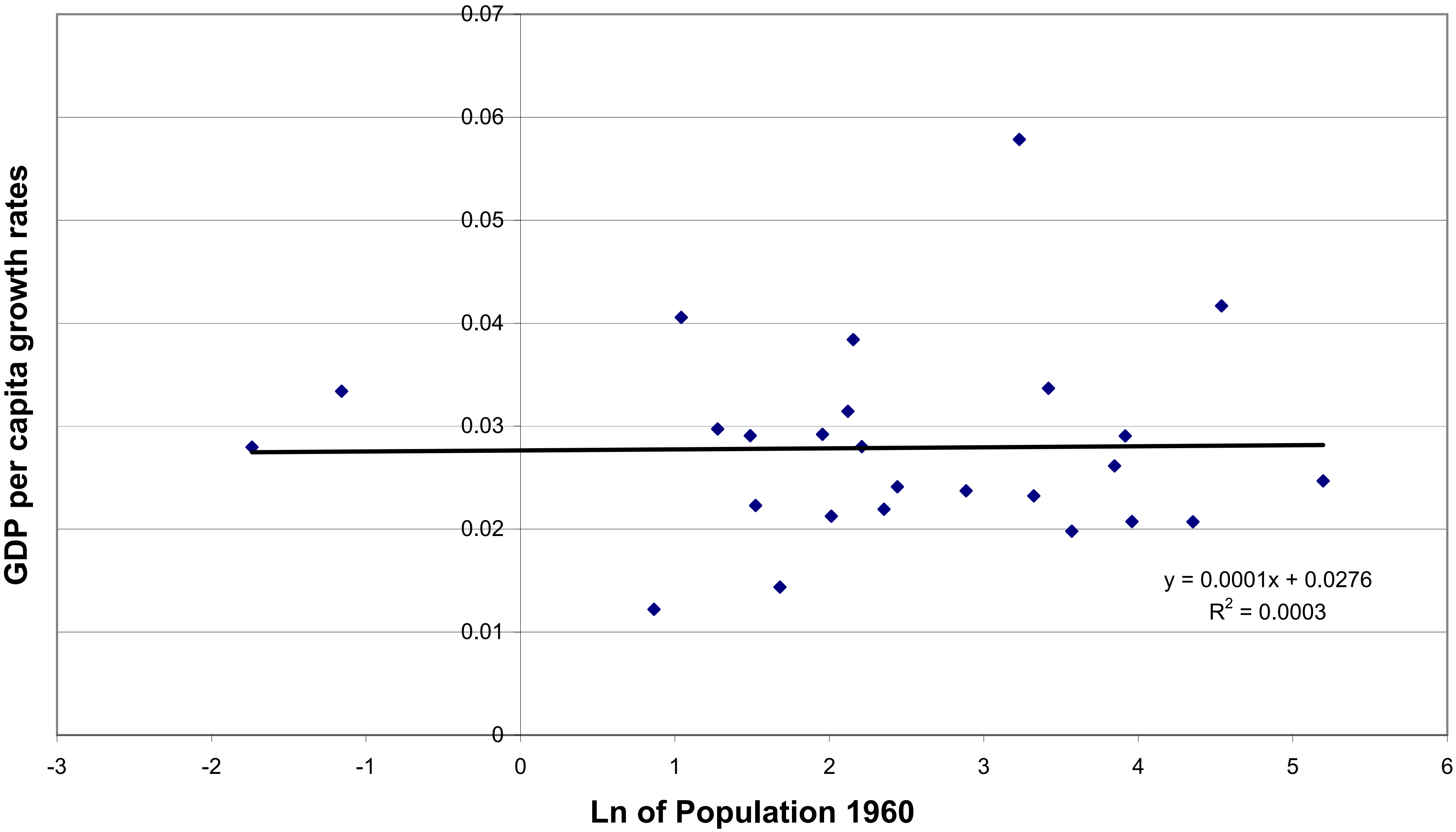


Figure 3: Employment and Private Business Productivity Growth Rate

Figure 4: Total FTE R&D Personnel and Productivity Growth

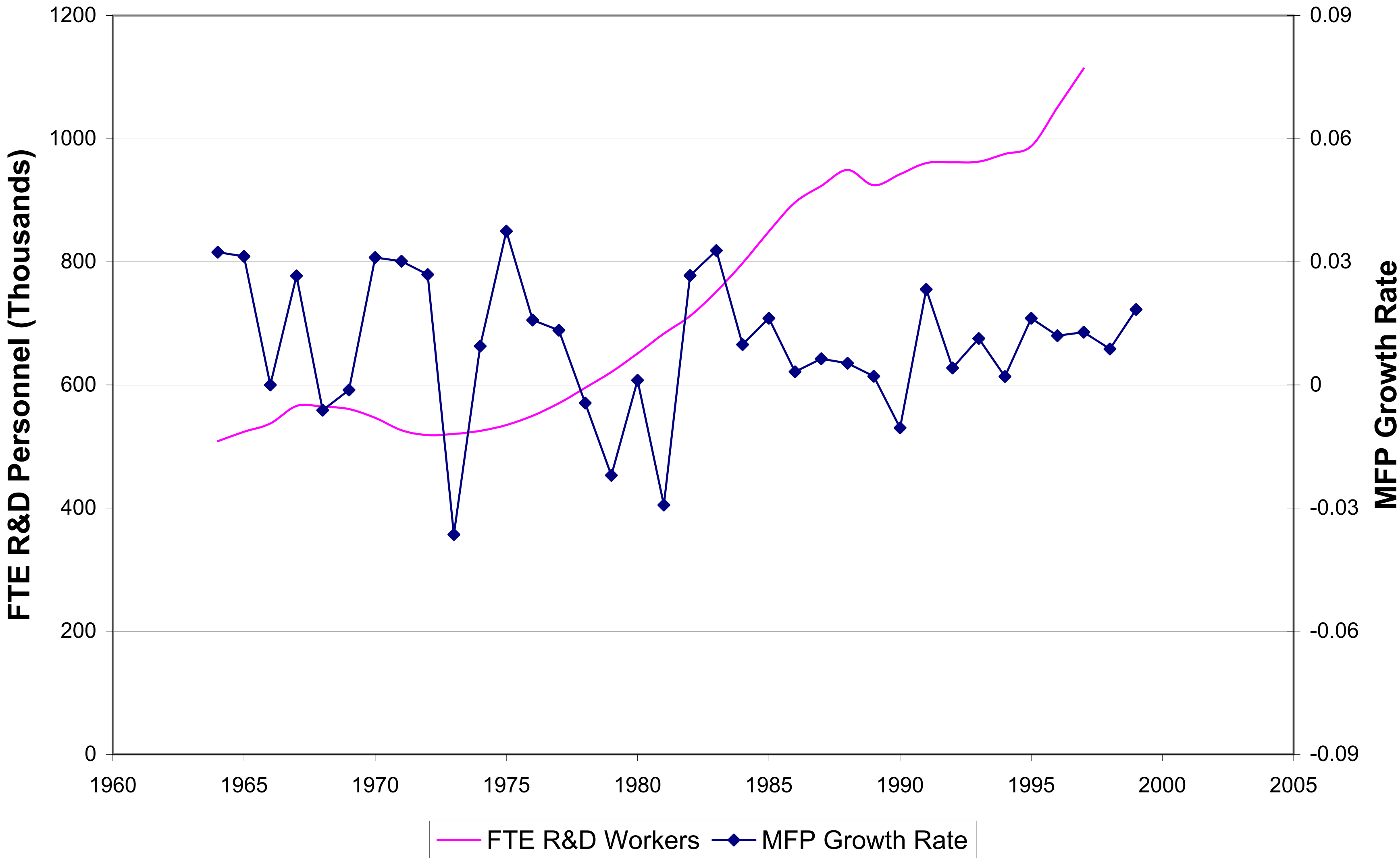


Figure 5: GDP per capita growth and population growth rates

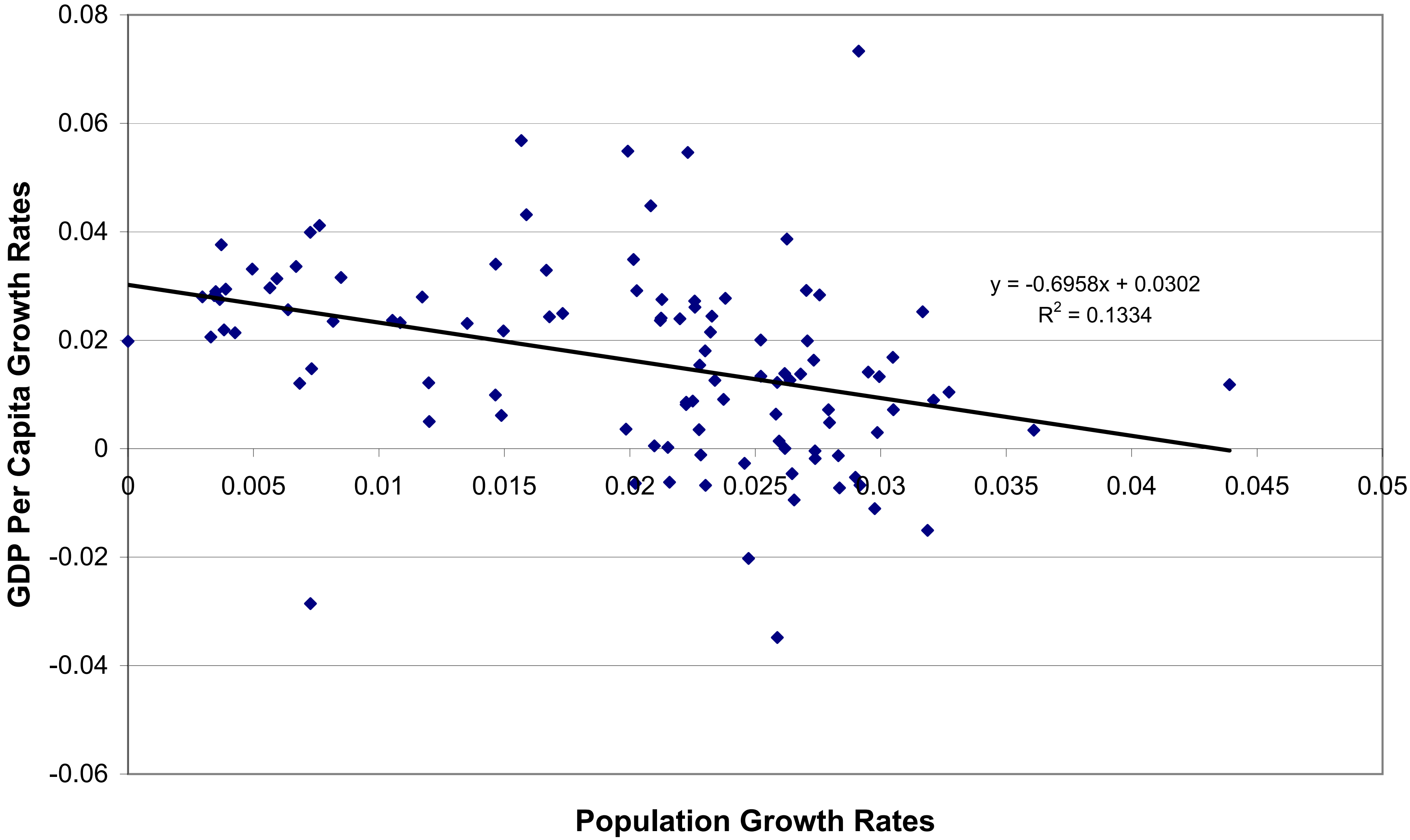


Figure 6: Population and Real GDP per capita growth rates (OECD)

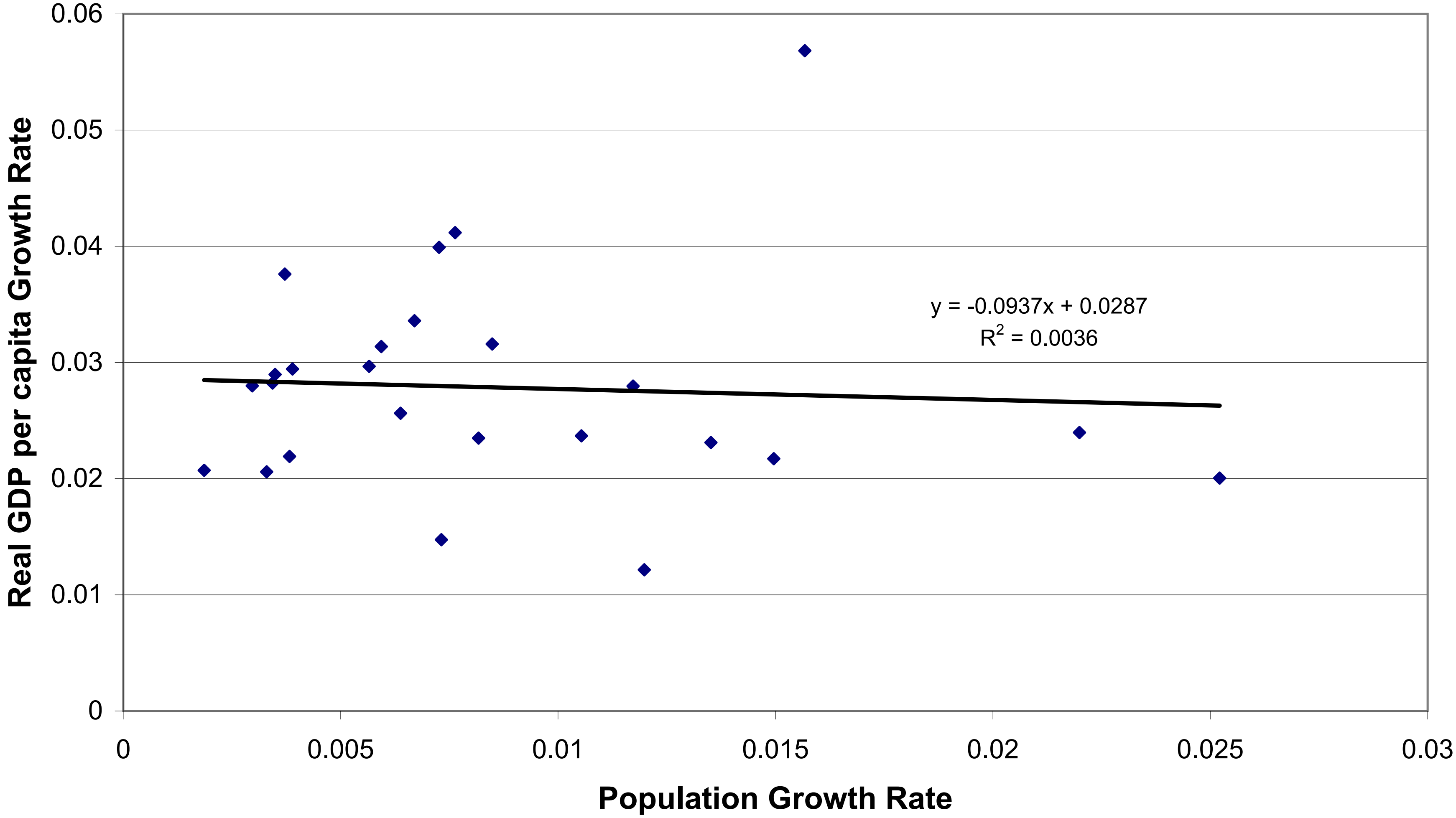


Figure 7: Population, Employment, R&D Personnel, and Establishments

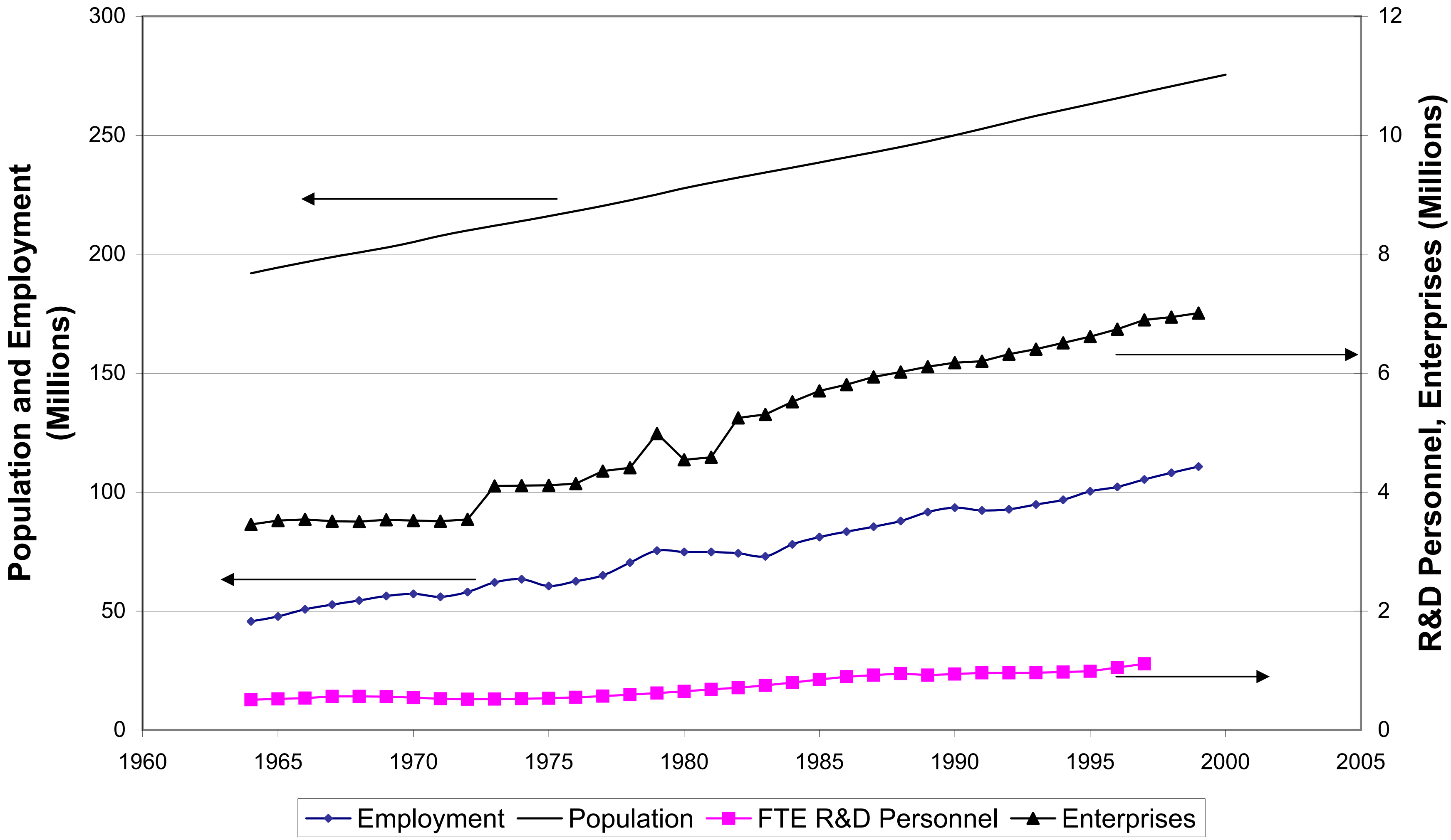


Figure 8: Per Establishment

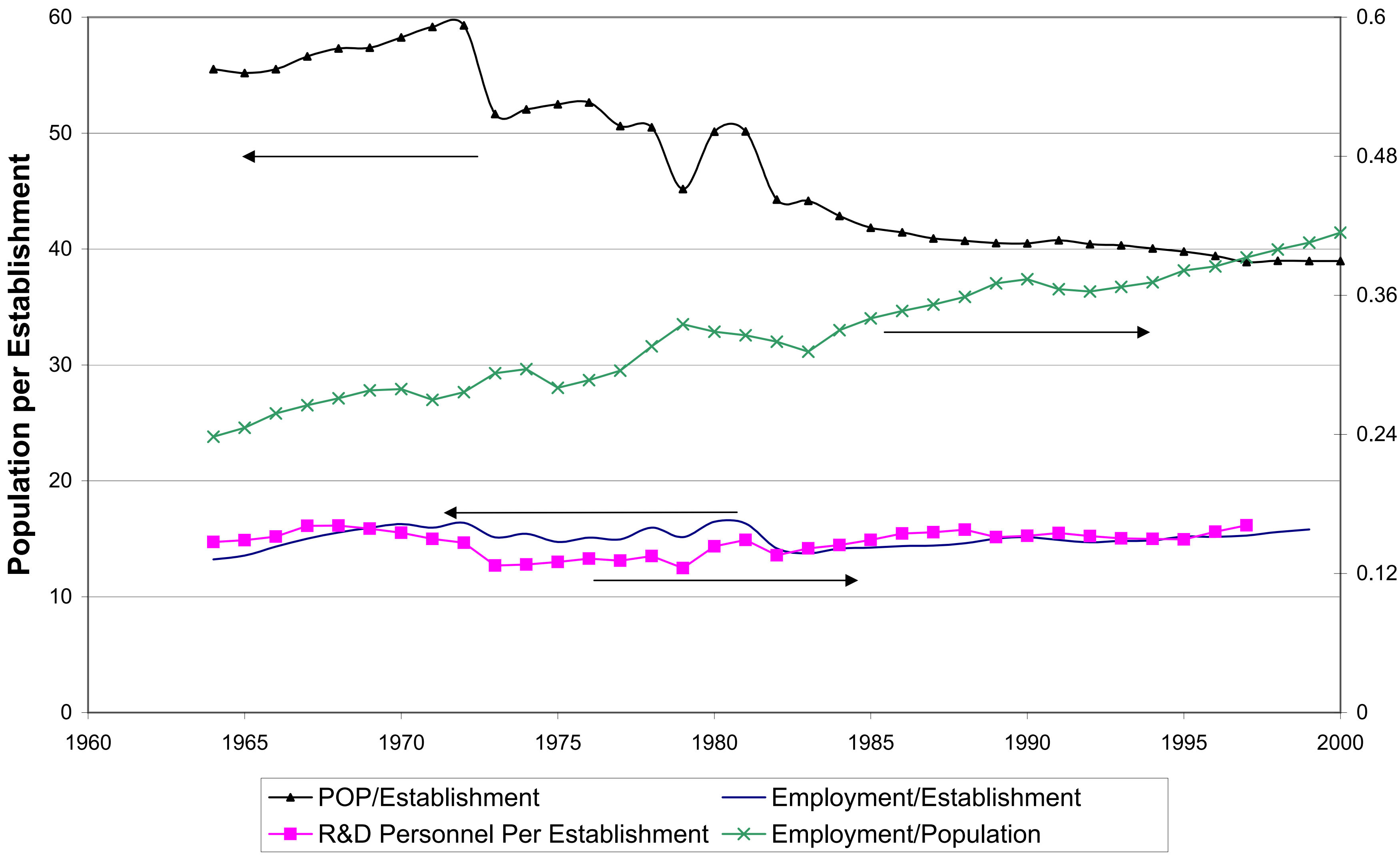


Figure 8b: Per Establishment

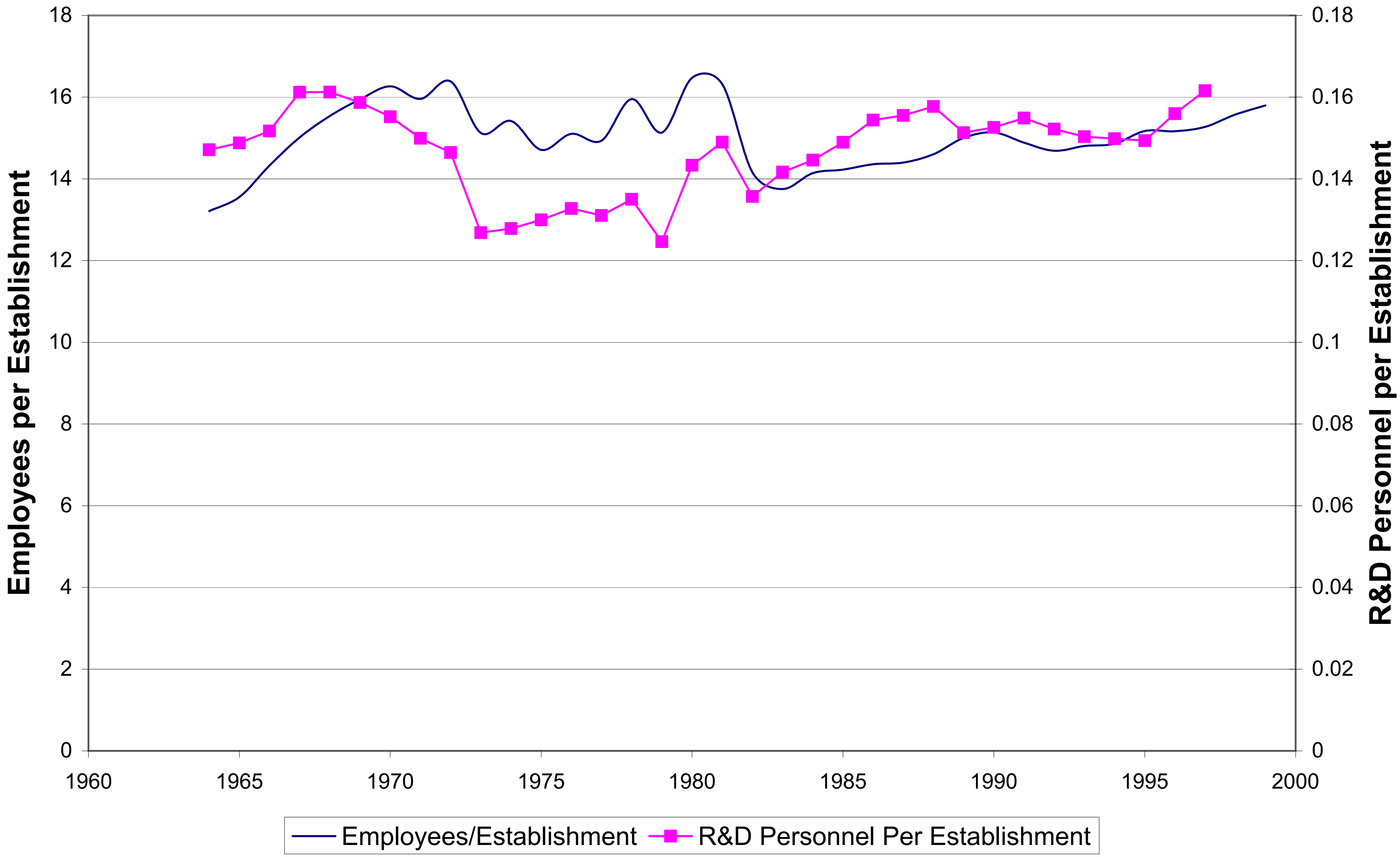
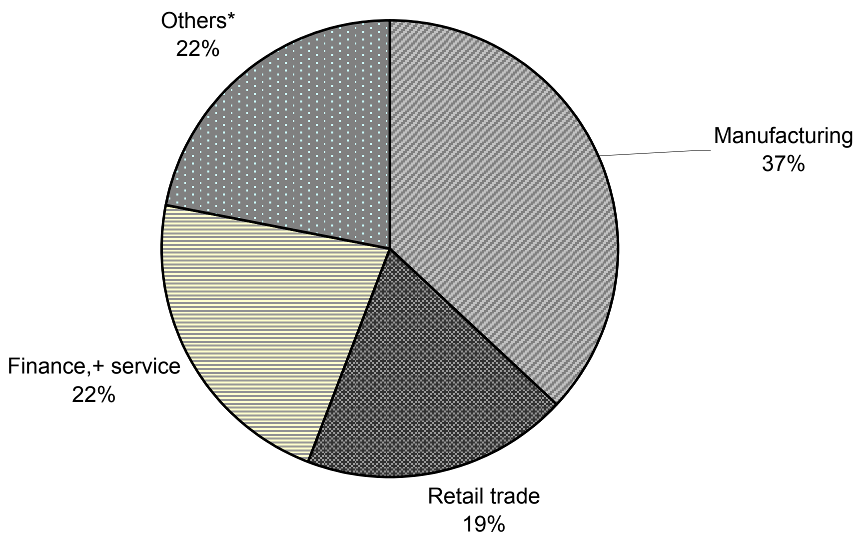


Figure 9: Percentage Share In Total Employment - 1964 and 2001

1964



Percentage Share In Total Employment - 2001

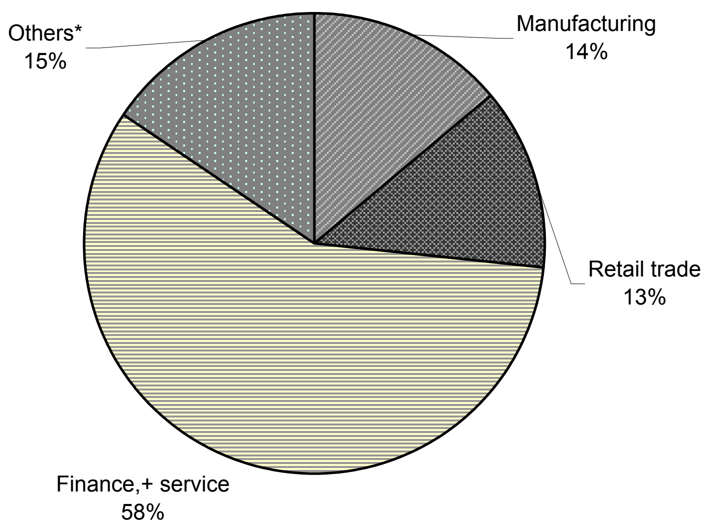


Figure 10: Changing Shares of Manufacturing and Services

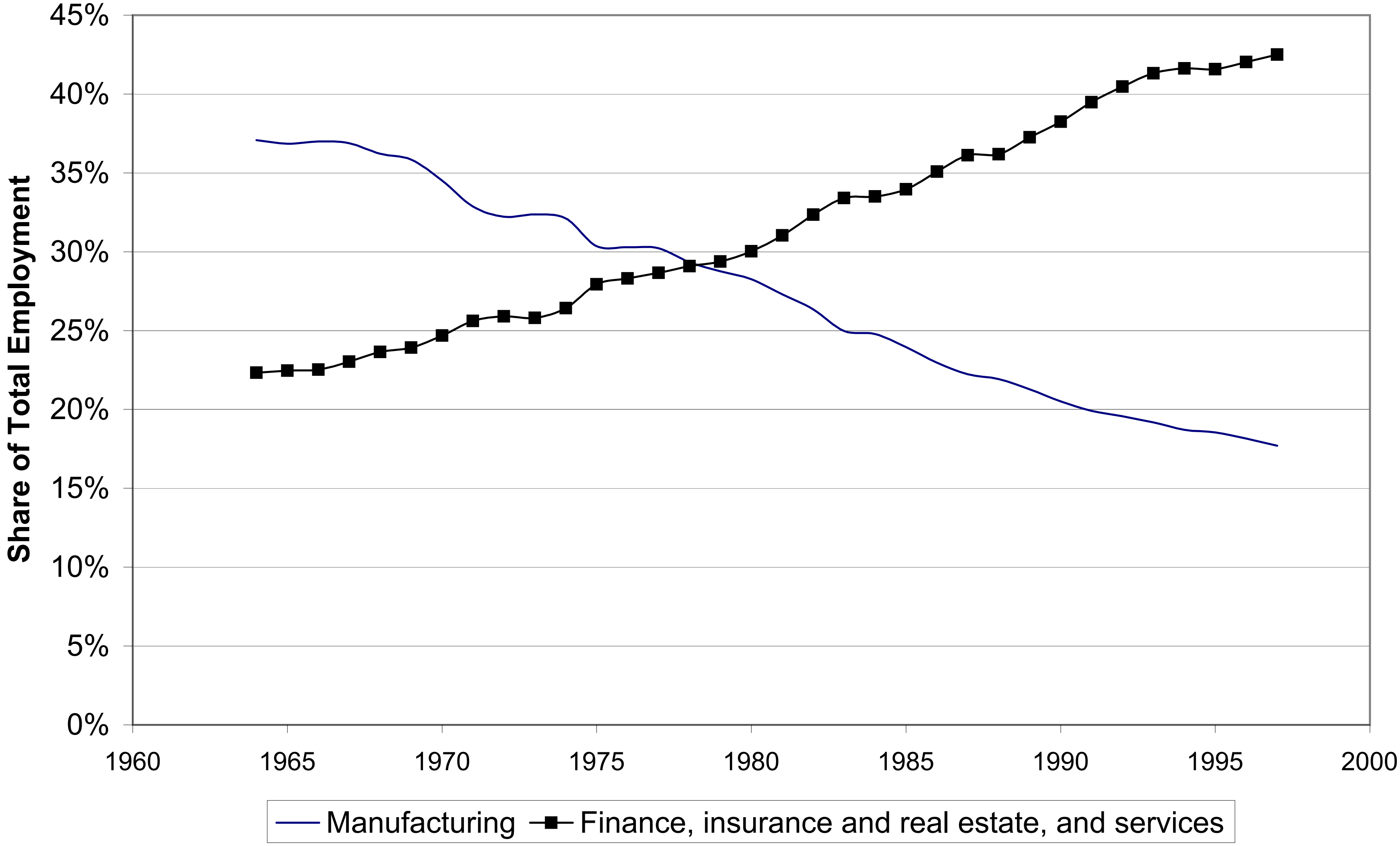


Figure 11: Average Establishment Size by Sector

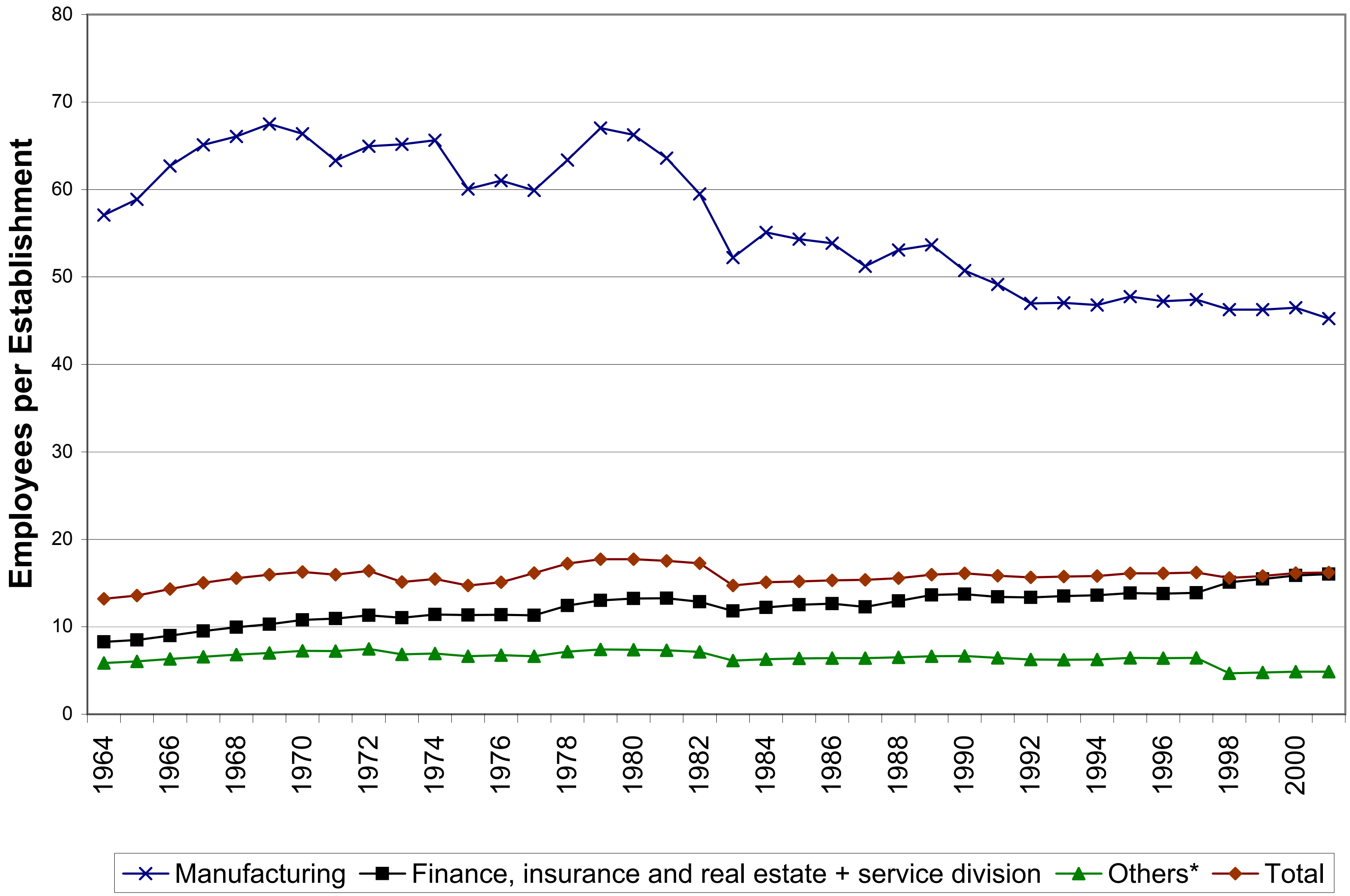


Table 7: Average Firm Size of OECD Countries

Year	Canada	Denmark	Finland	France	Italy	Netherlands	Portugal	UK	US
1981		10.1							
1982		10.1							
1983		10.1					19.5		
1984	9.7	10.5					19.0		
1985	9.7	10.9					18.3		
1986	9.7	11.5					17.6	33.8	
1987	10.0	11.5			9.4		17.3	33.6	
1988	10.4	11.4	11.3		9.4		16.1	32.9	
1989	10.6	11.6	10.4		9.5		15.6	32.2	21.4
1990	10.3	11.7	11.2	29.9	9.7		15.6	32.6	22.9
1991	10.1	11.7	10.1	29.1	9.6		14.9	31.5	22.5
1992	9.8	11.7	10.8	27.5	9.2		14.1		27.4
1993	9.6	11.8	10.7	26.5	9.2	5.7	13.2	28.1	22.2
1994	9.6	12.1	10.7	25.8		6.1	11.9	27.0	21.9
1995	9.9		10.2	27.0		6.3		25.7	22.2
1996	10.2		10.0	28.4		6.7		25.6	22.2
1997	10.6		10.3			6.8		25.7	
1998								25.3	
Average over Period	10.0	11.2	10.6	27.7	9.4	6.3	16.1	29.5	22.8