ENDOGENOUS TECHNOLOGICAL PROGRESS, POPULATION AND LONG RUN ECONOMIC GROWTH

A Thesis submitted for the Degree of Doctor of Philosophy

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Dedicated to my parents, my brother and to them

who make me complete…

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Abstract

The underlying central theme that drives this thesis is endogenous technological progress and its contributions to long run economic growth. Over the past four hundred years we have seen dynamic patterns of growth that have varied across countries and over time. In the eighteenth and nineteenth centuries Britain was the technological leader, with Germany and France catching up, and then in the twentieth century the world saw a new technological leader, where the United States forged ahead of Europe. This thesis is a collection of three self-contained studies where in each chapter one important technological epoch is examined back in time. Moreover, to understand the different forces of economic growth and to characterize each stage of development a time series estimation method is chosen, using dynamic time series techniques and estimation methods.

The first study of this thesis is a journal article co-authored with my thesis supervisors (revised and resubmitted to *Journal of Economic Growth*), where, using long historical data for Britain over the period 1620-2006, we seek to explain the importance of innovative activity and population growth in inducing the transition from the Malthusian trap to the post-Malthusian growth regime in Britain. Furthermore, the paper tests the ability of two competing second-generation endogenous growth models to explain the British Industrial Revolution. The results suggest that innovative activity was an important force in shaping the Industrial Revolution and that the British growth experience is consistent with Schumpeterian growth theory.

The second study in this thesis is a chapter solely written by me; however findings from this chapter have also been written up as a journal article and submitted to *"European Economic Review"*, where the article is currently under review. The journal paper titled *"Innovation, Technological Change and the British Agricultural Revolution"* and is co-authored with my thesis supervisors. In the second study, the roles of technological progress in advancing the productivity growth in British agriculture in the period 1620-1850 are examined. Two different indicators of technological progress are considered, namely, agricultural patents issued and number of technical books published on farming. In doing so, the

modern endogenous growth models have been tested, namely, the Schumpeterian and Semi-endogenous models of economic growth, where support was acquired in favour of Schumpeterian growth model.

The third and final study explores the contributions of technological progress on a sectoral basis to shed some light on the phenomenon of ‘America’s catching-up and forging ahead of Britain’. This study finds that agriculture and service sectors contributed significantly to the US take-off period. Furthermore, increased research intensity, R&D investments, together with increasing returns to land in the agricultural sector; and major transformations in the transport sector, paved the way for the American economy to grow faster than its counterparts in Britain.

Overall, contributions from all three chapters fill a number of important gaps in the literature and show that accurate explanations of the mechanisms behind technological epochs back in time can have significant policy implications for both advanced and currently growing economies.

General Declaration

In accordance with Monash University Doctorate Regulation 17 the following declarations are made:

I hereby declare that this thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

This thesis includes 0 original papers published in peer reviewed journals and 1 unpublished publication. The core theme of the thesis is *endogenous technological progress and its contribution to long run economic growth*. The ideas, development and writing up of all the papers in the thesis were the principal responsibility of myself, the candidate, working within the Economics Department under the supervision of Prof. Jakob B. Madsen.

The inclusion of co-authors reflects the fact that the work came from active collabouration between researchers and acknowledges input into team-based research.

In the case of chapter 2 my contribution to the work involved the following:

Thesis chapter	Publication title	Publication status	Nature and extent of candidate's contribution
2	Four Centuries of British Economic Growth: The Roles of Technology and Population	Revise and resubmit	Building motivation, data collection, performing initial estimations, writing up the first draft of the paper and presenting the final version to various conferences.

I have renumbered sections of submitted paper in order to generate a consistent presentation within the thesis.

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"I would maintain that thanks are the highest form of thought, and that gratitude is happiness doubled by wonder."

~ G. K. Chesterton (English writer, 1874-1936)

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Chapter 1

INTRODUCTION

"If macroeconomists look only at cross-country regressions deployed in the convergence controversy, it will be easy to be satisfied with the neoclassical models in which market incentives and government policies have no effect on discovery, diffusion, and technological advance. But if we make use of all the available evidence, economists can move beyond these models and begin once again to make progress toward a complete understanding of the determinants of long-run economic success. Ultimately, this will put us in a position to offer policy-makers something more insightful than the standard neoclassical prescription--more saving and more schooling."

- *Romer, 1994, page 20.*

Economic growth, in general, is defined as the annual rate of increase in a nation's per capita gross domestic product (GDP)[1]. The progress of a nation is intimately tied up with improvements in its overall stock of technical knowledge. Since the British industrial revolutions, the world has experienced enormous changes in terms of living standards and affordability, where some countries have become very rich and others have remained poor. The poorest countries currently have per capita income that is less than five percent of the per capita income in the developed world (Jones, 2002). Furthermore, the growth rates have varied substantially over time and across countries where the forerunners have leapfrogged others to become new leaders of the technological frontier. Thus, to understand these complex issues in the context of macroeconomic policies, it is

[1] See Aghion and Howitt (2009)

essential to know what drives growth in an economy and how this process can be sustained in the long run.

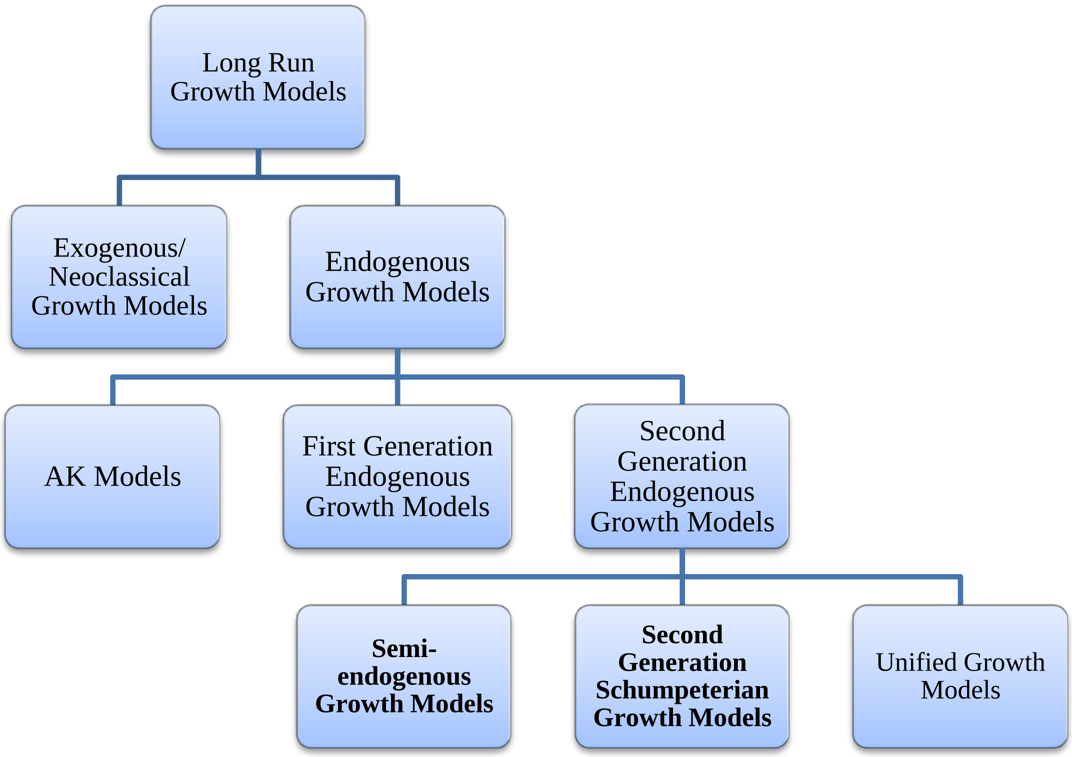
Section 1.1 will discuss briefly the evolution of growth theories starting from neoclassical to second generation endogenous growth models. Moreover, this section will demonstrate the intense debate that exists among various kinds of growth models and their applications to the real world. Section 1.2 will briefly discuss the main objectives of this study. Finally section 1.3 will provide a summary of each of the following chapters in this dissertation.

1.1. Evolution of New Growth Models

Every growth theory has a basic proposition that, in the long run, there must be continual advances in technological progress in the form of new goods, new markets, or new processes (Aghion and Howitt, 1998). But each theory has a different set of assumptions about the progress in technology or knowledge. Significant development in theories of growth economics started with the neoclassical model pioneered by Solow (1956) and Swan (1956). Since then this framework has offered a foundation for many subsequent models developed over the following decades. In terms of their origin, theories of economic growth can be classified under four broad categories:

I. Neoclassical or Exogenous Growth Models.
II. AK Models and First Generation Endogenous Growth Models.
III. Second Generation Semi-endogenous Growth Models.
IV. Second Generation Endogenous Growth Models.

Figure1. 1: Evolution of New Growth Models



I. Neoclassical or Exogenous Growth Models:

The central spirit of the neoclassical growth models lies in two basic equations; the production function and the capital accumulation equation:

$$Y = AK^{\alpha}L^{1-\alpha} \quad (1.1)$$

$$\dot{K} = sY - \delta K \quad (1.2)$$

where in equation (1.1), aggregate production (Y) is a function of the productivity parameter A, and current stocks of capital (K) and labour (L) and $0 < \alpha < 1$ is the share of capital in total income. Equation (1.2) shows that capital accumulation depends upon investment, which is equal to aggregate savings (saved at a rate s), minus capital depreciation (at a rate δ). This model implies that growth will occur through economic policies that induce people to save more. But due to diminishing marginal productivity, growth in national income will be less than the growth in capital stock, implying that the savings rate is less than the depreciation rate of capital. Over time the depreciation rate will catch up to the savings rate and growth will cease in the long run. Thus the model predicts that saving induced growth is short-lived and growth will continue in the long run only if there is some technological progress. However, in this class of model, technology is assumed to be exogenous to all economic forces. In other words, long run growth depends on unpredicted and disjoined shocks that cannot be altered by any economic policy. This conclusion led economists to a dead end, where nothing further could be predicted about the sources of technological progress.

Paradoxically, the same conclusion gave theorists new hope to look at the system through the lens of endogenous technological change, where economic policies have significant impacts on long run growth. Hence, the neoclassical model has remained a remarkable success that gave theorists the right beginning, even though the theory itself was incomplete in explaining growth in the long run. In the next few decades a series of models started to develop using the neoclassical model as their benchmark. An extensive literature is found in the handbook article of Jones and Manuelli (2005) and Aghion and Howitt (1998).

II. AK Models and First Generation Endogenous Growth Models:

To overcome the limitations of neoclassical growth models, the first version of fully endogenous growth models, called the AK model, was advanced by Frankel (1962). The model combines the features of neoclassical models and the Harrod-Domer models (Harrod, 1939; Domer, 1946), but unlike the latter, here long run growth rate depends permanently on higher savings rates in the economy. However, the basic feature of this model is that there is no clear distinction between capital accumulation and technological progress. Further versions of AK model were developed by Romer (1986), Lucas (1988), King and Rebelo (1990), Rebelo (1991), and more recently by Jones *et al.* (2000) and Acemoglu and Ventura (2002). Adding knowledge externalities to a firm's capital accumulation, these models are mainly dominated by the neoclassical models, but fail to provide an explanation for convergence of economies in the long run.[2]

AK theory was followed by a wave of first generation endogenous growth theories in the 1990s, generally known as '*innovation-based*' growth models, which recognize that intellectual capital – the source of technological progress, is distinct from physical and human capital (Romer, 1990; Segerstrom *et al.*, 1990; Grossman and Helpman, 1991a; 1991b; Aghion and Howitt, 1992). Romer (1990) develops a 'product variety model' of endogenous growth where new innovations come through new products in the market but not through improved product varieties. The *'innovation-based'* growth models were further advanced by the first generation Schumpeterian theory of Segerstrom *et al.* (1990) and Aghion and Howitt (1992), which focuses on quality-improving innovations that render old products obsolete through the process of 'creative destruction.' Innovation-based theory implies that the way to grow rapidly is not to save a large fraction of output but to devote a large fraction of output to research and development. What makes these growth theories 'endogenous' is that growth is a consequence of endogenous R&D. These models predict scale effects where, for sustained growth in productivity, continuous increases in R&D inputs are necessary.

However, for the US after the 1950s, Jones (1995) finds evidence that refutes the first generation Schumpeterian growth model. He proposes the semi-endogenous growth model discussed below.

III. Semi Endogenous Growth Models:

In 1995, Jones argued that the evidence for the United States after 1950 refutes the 'scale effect' of first generation endogenous growth theory.[3] While the number of workers engaged in R&D is constantly increasing over time, TFP growth is almost constant. To reconcile the facts, he developed a semi-endogenous growth model where he assumed diminishing returns to knowledge,

[2] Jones and Manuelli (2005) detail the limitations of AK models as compared to other endogenous growth models.

[3] Jones (2002) argued that productivity growth in the US had remained stationary during a period when population, and in particular the number of people engaged in R&D, had risen dramatically, which contradicts the first generation endogenous growth theory (Aghion and Howitt, 1992).

as opposed to constant returns in the first generation models. [4] The scale effect that is present in the first generation models vanishes due to this assumption, where the growth path of TFP is now bounded to a finite period. The model becomes consistent with the US evidence presented by Jones (1995).

Technology inputs, such as the number of workers engaged in R&D, are inextricably tied to the overall population in the economy. The higher is the population growth, the greater the proportion of workers engaged in R&D and the greater is the chance of finding new ideas or innovations. As growth rate of R&D workers cannot exceed the growth rate of the population in the long run, in equilibrium, economic growth is governed by population growth, which is exogenous to an economy. This justifies the name ‘semi-endogenous’ in this model. Although the growth rate of the economy turns out to be a function of parameters that are typically thought of as exogenous, growth in the model is endogenously derived from the pursuit of new technologies by rational, profit-maximizing agents. Semi-endogenous growth models were further developed by Kortum (1997) and Segerstrom (1998), based on the idea that a positive growth in R&D inputs is required to maintain sustained growth in TFP due to the assumption of diminishing returns to knowledge.

These models were quite intuitive; however policy makers remained puzzled that policies stimulating R&D would have, at most, transitory effects on productivity growth. Ha and Howitt (2007) show that, although semi-endogenous theory predicts that sustained productivity growth requires sustained growth in R&D input, in a limiting case when the growth rate of R&D inputs is falling, the theory implies an inverse U-shaped growth path for productivity over time, where productivity growth is falling initially but rising in the latter half of the period. Hence, in the second half, TFP growth becomes sustainable even with falling growth in R&D inputs. This finding becomes critical because R&D input, when measured as R&D labour implies that increased TFP growth would be associated with falling population growth in the long run. Since growth rate in R&D labour is equal to the population growth rate in the long run, the above finding

[4] See Jones (2005) “Growth and Ideas” for an extensive discussion of semi endogenous growth theory.

contradicts the main proposition of the semi-endogenous growth model, which states that, for maintaining sustained growth in productivity, sustained growth in R&D labour is necessary.

IV. Second Generation Endogenous Growth Models:

The newer version of endogenous growth models was developed by Aghion and Howitt (1998) and later extended by a number of authors, e.g., Peretto (1998), Howitt (1999), Peretto and Smulders (2002). They propose the second generation fully endogenous Schumpeterian growth models, where the assumption of constant returns to knowledge is retained from the first generation models, but they assume that the varieties and complexities of new innovations are increasing. Their argument follows the Schumpeterian growth models, where to ensure sustained TFP growth, the level of R&D has to increase over time to counteract the increasing range of products that lowers the productivity effects of R&D activity, otherwise called the 'product proliferation effect'. Product variety can be approximated by any variable that grows at the same rate as population in the long run. The model is consistent with US evidence presented by Jones (1995a). However, instead of focusing on an exogenous variable like population, these models are fully endogenous and retain most of the implications of first generation Schumpeterian growth models. With constant returns to knowledge, anything that increases the fraction of resources allocated to R&D will increase long run productivity growth.

Although this leads to an intense debate between Schumpeterian and semi-endogenous growth theories, in recent times the second generation Schumpeterian growth models have obtained most empirical support for the modern growth period after 1870. While Ha and Howitt (2007) test them for the US economy using data from 1950-2000, Madsen (2008b) test the two theories using panel and time series data from OECD countries from 1870 onwards, and Madsen *et al.* (2010) examine them using Indian data in the post 1950 period. All three studies acquired support in favour of Schumpeterian growth theory as against the semi-endogenous growth model.

Goodfriend and McDermott (1995), Galor and Weil (2000) and Galor (2005) take another major challenge to find a unified growth theory with underlying micro foundations that are consistent with the entire process of economic development from a period of Malthusian epoch, defined as pre-industrialization period before the mid eighteenth century, to modern economic growth. Although detailed discussion of these kind of theories is beyond the scope of this dissertation, the key elements in their model are the Malthusian elements, the engines of technological progress, the origin of human capital formation and the determinants of parental choice regarding the quantity and quality of children. They proposed a dynamic system where the growth rate of output per capita is nonlinear and evolution occurs through structural change permitting the economy to take-off and to converge to modern growth steady-state equilibrium. However, empirical specifications for this kind of model are yet to be investigated in the literature. The next section will discuss the aims and objectives of each chapter of this thesis.

1.1. Objectives of this Thesis

In search of a long run growth theory, the above discussion of various theoretical models suggests an intense ongoing debate among the second generation endogenous growth models. This thesis mainly focuses on the two competing second generation endogenous growth models, namely Schumpeterian and semi-endogenous growth models and tries to investigate empirically how these models best fit into technological epochs back in time such as the 'Industrial and Agricultural Revolution in England', the 'Great Divergence' and the 'American catching-up and forging ahead of the UK'. To the best of my knowledge, this study is the first that attempts to test the modern growth theories using long historical data spanning over more than three centuries.

While every theory has its own limitations, there is need for a search for a theory that can at least explain some of the biggest epochs back in time. Empirical testing of theoretical models and reasons behind technological revolutions would provide greater scope for modern theorists to explain these events back in history and for episodes that are yet to occur. Greasley and Oxley (1997) demonstrate that output fluctuations were very persistent during the period 1780-1851, and forces that are internal to the economy shaped the Industrial Revolution for Britain. This provides evidence that endogenous growth models could be more relevant in accounting for the glorious period of British industrialization than the neoclassical growth models. In a similar view, using cointegration and causality techniques, Oxley and Greasley (1998) suggest that the Industrial Revolution was shaped mostly by technological progress. This thesis has three essential objectives, in the form of three separate empirical studies, and contributes to the literature on economic growth and economic history.

The first and foremost objective pertains to the rigorous analysis of the role that innovative activity played in raising the productivity growth of Britain at the time of the First and Second Industrial Revolutions. Using long historical data for Britain, which spans for more than three centuries, the importance of innovative activity and population growth in inducing the transition from the Malthusian trap to the post-Malthusian growth regime in Britain is explained. Furthermore, the study tests the ability of two competing second-generation endogenous growth models, namely Schumpeterian and semi-endogenous growth models, to account for the British growth experience. This study is, to the best of my knowledge, the first that attempts to formally test whether there is a significant relationship between growth, innovative activity and population growth during the first and the second-phases of industrial revolutions in Britain, by using a direct measure of innovative activity and by allowing for land as a factor of production.

The second objective relates to examining the roles of technology in advancing productivity growth in British agriculture over the period 1620-1850. Theory, historiography and empirical evidence suggest that agriculture is the key to economic development. In explaining the different stages of economic development, Rostow (1959) claims that one of the essential conditions for successful take-off for the British economy was the technological revolution in agriculture. Deane (1969) and Overton (1996a; 1996b) argue that for England the Agricultural Revolution was closely associated with the Industrial Revolution, however, no empirical study has been conducted so far, which accounts for this particular event. This study examines the extent to which productivity advances in British agriculture in the period 1620-1850 were driven by technological progress, where technology is measured by 1) agricultural patents issued and 2) number of new book titles published on agricultural methods. To explain the roles of technological progress in British agriculture, Schumpeterian and semi-endogenous growth models are discriminated and tested empirically. The above objectives complement the uniqueness of this kind of studies to investigate such an event in history through the lens of modern growth theories.

The third and final objective of this thesis pertains to the rigorous analysis to find the sources of growth on a sectoral basis that closed the gap between the US and the UK at the start of the twentieth century. After the Industrial Revolutions, Britain was termed the ‘workshop of the world’. However, the US leapfrogged the UK and became the world leader by the end of the nineteenth century. What has helped this economy to flourish so quickly and achieve that, which Europe took sixteen centuries to breakthrough? What went wrong that the British productivity lead could not be maintained?

Many studies in the literature, starting from the famous dissertation work of Habakkuk (1962) and later by Rosenberg (1981), Oxley and Greasley (1995), Abramovitz and David (1996), Greasley and Oxley (1998), Broadberry (1998) and more recent studies such as Broadberry and Irwin (2006), have tried to explain the phenomenon of ‘American catching-up and forging ahead’. However, little attention has been given to investigating the sources of productivity advancements in sectors, particularly in those sectors that led the US to catch up and finally forge ahead of other economies in the twentieth century. This study seeks to answer these questions through the lens of the sectoral productivity gap between the US and the UK and R&D augmented investments in the advanced sectors of the American economy over the period 1840-2008.

Contributions from all three chapters fill a number of important gaps in the literature and have significant policy implications for both advanced and currently growing economies. The next section will detail the structure of the thesis followed here.

1.2. Structure of this Thesis

This study is a collection of three self-contained essays. However, they share a common theme in terms of the emphasis they place on productivity growth, technological progress and population growth, in the context of macroeconomic policies followed in the UK and in the US, over different phases in time. Further, the studies examine a sequel of events, which starts with the First Industrial Revolution in Britain along with the British Agricultural revolution in the period 1760-1850, followed by the Second Industrial Revolution in Britain in the period 1850-1913, and then followed by the transfer of technological leadership to the US at the start of the twentieth century, which continues in the twenty-first century. The thesis is organized as follows.

Chapter 2, a joint paper with my thesis supervisors, is motivated from the episode of 'Industrial Revolution of Great Britain', whose existence is still of great importance to the modern developing economies in achieving sustained growth over the long run. [5] It is always difficult to comprehend why Industrial Revolution happened at that time and in what respect Britain was special compared to other pre-industrial economies. Being one of the most significant events in world economic history, various contrasting theoretical explanations are offered by different growth theorists.[6] This makes our task of reconciling the facts with theories of economic growth more challenging. This chapter attempts to solve this puzzle through endogenous growth models allowing for land as an additional factor of production. Chapter 2 empirically investigates the following: i) whether the second-generation endogenous growth theories, augmented to allow for the population growth path, are useful in explaining the British Industrial Revolution; ii) whether the British growth experience during the period 1620-2006 can be used to discriminate between the second-generation endogenous

[5] Chapter two is submitted in a form of a paper, which is jointly written with my thesis supervisors Prof Jakob Madsen and A/Prof James Ang, Monash University, Australia. The paper is currently under '*revise and resubmit*' decision at '*Journal of Economic Growth*' (from May 2010). I fully acknowledge the credit of this paper under all our three names.

[6] See Clark (2007) for a comprehensive discussion of different growth models of British Industrial Revolution.

growth models; and iii) the role played by population growth during the whole transitional period.

Chapter 3 is a logical sequel of chapter 2[7]. While Deane (1969) and Overton (1996a; 1996b) support the view of the simultaneous existence of Agricultural and Industrial revolution in Great Britain, Allen (1999) describe it as a two-phase development, one before the First Industrial Revolution and the second after it. Clark (2002), with a more pessimistic view, raises doubt about the term 'Agricultural Revolution' itself in the context of England. This chapter seeks to contribute to the debate regarding the existence of an 'Agricultural Revolution' in terms of increased technological progress at the same time as the First Industrial Revolution in England. The primary objectives of this paper are to examine the role played by innovative activity during the British Agricultural Revolution and to test whether any second-generation innovation-based growth models can adequately explain British agricultural growth during the period 1620-1850.

Chapter 4 turns to a new episode in the literature of economic growth, where the factors behind the sectoral productivity growth are examined for the US and the UK from the mid-nineteenth century onwards to shed some light on the phenomenon of 'America's catching-up and forging ahead of the UK'. In this chapter, two hypotheses are proposed and formally tested, which are expected to contribute to closing the gap between these two economies. The hypotheses are: (1) US agricultural productivity increased to a great extent due to increasing returns to land coming from enormous land resources present in the US and technology augmented equipment investments in agriculture; (2) The US transport sector went through major transformations, for example, intensive use of highways and trucking, that increased the productivity in the service sector. While the agricultural miracle intensified the take-off process, revolution in the service sector sustained the lead until 1970. Inadequate land resources in the UK as

[7] Although chapter 3 is submitted as a chapter in the thesis, solely written by me, I have written another paper out of it, co-authored with my thesis supervisors, Prof Jakob Madsen and A/Prof James Ang, Monash University, Australia. This paper is currently under review at '*European Economic Review*' (from February 2010).

compared to the US could not generate any advantage for the former with low investments in technology embodied machinery.

Finally chapter 5 closes this discussion and brings together the findings from all the three empirical chapters and their relevance to the literature on economic growth and economic history. It also provides contributions made by this thesis and directions for future research.

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Declaration for Thesis Chapter 2

Declaration by candidate

In the case of Chapter 2, the nature and extent of my contribution to the work was the following:

Nature of contribution	**Extent of contribution (%)**
My supervisors have guided me to build the motivation of the chapter and then I collected all the data necessary for the estimation. This chapter uses an extensive data base, which covers the period from 1620-2006. I have performed all the initial estimations and written up the first draft of the chapter. The chapter has been presented by myself in various conferences including '14th Australasian Macroeconomics Workshop' and 'Econometric Society Australasian Meeting 2009'. The final version of the chapter is a joint effort of my supervisors and myself.	40

The following co-authors contributed to the work. Co-authors who are students at Monash University must also indicate the extent of their contribution in percentage terms:

Name	**Nature of contribution**	**Extent of contribution (%) for student co-authors only**
Jakob B. Madsen	Discussion + Writing up of the paper	
James B. Ang	Discussion + Writing up of the paper	

Candidate's Signature	[redacted]	**Date** 21.05.10

Declaration by co-authors

The undersigned hereby certify that:

(1) the above declaration correctly reflects the nature and extent of the candidate's contribution to this work, and the nature of the contribution of each of the co-authors.
(2) they meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;
(3) they take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;
(4) there are no other authors of the publication according to these criteria;
(5) potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit; and
(6) the original data are stored at the following location(s) and will be held for at least five years from the date indicated below:

Location(s)	Department of Economics, Monash University, Caulfield campus.

[Please note that the location(s) must be institutional in nature, and should be indicated here as a department, centre or institute, with specific campus identification where relevant.]

Signature 1	[redacted]	**Date** 21.05.10
Signature 2		21.05.10

Chapter 2

FOUR CENTURIES OF BRITISH ECONOMIC GROWTH: THE ROLES OF TECHNOLOGY AND POPULATION

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Abstract: Using long historical data for Britain over the period 1620-2006, this paper seeks to explain the importance of innovative activity and population growth in inducing the transition from the Malthusian trap to the post-Malthusian growth regime in Britain. Furthermore, the paper tests the ability of two competing second-generation endogenous growth models to explain the British Industrial Revolution. The results suggest that innovative activity was an important force in shaping the Industrial Revolution and that the British growth experience is consistent with Schumpeterian growth theory.

Keywords: Endogenous growth; British Industrial Revolution

JEL classification: O30; O40

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"All we need (to) explain is why in the millennia before 1800 there was in all societies – warlike, peaceful, monotheist, polytheist – such limited investment in the expansion of useful knowledge, and why this circumstance changed for the first time in Britain sometime around 1800. Then we will understand the history of mankind."

- Gregory Clark, 2007, page 207.

2.1. Introduction

Before the late 18th century, per capita growth rates were either zero or miniscule and average per capita incomes in different regions of the world were quite similar Galor (2005; Maddison, 2007). Galor and Weil (2000), Hansen and Prescott (2002) and Galor (2005) argue that this period of stagnation can be described as the Malthusian epoch. Instead of resulting in improved standards of living, technological progress led to increased population. The onset of the Great Divergence was around 1760 on the eve of the First Industrial Revolution in Britain. It transformed the British economy from the Malthusian trap to the post-Malthusian epoch during which the rate of technological progress outpaced the population growth drag, resulting in positive per capita growth rates. However, the British Industrial Revolution is still one of the great mysteries in the history of human evolution. Various interpretations have been presented by economic historians and growth theorists to explain this extremely significant series of events. Consequently, the reconciliation of historical facts with modern growth theories presents us with a challenging task.

Economic growth literature contains extensive coverage of Britain due mainly to its preeminent position in the First Industrial Revolution and the availability of well-documented historical facts and data. However, despite being one of the most significant events in economic history, little is known about the part played by innovation in freeing the British economy from its Malthusian straitjacket. The literature emphasizes different roles played by technology during the Industrial Revolution. Crafts (1995) suggests that the augmented neoclassical growth model is the appropriate tool for modelling growth during the Industrial Revolution and that the most important innovations were exogenous during that period. Based on the statistical properties of productivity data, historiography and growth accounting exercises that give some importance to residual productivity, Crafts (1995) concludes that both the *AK* model of Rebelo (1991) and the endogenous growth model of Grossman and Helpman (1990) are incapable of explaining the growth rates experienced by England during the Industrial Revolution.

However, several studies have stressed that the Industrial Revolution was associated with a high level of innovative activity (see Sullivan, 1989; Galor, 2005; Mokyr, 2005); Clark, 2007; Greasley and Oxley, 2007; Khan and Sokoloff, 2007). Sullivan (1989, p. 424) describes the period 1762-1851 as the 'Age of Invention' for England' during which patentable inventions increased markedly. Greasley and Oxley (1997) demonstrate that output fluctuations were very persistent during the period 1780-1851, and this provides evidence that endogenous growth models are more relevant in accounting for the glorious period of Britain's industrialization than the neoclassical growth model. In a similar vein, using cointegration and causality techniques, Oxley and Greasley (1998) suggest that the Industrial Revolution was shaped mostly by technological progress.

Crafts (1995) and Oxley and Greasley (1998) focus on the validity of the first-generation endogenous growth models of Grossman and Helpman (1990) and Rebelo (1991) in explaining the Industrial Revolution. However, the second-generation endogenous growth models have taken over from the first-generation models following Jones' (1995b) critique of first-generation models. In particular, Jones (1995b) notes that the number of R&D workers increased substantially during this period while the US post-WWII growth rates have remained relatively constant. This observation is inconsistent with the predictions of the first-generation endogenous growth models where productivity growth is proportional to the number of R&D workers.

The second-generation endogenous growth models overcome this unwarranted property of the first-generation growth models by abandoning the assumption of constant returns to scale in ideas production (semi-endogenous growth models) or by assuming that the effectiveness of R&D is diluted due to the proliferation of products when an economy expands (Schumpeterian growth models) (Aghion and Howitt, 1998; Howitt, 1999; Peretto and Smulders, 2002; Ha and Howitt, 2007). Thus, given that the first-generation endogenous growth models are unlikely to account for the productivity growth in Britain since 1620, the second-generation endogenous growth models may be more consistent with the British growth experience. However, it remains to be seen whether any of these modern innovation-based growth models, extended to allow for population growth drag, are capable of explaining the glorious period of Britain's industrialization, considering that most of the historiography gives domestic considerations a leading role as factors that shaped the Industrial Revolution (see Oxley and Greasley, 1998).

The contribution of this paper is to examine: 1) whether the second-generation endogenous growth theories, augmented to allow for the population growth path, are useful in explaining the British Industrial Revolution; 2) whether the British growth experience during the period 1620-2006 can be used to discriminate between the second-generation endogenous growth models; and 3) the role played by population growth during the whole transitional period, particularly the reductions in the population growth rate after 1813 and then after 1907. This paper is, to the best of our knowledge, the first that attempts to formally test whether there is a significant relationship between growth, innovative activity and population growth during the first and the second-phase of the industrial revolution in Britain, by using a direct measure of innovative activity and by allowing for land as a factor of production.

The paper proceeds as follows: the next section shows the empirical implications of various endogenous growth theories and extends the growth framework used by Ha and Howitt (2007) and Madsen (2008b) to allow for land as a fixed factor of production. Section 3 discusses the construction of variables and provides some graphical analyses. Using very long historical data over the period 1620-2006, the empirical analysis is performed and the results are presented and discussed in Section 4. Section 5 provides an anatomy of the British Industrial Revolution. The last section concludes.

2.2. Innovation-Based Growth with Land as a Fixed Factor of Production

When land is a significant factor of production, labour productivity growth is a race between population growth and technological progress. Technological progress is determined by innovative activity. This section incorporates the implications of population growth into the second-generation endogenous growth models and shows how to discriminate between Schumpeterian and semi-endogenous growth models.

Consider the following homogenous Cobb-Douglas production function:

$$Y = AK^{\alpha}\overline{T}^{\beta}L^{1-\alpha-\beta}, \tag{2.1}$$

where Y is real output, K is capital stock, $\overline{T}$ is a fixed amount of land, L is labour, α is the share of income going to capital and β is the share of income going to land under the maintained hypothesis of perfect competition. The production function exhibits constant returns to scale in K, $\overline{T}$ and L and increasing returns to scale in A, K, $\overline{T}$ and L altogether.

Eq. (2.1) can be written as per capita output so that:

$$\frac{Y}{L} = A^{1/(1-\alpha)}\left[\frac{K}{Y}\right]^{\alpha/(1-\alpha)}\overline{T}^{\beta/(1-\alpha)}L^{-\beta/(1-\alpha)}. \tag{2.2}$$

Taking logs and differentiating yields labour productivity growth along the balanced growth path:

$$g_y = 1/(1-\alpha)g_A - \beta/(1-\alpha)g_L \tag{2.3}$$

where g_y is labour productivity growth, g_A is the growth in total factor productivity and g_L is the growth in the labour force. Here, the first derivative of the K-Y ratio is set to zero because the K-Y ratio is constant along the balanced growth path. The K-Y ratio is included in some of the empirical estimates to allow for transitional dynamics.

The role of capital for growth is suppressed in Eq. (2.3) under the assumption that the economy is on its balanced growth path. Capital stocks cannot act as an independent growth factor along the balanced growth path since it is driven entirely by technological progress. Labour productivity in Eq. (2.2) is cast in terms of the *K*-*Y* ratio to filter out the technology-induced capital deepening (Klenow and Rodriguez-Clare, 1997). The reason why productivity growth triggers capital deepening is that technological progress increases expected earnings per unit of capital and, through the channel of the equity market, brings Tobin's *q* in excess of its steady-state value. This initiates a capital deepening process that terminates when Tobin's *q* reaches its steady-state equilibrium, which may not be one in the presence of taxes, technological progress and population growth (see Madsen and Davis, 2006). The *K*-*Y* ratio changes transitionally due to changes in time-preferences and taxes.

In the case when land is omitted as a factor of production ($\beta = 0$), Eq. (2.3) reduces to a standard neoclassical growth model in which labour productivity growth is driven entirely by technological progress and independently of population growth. Growth is independent of population growth along the balanced growth path in these models because capital stock endogenously adjusts until the *K*-*L* ratio returns to its initial level following a population shock. When land is an essential factor of production, population growth reduces labour productivity. Population growth slows growth in Eq. (2.3) because of diminishing returns introduced by land as a fixed factor of production. The greater the importance of agricultural production in total output, the more population growth acts as a growth-drag on the economy.

The population growth drag was potentially important for labour productivity growth during the first part of the period considered in this paper. Agriculture was the dominant mode of production in Britain up to the Second Industrial Revolution. In 1600 almost 75% of the English working population was employed in the agriculture sector (Allen, 2001). Agriculture remained the dominant mode of production over the next two centuries. The fraction of the working population in agriculture was 35% in 1800 (Allen, 2001), 28% in 1851 and 12% in 1901 (Mitchell, 1988). Thus, population growth rates lowered per capita income growth rates almost on a one-to-one basis around 1600 and were still very influential for per capita growth over the next two centuries.

While population affects growth directly, innovative activity influences growth indirectly through the channel of ideas production. There are three established theories of ideas production functions and they have quite different implications for how innovative activity is transformed to technological progress and, consequently, growth. In the first-generation endogenous growth models of Romer (1990), Segerstrom *et al.* (1990), Grossman and Helpman (1991) and Aghion and Howitt (1992), ideas production is associated with the number of researchers. In the semi-endogenous growth models of Jones (1995a; 1995b), Kortum (1997) and Segerstrom (1998), R&D inputs are required to grow permanently to maintain sustained ideas production following the assumption of diminishing returns to knowledge. According to the Schumpeterian models of Aghion and Howitt (1998), Dinopoulos and Thompson (1998), Peretto (1998), Howitt (1999) and Peretto and Smulders (2002), a positive constant rate of ideas production can be maintained provided that R&D per worker remains constant. In other words, R&D has to increase over time to counteract the increasing range of products that lowers the productivity effects of R&D activity in order to ensure sustained ideas production.

It is not clear which of the second-generation endogenous growth theories can best describe the British growth experience and whether any of these theories can explain innovation-induced growth over all of the four centuries considered in this paper. Although Ha and Howitt (2007), Madsen (2008b) and Madsen *et al.* (2010) have found that Schumpeterian growth theory is most consistent with the growth experience under modern growth regimes, there is no assurance that the theory will work during the Malthusian and the post-Malthusian growth regimes, as highlighted by Howitt and Mayer-Foulkes (2005). Parente and Prescott (2005) argue that the knowledge term in the production function should be decomposed into two components: 1) the technological knowledge that is available domestically and on a worldwide scale, and 2) effective utilization of technology. The latter depends on how effectively technology is used and the extent of efficiency of operations within organizations. If the innovations during the British

Industrial Revolution were not used effectively, positive growth rates would not have transpired. Based on historical evidence, Monteiro and Pereira (2006) argue that many growth spurts in history failed to become sustained growth regimes because insufficient human capital was provided to deal with the increasing complexity of innovations. This hypothesis is consistent with the finding of Clark (1987), who shows that the same technology was used in the textile industry in China, Japan, India and the UK around 1920 and yet labour productivity in textiles was markedly different across these countries.

The following general ideas production function can be used to discriminate between different endogenous growth models (Ha and Howitt, 2007; Madsen, 2008b):

$$g_A = \frac{\dot{A}}{A} = \lambda\left(\frac{X}{Q}\right)^{\sigma} A^{\phi-1} \qquad 0<\sigma\le 1,\ \phi\le 1, \qquad (2.4)$$

$Q \propto L^{\kappa}$ in steady state,

where σ is the duplication parameter (zero if all innovations are duplications and 1 if there are no duplicating innovations), ϕ is the returns to scale in knowledge, κ is the coefficient of product proliferation, λ is the research productivity parameter, Q is a measure of product variety, L is employment or population and X is R&D inputs for semi-endogenous growth models or the productivity-adjusted R&D inputs for Schumpeterian growth models. The productivity adjustment in Schumpeterian models recognizes that there is a tendency for decreasing returns to R&D due to increasing complexity of innovations (Ha and Howitt, 2007). Semi-endogenous growth theory assumes that $\phi<1$, $\sigma>0$ and $\kappa=0$ while Schumpeterian models assume that $\phi=1$, $\sigma>0$ and $\kappa=1$. First-generation endogenous growth theory assumes that $\phi=1$, $\sigma>0$ and $\kappa=0$.

Schumpeterian growth models maintain the assumption from first-generation endogenous growth models of constant returns to the stock of R&D knowledge. However, they assume that the effectiveness of R&D is diluted due to the proliferation of products as the economy expands. Thus, growth can still be sustained if R&D is kept in a fixed proportion to the number of product lines, which is in turn proportional to the size of population in the steady state. As such, to ensure sustained ideas production, R&D has to increase over time to counteract the increasing range and complexity of products that lowers the productivity effects of R&D activity.

Assuming that shocks, e_t, are identically and normally distributed with a mean of zero, Eq. (2.4) forms the following model (see Ha and Howitt, 2007):

$$\Delta \ln A_t = \ln \lambda + \sigma[\ln X_t - \ln Q_t + (\frac{\phi - 1}{\sigma}) \ln A_t] + e_t, \quad (2.5)$$

where e_t are independently and identically distributed errors. Given that $\Delta \ln A_t$ is stationary, it follows that variables in the square brackets are cointegrated. Following the parameter restrictions discussed above, semi-endogenous growth theory requires that: (i) both $\ln X_t$ and $\ln A_t$ be non-stationary and integrated at the same order; and (ii) both variables are cointegrated with the cointegrated vector of $[1 \ (\phi - 1/\sigma)]$, in which the second element is expected to be negative. Schumpeterian growth theory predicts: (i) $\ln(X/Q)_t$ is stationary; and (ii) $\ln X_t$ and $\ln Q_t$ is cointegrated with the cointegrated vector of $[1 \ -1]$.

Imposing the restrictions suggested by the two second-generation endogenous growth models implies that the terms υ_t and ς_t in the following equations are stationary:

$$\upsilon_t = \ln X_t + \left(\frac{\phi - 1}{\sigma}\right) \ln A_t \qquad \text{Semi-endogenous growth theory} \quad (2.6)$$

$$\varsigma_t = \ln X_t - \ln Q_t. \qquad \text{Schumpeterian growth theory} \quad (2.7)$$

Taking logs on Eq. (2.2) and combining it with Eq. (2.6) yields:

$$\ln\left(\frac{Y}{L}\right)_t = \frac{\sigma}{(1-\alpha)(1-\phi)}\ln X_t + \alpha/(1-\alpha)\ln\left[\frac{K}{Y}\right] + \beta/(1-\alpha)\ln\overline{T} - \beta_t/(1-\alpha)\ln L_t + \frac{\sigma}{(1-\phi)}\upsilon_t$$

$$\Rightarrow \quad \ln\left(\frac{Y}{L}\right)_t = \psi + \frac{\sigma}{(1-\alpha)(1-\phi)}\ln X_t - \beta_t/(1-\alpha)\ln L_t + \frac{\sigma}{(1-\alpha)(1-\phi)}\upsilon_t \qquad (2.8)$$

Where $\psi = \alpha/(1-\alpha)\ln(K/Y) + \beta/(1-\alpha)\ln\overline{T}$. Thus using cointegration technique, equations (2.7) and (2.8) can be used to test whether the two second-generation models are consistent with British historical data. Note that here β_t is allowed to vary over time in Eq. (2.8).

However, cointegration tests are necessary, but not sufficient, conditions for second-generation growth models to be consistent with the growth process (Madsen, 2008b). A sufficient condition is that these models can explain long-run growth. More importantly, an important part of this paper is to examine the extent to which growth in Britain has been driven by innovations. Another aim is to explain the role played by innovations in the transformation of the British economy from the Malthusian trap to the post-Malthusian and the modern growth regimes (see Goodfriend and McDermott, 1995; Galor and Weil, 2000; Hansen and Prescott, 2002; Galor, 2005).

The following growth model is regressed: 1) to examine the importance of innovations during the different growth epochs in Britain; 2) to discriminate between semi-endogenous and Schumpeterian growth models; and 3) to evaluate the importance of demographic transitions on growth:

$$\Delta\ln y_t = b_0 + b_1\Delta\ln X_t + b_2\ln(X/Q)_t + b_3 as_t\Delta\ln L + b_4\Delta\ln TO_t + b_5\Delta\ln(M/Y)_t + b_6\ln UNC_t + b_7\Delta\ln(I/K)_t + u_t, \qquad (2.9)$$

where y_t is productivity; X_t is measured by the number of patent applications by domestic residents; $(X/Q)_t$ is research intensity, which is measured by patent applications over the labour force; as_t is the share of agriculture in total GDP; L_t is labour force; TO_t is trade openness; M_t is money supply and Y_t is nominal GDP; UNC_t is macroeconomic uncertainty; I_t is non-residential real gross investment; K_t is real capital stock; and u_t is a stochastic error term. Trade openness is measured as the sum of exports and imports over GDP. Macroeconomic uncertainty is measured by the five-year standard deviation of the annual growth of the consumer price index. Here, semi-endogenous growth theory predicts $b_1 > 0$, whereas Schumpeterian growth models predict that $b_2 > 0$. Eq. (2.9) is estimated in 5-year non-overlapping first differences.

Eq. (2.9) combines the predictions from Eq. (2.3) that per capita income growth is determined by technological progress and population growth and the predictions of second-generation growth models on technological progress (see Madsen, 2008b for the derivation). The relationship between growth and R&D as predicted by endogenous growth models expresses steady-state relationships. However, Britain is unlikely to have been in its steady state over most of the past four centuries. Since capital is usually the variable that adjusts to bring the economy back to its steady state following a shock, the investment to capital ratio is included in the model to allow for transitional dynamics in the periods in which investment is available (i.e., after 1780). This ratio may also capture potential positive externalities associated with investment in fixed capital. The control variables are only included in some of the estimations because they are not available over the entire period.

Trade openness, macroeconomic uncertainty and the ratio of money to income are included in the regressions as control variables. Openness is included because it is often considered as being important for growth for various reasons (see Vamvakidis, 2002) Lucas, 2007; Madsen, 2009). Trade openness is not an ideal proxy for openness. However, better data on openness, such as tariffs and non-tariff trade barriers, are not available for over four centuries. The variable $(M/Y)_t$ is a proxy for financial deepening. Increases in financial deepening have been found to be important for growth (see, e.g., Rousseau and Sylla, 2005). Financial deepening influences income positively because it eases the access to credit which in turn facilitates more efficient use of resources. Inflation variability as a proxy for macroeconomic uncertainty is a drag on the economy because it is often associated with fiscal mismanagement, wars, and crop failures.

Annual data covering the period 1620-2006 are used in the estimates. Different data periods are considered in the estimates to check: 1) the validity of the model during different periods in British history; 2) whether the coefficients are structurally stable; and 3) the extent to which second-generation endogenous growth models can explain different eras of British history or whether these models are consistent with growth since the scientific Enlightenment or only recently. The following sample periods are considered in the analyses: 1) 1620-1850, 2) 1760-1850, 3) 1620-1913, 4) 1760-1913, 5) 1620-2006 and 6) 1760-2006. The periods ending in 1850 contain the First Industrial Revolution whereas the periods up to 1913 include both the First and the Second Industrial Revolution. Sullivan (1989) characterizes the First Industrial Revolution period (1760-1850) as the 'Age of Invention' in England, as reflected by a dramatic increase in the propensity to patent. The first sample period thus reflects Britain's transformation from a stagnant economy to a developed nation. Estimates covering the Second Industrial Revolution during the period from 1850 to 1913 cannot be undertaken with any confidence since it would result in only six degrees of freedom in the estimates where all variables in Eq. (2.9) are included. Therefore, we have chosen to focus on the periods that cover the first available observation or the onset of the First Industrial Revolution to the end of the Second Industrial Revolution.

2.3. Data and Graphical Analysis

Testing the role played by innovations in British growth over the period from 1620 to 2006 is not an easy task because of the difficulties associated with the measurement of labour productivity and innovative activity. Labour productivity is difficult to measure because employment and annual hours of work are not available on a regular basis until after 1870 and because the measurement of GDP is controversial. Harley (1982) and Crafts (1985) argue that the aggregate output data compiled by Deane and Cole (1962), which are available from 1700, tend to overestimate growth during the period 1770-1815. The GDP data from Feinstein (1972) are available first from 1855, while data from Lindert and Williamson (1982) are available only for the years 1688, 1759 and 1801/03.

In view of the above considerations, we use three different measures of labour productivity that are all spliced with per capita GDP from Maddison (2008) after 1830. The first measure is GDP per capita using the income data for England and Wales compiled by Clark (2001). These data are available on decadal frequencies from 1620. The second measure is per capita industrial production. Industrial production is compiled by Crafts and Harley (1992) and is available on an annual basis from 1700. The third measure is real wages, which are available on an annual basis since 1620. Real wages are measured as the unweighted average of nominal wages among skilled and unskilled workers in Oxford and London and divided by consumer prices. The data are compiled by Allen (2001). Real wages is an ideal measure of labour productivity provided that these data are representative for all professions in Britain and that labour's income share is constant. However, labour's income share is not constant over time and the wage data may only be approximately representative for all professions. Comparing wage data against labour productivity in 19th century Britain, Bairoch (1989) and Angeles (2008) find that real wages are excellent indicators of labour productivity.

Although the post-1830 per capita GDP data from Maddison (2008), which are mostly based on Feinstein's (1972) estimates, are probably the mostly widely used and most widely accepted data, they do have pitfalls. Income and population data cover the Republic of Ireland up to its independence in 1922. Data covering Britain only during the period 1830-1922 are not yet available.[1] The inclusion of Ireland in the period 1830-1922 gives rise to two potential problems. First, the Great Irish Famine in the mid 19th century resulted in a temporary but marked decline in the Irish population. Since the Malthusian mechanism is catered for in the model this dip in the population size should not constitute a problem; however, such a large shock may affect the dynamic adjustment and, as such,

[1] While the United Kingdom includes the Republic of Ireland during British rule over the period 1801-1922, we use the term Britain throughout the manuscript because the Republic of Ireland is not included in the data in most of the estimation periods.

interfere with the estimates. To overcome this problem an impulse dummy was included in 1855. Second, when Ireland gained independence, the size of the population in Maddison's data shrunk by three million. Since GDP is reduced by almost the same proportion per capita, GDP is not too severely affected by the transition. However, the population growth rate shrinks artificially and, therefore, gives rise to a population measurement error. A dummy variable for 1925 was included in the estimation to address this problem.

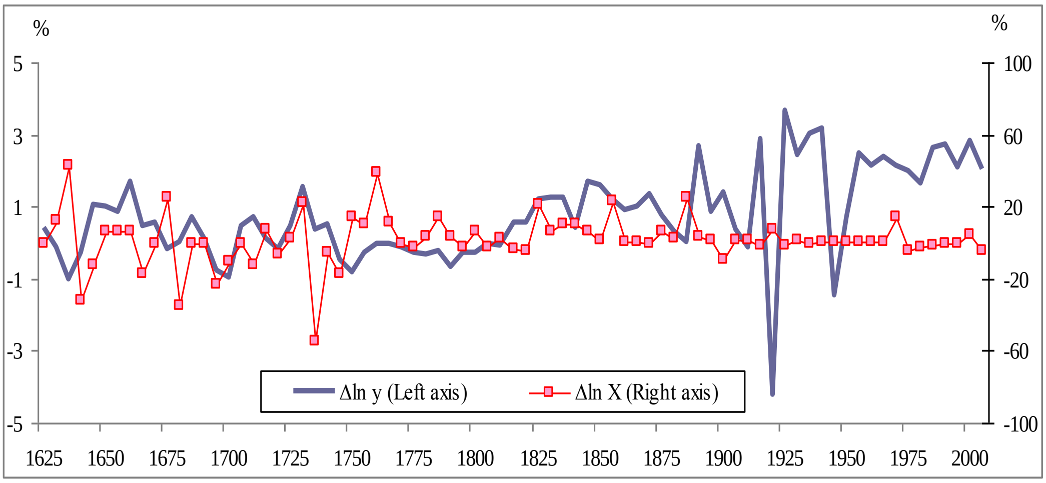
The number of patent applications by domestic residents as opposed to patents granted to residents is used as the measure of innovative activity (X_t) since the granting propensity varies substantially over the processing period (Griliches, 1990). Patent data are available back to 1620. They are measured directly from patent counts without errors, and are the only currently available historical data on innovative activity. The main criticisms against patents as measures of innovative activity are that the quality of patents varies over time, not all innovations are patented, that the propensity to patent may change over time, and that the high costs of patenting give inventors strong incentives to keep their inventions secret (see Boehm and Silberston, 1967). While the law of large numbers tends to render the average quality of patents relatively constant over time in recent years (Griliches, 1990), this law is unlikely to hold in the early part of the sample period when the number of patents was quite modest.

A major concern is whether the propensity to patent has changed over a span of four centuries considered in this study. In probably the most detailed examination of the quality of British patents over the past four centuries, Sullivan (1989) does not find any evidence of shifts in the propensity to patent in individual industries nor changes in the industrial distribution of patents. Regarding the expense of patents, their high costs of acquisition should at least, in principle, have led to patents of higher quality and, as such, weeded out low-quality ones that are unimportant for growth. Thus, high costs of patents may improve their average quality as a measure of innovative activity and, as such, count in favour of patents as measures of innovative activity. This line of reasoning is supported by the findings of Khan and Sokoloff (2007). They find that 87 percent of the great inventors in Britain over the period from 1750 to 1930 were patentees, indicating that most of the important innovations are captured by patent counts.

Furthermore, Griliches (1990) concludes that "in spite of all the difficulties, patent statistics remain a unique resource for the analysis of the process of technical change". However going as far back as four centuries, one cannot deny that there are flaws in patents as indicators of innovative activity. What that essentially means is that the number of patents is potentially a noisy measure in large parts of the estimation period and, as such, may bias the parameter estimates towards zero. Thus, our estimates are likely to understate the importance of innovative activity for growth during the past four centuries of British history.

Product variety (Q_t) is proxied by the size of the population since the number of products or product lines is equal to the population size in the steady state in Schumpeterian growth models. The income share of agriculture (β_t) is measured as the share of agriculture in total income, and this is denoted as_t in the empirical estimates below. More details on data sources and the construction of variables are provided in Appendix 2A.2.

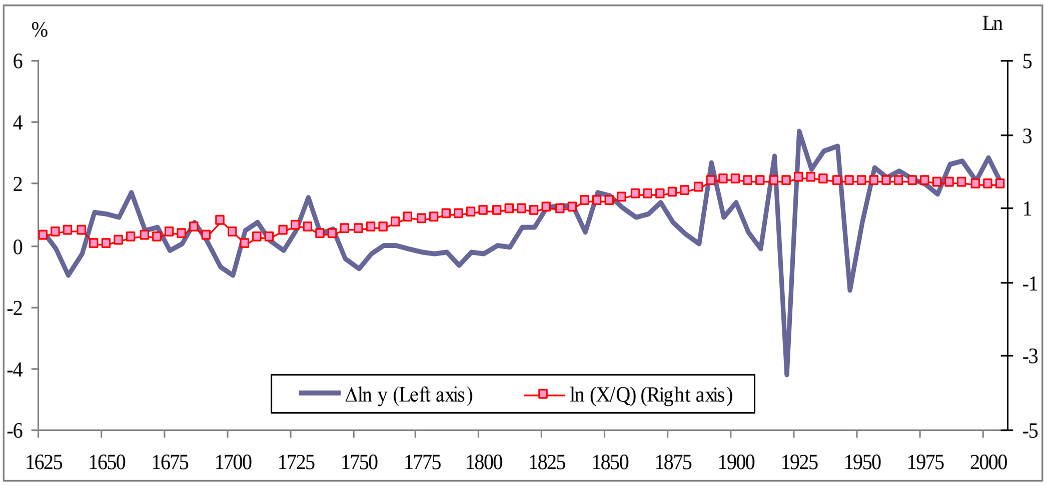
Figure 2.1: Annual growth rates of labour productivity and patent applications, 1620-2005



Notes: Data are in measured in 5-year differences. The growth rates are annualized.

Figure 2.1 displays the growth rates in per capita GDP and patent counts over the period 1620 to 2005. The data are annualized growth rates in five-year intervals. Productivity growth can naturally be subdivided into the Malthusian epoch with average annual growth rates of 0.15% (1620-1825), the post-Malthusian growth regime with average growth rates of 1.12% (1825-1890) and the modern growth regime with average growth rates of 1.65% (1890-2005) (Galor, 2005). Although the First Industrial Revolution started in around 1760, labour productivity growth rates remained miniscule up to circa 1825. This may seem paradoxical given high and increasing innovative activity. However, Britain was still trapped in the Malthusian regime in which the improved living standards derived from technological progress were translated into increasing population growth rates. Population growth rates increased gradually from zero at the beginning of the 18th century to 1.5% at the beginning of the 19th century, as shown in Section 5 below. With population growth rates of 1.5%, significant technological progress was required just to maintain living standards during the first phase of the industrial revolution.

Figure 2.2: Annual growth rates of labour productivity and the ratio of patent applications to labour force



Notes: data for the growth rates of per capital real GDP are in 5-year differences whereas those of patent applications / labour force are in 5-year averages.

Semi-endogenous growth theory predicts a positive relationship between per capita income growth and growth in innovative activity. Figure 2.1 shows that there is no clear-cut relationship between the two variables, particularly after

1800. Thus, the figure gives no clear evidence in favour of semi-endogenous growth theory. Figure 2.2 displays the time-series path of research intensity (X/Q) and per capita income growth in annualized five-year intervals. Research intensity increased over the first three centuries and appears to have stabilized at an approximately constant rate after 1890. Apart from the period 1750-1825, the trend per capita income growth rates and research intensity approximately coincide, as predicted by Schumpeterian theories of economic growth. The gap between research intensity and growth between 1750 and 1820 can, to a large extent, is explained by an extraordinary high population growth rate during that period, which created a wedge between ideas production and per capita income growth rates.

2.4. Empirical Tests of Second-Generation Growth Theories

In the first part of the empirical analysis we undertake integration and cointegration tests to focus on the long-run relationships as predicted by semi-endogenous and Schumpeterian growth theories (Eqs. 2.7 and 2.8). The growth equation (Eq. 2.9) is estimated in the second part of this section. Annual data are used in the integration and cointegration tests while five-year non-overlapping data are used in the growth estimates to filter out business cycle influences, as mentioned above. Labour productivity is measured by per capita GDP throughout this section. The estimates in which per capita industrial production and real wages are used for labour productivity are shown in Appendix 2A.1. However, the main results from these estimates are discussed in the following.

2.4.1. Integration and cointegration analyses

First, integration and cointegration tests are undertaken (Eqs. 2.7 and 2.8). Unit root tests for the entire sample period are performed using the conventional Augmented Dickey-Fuller (ADF) and the Zivot and Andrews (1992) tests, where the latter accounts for the possible presence of an endogenous structural break. It tests the null of a unit root against the alternative of trend stationarity with an unknown break in the series.

The results in Table 2.1 show that output per capita ($\ln(Y/L)_t$), patent applications ($\ln X_t$), and the population growth drag ($as_t \ln L_t$) are integrated of order one whereas research intensity ($\ln(X/Q)_t$) is stationary, as predicted by both classes of models. The results are significant at the 1% level and are not sensitive to the choice of unit root tests. Regarding $\ln(Y/L)_t$, the results are consistent when real wages and industrial production data are used to construct the alternative measures of aggregate output (see Appendix 1). Thus, we can proceed by testing whether labour productivity ($\ln(Y/L)_t$), innovative activity ($\ln X_t$) and the population growth drag ($as_t \ln L_t$) are cointegrated (semi-endogenous growth) and whether $\ln X_t$ is cointegrated with $\ln Q_t$ (Schumpeterian growth).

Table 2.1: Unit root tests (1620-2006)

	ADF		Zivot-Andrews		
	Levels	1st differenced	Levels	1st differenced	Conclusion
Labour productivity [$\ln(Y/L)_t$]	0.83 (0.99)	-13.13*** (0.00)	-2.68 (BP = 1784)	-13.97*** (BP = 1811)	$I(1)$
Patent applications ($\ln X_t$)	-2.79 (0.21)	-12.73*** (0.00)	-4.18 (BP = 1853)	-13.05*** (BP = 1706)	$I(1)$
Population drag [$as_t \ln L_t$]	-1.67 (0.91)	-4.72*** (0.00)	-3.32 (BP = 1877)	-24.15*** (BP = 1860)	$I(1)$
Patent applications / labour force [$\ln(X/Q)_t$]	-4.01*** (0.00)	-12.79*** (0.00)	-5.24** (BP = 1884)	-13.08*** (BP = 1706)	$I(0)$

Note: *p*-values for the ADF tests are indicated in parenthesis. For the Zivot-Andrews tests in levels, the 1% and 5% critical values are -5.57 and -5.08, respectively. At first-differenced, the values are -5.43 and -4.80, respectively. The endogenously determined break point (BP) for each series is indicated in the parenthesis. ** and *** indicate 5% and 1% significance, respectively.

Table 2.2 and Table 2.3 display the results of the cointegration tests. The regression results are based on the Johansen (1988) procedure. First, consider the results for semi-endogenous growth theory in Table 2.2. The estimated coefficients of $as_t \ln L_t$ are highly significant in five out of six cases and have the sign predicted by the theory. These results confirm that population growth is a drag on per capita output when land is a significant factor of production. Regarding the tests of semi-endogenous growth theory, the results show that the null of no cointegrated relationship between labour productivity, patenting activity and the population growth drag cannot be rejected, except for the estimates covering the sample periods 1760-1850 and 1760-2006.

Table 2.2: Johansen cointegration tests for semi-endogenous growth theory (Eq. 2.8).

Period	Hypothesis	Trace statistic	Max-eigenvalue statistic	Cointegrating Vector [ln *Y/L*, ln *X*, *as*ln*L*]	
1620-1850	$r=0$	25.71	22.86**	1, -0.09***, 3.82*** (-8.82) (7.16)	α =0.01 (0.79)
	$r\leq 1$	2.85	1.93		
	$r\leq 2$	0.92	0.92		
1760-1850	$r=0$	18.67	11.74	1, -0.14***, 5.69*** (-5.79) (4.49)	α =-0.03 (-1.59)
	$r\leq 1$	6.93	5.71		
	$r\leq 2$	1.22	1.22		
1620-1913	$r=0$	40.93***	28.38***	1, -0.06***, 2.46*** (-6.27) (5.96)	α =0.01** (2.44)
	$r\leq 1$	12.56	11.87		
	$r\leq 2$	0.68	0.68		
1760-1913	$r=0$	30.83**	20.53*	1, 0.27***, 6.81*** (2.74) (2.82)	α =0.01*** (2.71)
	$r\leq 1$	10.29	9.97		
	$r\leq 2$	0.32	0.32		
1620-2006	$r=0$	30.95**	22.22**	1, 0.19**, 3.17 (2.09) (1.45)	α =0.01*** (3.97)
	$r\leq 1$	8.74	6.97		
	$r\leq 2$	1.77	1.77		
1760-2006	$r=0$	24.32	16.24	1, 6.54**, 6.17* (2.38) (1.90)	α =0.01*** (2.65)
	$r\leq 1$	8.08	7.98		
	$r\leq 2$	0.10	0.10		

Note: the null hypothesis is that there is *r* cointegrating relationship between the variables. An intercept but no trend is included in the estimation. The optimal lag length is pinned down using the SBC. Critical values are taken from Mackinnon *et al.* (1999). α is the error-correction term associated with the $\Delta\ln(Y/L)$ equation. Figures in parenthesis indicate *t*-statistics.

Furthermore, there is only a significant long-run relationship between the variables in two of the six cases (the periods 1620-1850 and 1620-1913). However, in both of the latter cases, the speed of adjustment is positive, which is inconsistent with a gradual adjustment of per capita income towards the steady state as predicted by the theory. Finally, the coefficient estimates are highly sensitive to estimation period. Overall the results in Table 2.2 provide no support for semi-endogenous growth theory. These results are supported by the estimates in Appendix 2.A1 in which the other two measures of labour productivity are used.

Table 2.3: Johansen cointegration tests for Schumpeterian growth theory (Eq. 2.7)

Period	Hypothesis	Trace statistic	Max-eigenvalue statistic	Cointegrating Vector [ln *X*, ln *Q*]	
1620-1850	$r=0$	32.02***	25.21***	1, 2.65*	α = -0.01
	$r\leq 1$	6.81	6.81	(1.83)	(-0.44)
1760-1850	$r=0$	23.47***	15.26**	1, -2.17***	α = -0.16**
	$r\leq 1$	8.21	8.21	(-6.46)	(-1.96)
1620-1913	$r=0$	34.43***	27.49***	1, -2.97***	α =-0.12***
	$r\leq 1$	6.94	6.94	(-12.53)	(-2.86)
1760-1913	$r=0$	19.18**	17.41**	1, -3.31***	α = -0.16***
	$r\leq 1$	1.88	1.88	(-28.36)	(-4.23)
1620-2006	$r=0$	32.65***	31.72***	1, -3.25***	α =-0.12***
	$r\leq 1$	0.93	8.08	(-26.63)	(-3.93)
1760-2006	$r=0$	16.38**	9.37	1, -2.21***	α =-0.05***
	$r\leq 1$	7.02	7.02	(-7.60)	(-3.02)

Note: the null hypothesis is that there is *r* cointegrating relationship between the variables. An intercept but no trend is included in the estimation. The optimal lag length is pinned down using the SBC. Critical values are taken from Mackinnon *et al.* (1999). α is the error-correction term associated with the $\Delta \ln X$ equation. Figures in parenthesis are *t*-statistics.

The results in Table 2.3 provide strong support for Schumpeterian growth theory. The null hypothesis of no cointegration between the innovative activity and product variety is rejected in all the regressions. Furthermore, the estimated coefficients of $\ln Q_t$ are statistically and economically significant at the 1% level in nearly all cases. The statistical and economic significance of the coefficients of the error-correction term provides further evidence in favour of the presence of a long-run relationship between the variables. On average, the economy takes about eight years to adjust towards equilibrium following a shock to the steady state. Finally, the estimated coefficients of product variety are fairly constant for different estimation periods.

2.4.2. Estimates of per capita real GDP growth

Eq. (2.9) is regressed to further examine the validity of each second-generation growth theory and to examine the role played by innovations during the First and Second Industrial Revolutions. The regression results are presented in Table 2.4.[2] The estimated coefficients of population growth are consistently negative and highly significant in almost all regressions, reinforcing some of the results in Table 2.2 that population growth has been a drag on productivity growth during the industrial revolutions. The estimated coefficients of population growth times the agricultural output share is on average -1.83, which is not far from the prediction of $-(1-\alpha)^{-1}$ (assuming that α is roughly 0.3), noting that as_t is likely to be underestimated.

[2] Five dummy variables were considered in the estimations. The last dummy captures the abrupt changes in per capita GDP growth during the period 1645-1660. The second dummy captures the sudden increases in per capita growth in the years 1780-1810. The third dummy captures the severe negative growth in per capita GDP in the years 1915-1930. The fourth dummy captures the Great Irish Famine during the period 1847-1851. The fifth dummy is in 1925 as the Irish Republic becomes independent from Britain in 1922. Since the estimates were unaffected by their inclusion, the dummy variables were omitted from the estimates.

Table 2.4: Estimates of per capita real GDP growth equation (Eq. 2.9)

Period	$\Delta \ln X_t$	$\ln (X/Q)_t$	$as_t \Delta \ln L_t$	$\Delta \ln TO_t$	$\Delta \ln (M/Y)_t$	$\ln UNC_t$	$\Delta \ln (I/K)_t$
	0.01		-1.37***				
	[0.44]		[0.00]				
		0.81*	-1.51***				
1620-		[0.06]	[0.00]				
1850	0.01	1.02***	-1.22***				
	[0.93]	[0.01]	[0.00]				
	0.01	1.05***	-1.35***	-0.02	0.01	0.11	0.08
	[0.97]	[0.01]	[0.01]	[0.69]	[0.55]	[0.91]	[0.60]
	0.02		-2.12**				
	[0.34]		[0.02]				
		2.89***	-1.37**				
1760-		[0.00]	[0.04]				
1850	0.01	2.84***	-1.28**				
	[0.31]	[0.00]	[0.04]				
	0.01	2.47***	-2.60***	0.03	-0.02	1.76	0.37*
	[0.79]	[0.00]	[0.01]	[0.47]	[0.62]	[0.18]	[0.06]
	0.01		-1.61***				
	[0.48]		[0.00]				
		0.65***	-1.74**				
1620-		[0.00]	[0.00]				
1915	0.01	0.65***	-1.75***				
	[0.89]	[0.00]	[0.00]				
	0.00	0.79***	-1.82***	-0.03	-0.02	0.76	0.11**
	[0.71]	[0.00]	[0.00]	[0.43]	[0.42]	[0.28]	[0.02]
	-0.01		-2.77***				
	[0.69]		[0.00]				
		0.87**	-1.45*				
1760-		[0.04]	[0.07]				
1915	-0.01	0.87**	-1.47*				
	[0.91]	[0.05]	[0.08]				
	0.01	1.37***	-1.44**	0.01	-0.04	1.80	0.12**
	[0.62]	[0.00]	[0.04]	[0.80]	[0.27]	[0.11]	[0.03]
	0.01		-2.51***				
	[0.85]		[0.00]				
		0.85***	-2.02***				
1620-		[0.00]	[0.00]				
2005	-0.01	0.87***	-1.99***				
	[0.56]	[0.00]	[0.00]				
	0.00	0.75***	-1.86***	-0.07**	-0.07	-0.55	-0.01
	[0.89]	[0.00]	[0.00]	[0.03]	[0.30]	[0.40]	[0.89]
	-0.03		-3.58***				
	[0.21]		[0.00]				
		1.06**	-1.79**				
1760-		[0.02]	[0.03]				
2005	-0.21	1.17***	-1.86**				
	[0.35]	[0.01]	[0.03]				
	-0.01	1.24**	-1.46	-0.06	-0.08	-0.08	0.01
	[0.75]	[0.03]	[0.27]	[0.24]	[0.32]	[0.93]	[0.92]

Note: the Newey-West procedure was used to obtain heteroskedasticity consistent robust estimates. An intercept was included in the estimation but the estimates are not reported. p-values are reported in square brackets. *, ** and *** denote significance levels at 10%, 5% and 1%, respectively.

The estimated coefficients of research intensity give strong support for Schumpeterian growth theory, while the estimated coefficients of the growth in patents give no support for semi-endogenous growth theory. The estimated coefficients of growth in patenting ($\Delta \ln X_t$) are all insignificant while the estimated coefficients of research intensity ($\ln(X/Q)_t$) are all highly significant regardless of the estimation periods and regardless of whether control variables are included. Our results are also not very sensitive to the use of alternative measures of GDP (see Appendix 2.A1). Finally, the estimated coefficients of research intensity and population growth are surprisingly stable across estimation periods and quite consistent with the model predictions. The only exception is the period 1760-1850 in which the absolute value of the coefficients of population growth and research intensity are higher than the model predictions. This probably reflects a small sample problem.

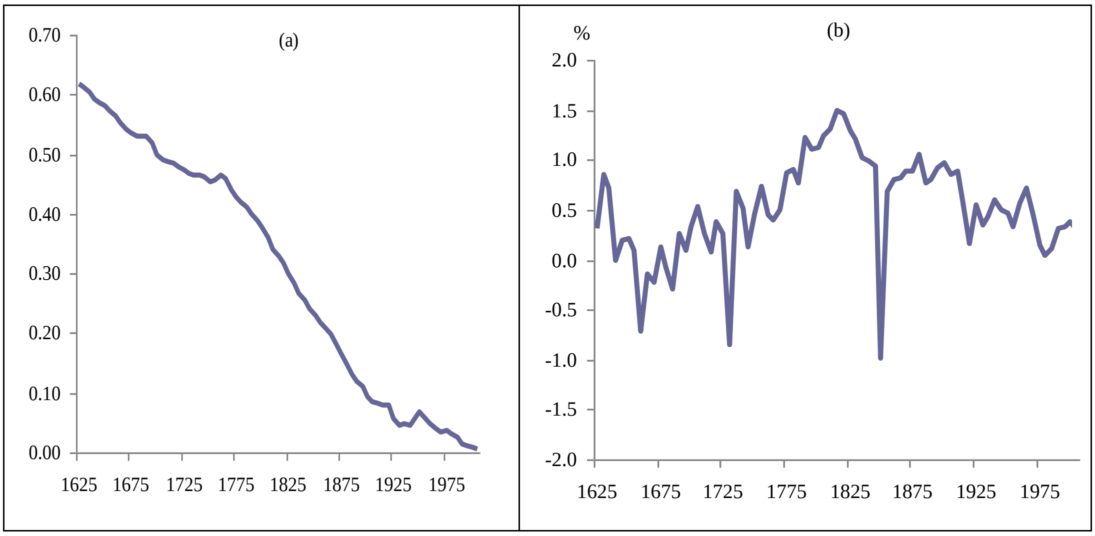
The control variables are generally not very significant. In the single case where the coefficient of openness is significant, it is of the wrong sign. This result suggests that openness was not the key factor behind the British industrialization. The result finds support from the estimates of Oxley and Greasley (1998). The estimated coefficient of the investment to capital ratio is significant in three of the six cases, indicating that transitional dynamics have influenced growth during the First and the Second Industrial Revolution.

Considering the estimation results from the cointegration equations and the growth equations, there is consistently very strong evidence in favour of Schumpeterian growth theory and very little support for semi-endogenous growth theory. This has very important implications for the growth experience in Britain over the past four centuries and for future growth. Schumpeterian growth theory predicts that R&D has permanent growth effects as long as research intensity remains non-zero. Thus, as long as the fraction of resources in the economy allocated to R&D remains constant, Britain will experience the same growth rate in this century as it experienced in the last century.

2.4. The Anatomy of Growth during the British Industrial Revolution

The empirical estimates give support to the hypothesis that productivity growth in Britain, until the 20th century, was a race between technological progress and population growth. The research intensity was relatively low before the First Industrial Revolution around 1760. However, since the population growth rate was on average also very close to zero before the First Industrial Revolution (see Figure 2.3b), innovations led to small positive per capita growth rates. The period 1760-1813 is remarkable. The marked increase in research intensity should have led to significant economic progress during that period. However, the population growth rate was extraordinarily high and increased to such an extent that per capita income growth rates became negative. It appears that during this period the economy was in a Malthusian trap and the straitjacket was only broken first when the Second Industrial Revolution started in the latter half of the 19th century. Although the population growth rate slowed somewhat after 1813, it remained a drag on the economy during the first half of the 19th century as agriculture remained important during that period (see Figure 2.3a).

Figure 2.3: Population growth rates and share of agriculture in total income, 1620-2005



Notes: the growth rates of population are annualized growth rates measured in 5-year difference. The share of agriculture in total income is measured in 5-year average.

Table 2.5 displays the simulations of the contribution to *changes* in per capita productivity growth rates of *changes* in research intensity and *changes* in population growth rates based on the coefficient estimates in Table 2.4 (see notes to Table 2.5for details). The simulations will shed light on the forces behind the increasing growth rates during the British industrialization.[3] The first column shows actual changes in per capita growth rates while the second and the third columns show the contributions of research intensity and population growth to changes in per capita growth rates. The simulation results show that changes in research intensity and population growth rates explain actual changes in per capita income growth rates rather well. This provides further evidence in favour of the extended Schumpeterian growth model.

During the transition to the First Industrial Revolution over the period from 1620-1760 to 1761-1850, per capita growth rates increased by a miniscule 0.14 of a percentage point. Increasing research intensity pushed the growth rate up by 0.6% while the increasing population growth reduced growth rates by 0.3%. During the transition from the First to the Second Industrial Revolution in the periods 1760-1850 to 1851-1915, per capita growth rates increased by 0.72 percentage points. Almost all the increase in growth is explained by increasing research intensity (0.69 percentage points), which reinforces the findings above that innovation played a key role during the British Industrial Revolution. The increasing growth rate was further strengthened by decreasing population growth rates (0.30 percentage points). While the positive population growth rates continued putting downward pressure on growth, the negative growth pressure was smaller during the Second than the First Industrial Revolution. Finally, comparing the modern growth regime in the period from 1916 to 2005 with the pre-1916 period suggests that most of the 1.4 percentage point increase in the growth rate is explained by increasing research intensity (0.8 percentage points) while the reduced population growth has also been influential for the increasing growth rates (0.3 percentage points).

[3] The simulations cannot be easily conducted in growth terms because the log of research intensity in the growth regressions influence the constant term, as research intensity is a level variable. In other words the inclusion of research intensity will alter the magnitude of the constant term, which renders it difficult to disentangle the growth effects of research intensity.

Table 2.5: Simulation results

Period	Actual changes in $\Delta \ln y_t$ (%)	Contribution from ln $(X/Q)_t$ (%)	Contribution from $as_t \Delta \ln L_t$ (%)
(1620-1760) to (1761-1850)	0.136	0.585	-0.314
(1760-1850) to (1851-1915)	0.723	0.686	0.299
(1620-1760) to (1761-1915)	0.431	0.611	-0.252
(1620-1915) to (1916-2005)	1.363	0.777	0.307

Notes: The average estimated coefficients of research intensity and population growth in Table 4 are used in the simulations for the relevant periods. The average estimates in rows two to four in Table 4 are used in the simulations over the period (1620-1760) to (1761-1850) and so forth.

The finding that population growth was a major drag on British per capita income growth up to the Second Industrial Revolution raises the question of why it took so long for the British economy to be freed from its Malthusian straitjacket. Galor and Weil (2000) argue that the returns to human capital during the Second Industrial Revolution increased to such an extent that it gave parents a strong incentive to care for the education of their off-springs. The evidence of Britain shows that there was not much demand for skilled labour during the First Industrial Revolution whereas there was a high demand for skills during the Second Industrial Revolution (Galor, 2005).

The finding that per capita growth was predominantly driven by research intensity and population growth may appear too simplistic to capture the entire development of Britain from a Malthusian growth regime through to the modern growth regime. However, research intensity captures many factors that are often highlighted as being responsible for growth during the Industrial Revolution as well as the key aspects of unified theories of economic growth. The unified theories of economic growth of Goodfriend and McDermott (1995), Galor and Weil (2000), Jones (2001), Hansen and Prescott (2002) and Lucas (2009) all focus on innovations and population growth as the principal drivers of per capita income growth. The results in this paper are also broadly consistent with the hypotheses that Britain took off because of institutions (North, 1981), religion (Weber, 1905), or the high fertility rates among the special class of entrepreneurs and innovators

(Galor and Moav, 2006); (Clark, 2007). All these theories focus on the underlying causes of the surge in innovative activity.

Increasing division of labour is a well-known feature of development (see, e.g., Smith, 1776). However, it is not an independent contributor to growth but a result of new methods made available by innovations. The transition from home to factory production of clothes was rendered possible by the invention of the spinning jenny, the water frame and the flying shuttle, and not because of the independent decisions of entrepreneurs. Similarly, the productivity gains from the transformation from agriculture to manufacturing are often highlighted by the literature as independent factors in growth. However, manufacturing was more productive than agriculture because of past innovations, and, particularly, because the innovation-induced productivity advances in agriculture, which was often derived from innovations in manufacturing, had resulted in excess labour that found work in manufacturing.

Although trade openness has been controlled for in the regressions above, knowledge spillovers have not been controlled for. Coe and Helpman (1995) and Madsen (2007; 2008a) find that international knowledge spillovers have been important for productivity growth in OECD countries. While international patent data are generally available after 1870, there are very few records of international knowledge production before that period and several countries did not have a formal patent system before circa 1880. Although Britain developed the world's most advanced technology during the First Industrial Revolution, knowledge was still transferred to Britain from Italy and the Netherlands before the First Industrial Revolution and probably also during the Industrial Revolution. Unfortunately, we were not able to find early data on knowledge in Italy and the Netherlands to control for the effect of spillovers in the estimation.

An important issue is whether the increasing innovative activity during the industrial revolutions to some extent has been a result of feedback-effects from productivity growth. Oxley and Greasley (1998) find that this is not the case. They find a two-way relationship between industrial production and all variables investigated except for patents, where they find only a one-way direction from patents to industrial production. On this basis, they argue that "technological change was an independent cause of industrial change" (p. 1396).

2.5. Conclusion

Although innovations and population growth are the key ingredients in almost all theories of the Great Divergence, the British Industrial Revolution and unified theories of economic growth, almost no empirical work has been done to explain the British growth in the context of innovations and population growth. The lack of any correlation between economic growth and the level of innovative activity, as predicted by first-generation endogenous growth theories, has probably discouraged researchers from focusing on innovation-driven growth to explain the transformation of the British economy from the Malthusian epoch to modern economic growth. New developments within endogenous growth theory have overcome the difficulties associated with the first-generation growth models and enabled us to reconsider the role played by innovative activity during the British Industrial Revolution.

By introducing land as a factor of production in the endogenous growth models, this paper has shown that innovations and population growth have been the principal factors explaining per capita growth rates in Britain since 1620. Furthermore, it was shown that the functional relationship between growth and innovation follows that of the Schumpeterian growth model rather than the semi-endogenous growth model. In fact, very strong support for Schumpeterian growth theory was found. The significance of this result is not only that research intensity has played a major role in British growth history but also that R&D has permanent growth effects and that the productivity growth rate remains constant and positive as long as the number of researchers is kept at a constant proportion of the number of product lines or the size of the population.

Simulations of the model showed that innovative activity and population growth were economically significant determinants of per capita growth during most British history over the past four centuries. Population growth was a significant growth drag up to the mid 19th century because land was, until then, a significant factor of production. Despite a surge in innovative activity during the First Industrial Revolution, per capita growth rates were rendered negative by a marked increase in population size. Significant positive per capita growth rates were first experienced after the start of the Second Industrial Revolution due to the increase in research intensity. Furthermore, declining population growth combined with a reduction of the importance of land as a factor of production.

The results of this paper have implications for growth modelling and the history of the British Industrial Revolution. Endogenous growth models are assumed to apply only to modern economic growth where land is not a factor of production. Furthermore, endogenous growth models are thought not to have empirical counterparts back in history because innovative activity is often assumed to be of an informal character before WWII (Howiit and Mayer-Foulkes, 2005). However, this study has shown that Schumpeterian growth theory can adequately account for British growth through history once the population growth drag is allowed for in the regressions. The results of the paper are important for the history of the British Industrial Revolution because they show that innovations were the principal source of growth during that period. Any attempt to answer the question of what caused the British Industrial Revolution, like most of the available theories, should therefore, focus on factors that were responsible for the surge in innovative activity during the Industrial Revolution.

2A.1. Estimates based on Alternative GDP Measures

This section performs some robustness checks on the results using real wages and per capita industrial production as alternative measures of GDP before 1830. The data are spliced with per capita data from Maddison (2008) after 1830. The real wages data are estimated by Allen (2001) and are available from 1620 and the industrial production data are estimated by Crafts and Harley (1992) and are available from 1700. First, consider the unit test results reported in Table 2A.1. For both income estimates, $\ln(Y/L)_t$ is $I(1)$ at the 1% level, which is consistent with the estimates in the text.

Table 2A.1: Unit root tests for $\ln(Y/L)_t$

	ADF		Zivot-Andrews		
	Levels	1st differenced	Levels	1st differenced	Conclusion
Real wages (1620-2006)	0.09	-14.11***	-3.45	-14.73***	$I(1)$
	(0.99)	(0.00)	(BP = 1836)	(BP = 1848)	
Per capita industrial production (1700-2006)	-1.72	-18.84***	-4.53	-18.11***	$I(1)$
	(0.74)	(0.00)	(BP = 1827)	(BP = 1815)	

Note: *p*-values for the ADF tests are indicated in parenthesis. For the Zivot-Andrews tests in levels, the 1% and 5% critical values are -5.57 and -5.08, respectively. At first-differenced, the values are -5.43 and -4.80, respectively. The endogenously determined break point (BP) for each series is indicated in the parenthesis. ** and *** indicate 5% and 1% significance, respectively.

The Johansen cointegration tests for semi-endogenous growth theory using these alternative measures of GDP are reported in Table 2A.2. Note that a separate analysis for the test of Schumpeterian growth theory is not required in this Appendix since it involves only examining the trends of patent applications and labour force. First, consider the estimates in the upper half of the table in which real wages are used for productivity. Although the evidence of cointegration is very strong, the estimated coefficients of patents in the cointegrating vectors of productivity have signs opposite to that predicted by semi-endogenous growth theory. The estimated coefficients of population are significant and have the right signs. In the estimates in the lower half of the table in which industrial production is used, the estimated coefficients of patents and population are economically and statistically significant and have the right signs. However, the null hypothesis of no cointegration cannot be rejected at conventional significance levels. Thus, there is no evidence in favour of semi-endogenous growth theory in the estimates using industrial production either.

Table 2A.2: Johansen cointegration tests for semi-endogenous growth theory (Eq. 2.8)

Period	Hypothesis	Trace statistic	Max-eigenvalue statistic	Cointegrating Vector [ln *Y/L*, ln *X*, *as*ln*L*]	
	I. Measuring productivity by real wages				
1620-1850	$r=0$	43.10***	37.72***	1, 0.12***, 2.98*** (8.59) (4.35)	α =-0.24*** (-5.83)
	$r\leq 1$	5.38	5.12		
	$r\leq 2$	0.26	0.26		
1760-1850	$r=0$	34.75**	30.48***	1, 0.21***, 3.09*** (14.38) (3.54)	α =-0.49*** (-5.63)
	$r\leq 1$	4.27	2.98		
	$r\leq 2$	1.29	1.29		
1620-1913	$r=0$	50.05***	37.72***	1, 0.09***, 4.85*** (11.16) (12.95)	α =-0.21*** (-5.97)
	$r\leq 1$	12.34	12.34		
	$r\leq 2$	0.00	0.00		
1760-1913	$r=0$	40.09***	28.36***	1, 0.18***, 6.35*** (9.93) (14.49)	α =-0.22*** (-4.33)
	$r\leq 1$	11.73	11.71		
	$r\leq 2$	0.02	0.02		
1620-2006	$r=0$	38.44***	28.05***	1, 0.11***, 5.53*** (7.35) (15.58)	α =-0.11*** (-4.95)
	$r\leq 1$	10.39	10.02		
	$r\leq 2$	0.37	0.37		
1760-2006	$r=0$	35.18**	18.79	1, 0.19***, 6.45*** (5.41) (12.71)	α =-0.07*** (-3.26)
	$r\leq 1$	26.39**	13.60		

	$r \le 2$	2.79	2.79		
	II. Measuring productivity by per capita industrial production				
1700-1850	$r = 0$	31.24**	18.71	1, -0.36***, 8.36*** (-8.35) (6.19)	α =-0.05 (-1.31)
	$r \le 1$	12.53	11.12		
	$r \le 2$	1.40	1.40		
1760-1850	$r = 0$	21.75	14.78	1, -0.37***, 6.81*** (-12.03) (3.79)	α =-0.03 (-0.74)
	$r \le 1$	6.98	4.05		
	$r \le 2$	2.92	2.92		
1700-1913	$r = 0$	38.54***	25.84**	1, -0.07*, 2.36* (-1.84) (1.72)	α =0.01 (1.47)
	$r \le 1$	12.70	10.81		
	$r \le 2$	1.89	1.89		
1760-1913	$r = 0$	25.84	13.99	1, -0.47***, -1.42 (-9.11) (-1.11)	α =-0.02 (-1.52)
	$r \le 1$	11.85	11.41		
	$r \le 2$	0.44	0.44		
1700-2006	$r = 0$	25.77	17.83	1, -2.58***, -11.39 (-3.94) (-0.86)	α =-0.00** (-2.28)
	$r \le 1$	7.93	7.86		
	$r \le 2$	0.07	0.07		
1760-2006	$r = 0$	25.77	17.84	1, -2.58***, -11.39 (-3.94) (-0.87)	α =-0.00** (-2.27)
	$r \le 1$	7.93	7.86		
	$r \le 2$	0.07	0.07		

Note: the null hypothesis is that there is *r* cointegrating relationship between the variables. An intercept but no trend is included in the estimation. The optimal lag length is pinned down using the SBC. Critical values are taken from Mackinnon *et al.* ((1999)). α is the error-correction term associated with the $\Delta\ln(Y/L)$ equation. Figures in parenthesis indicate *t*-statistics. For panel II, the first available observation is 1700.

Finally, we report the 5-year difference estimates based on the alternative measures of GDP in Table 2A.3 and Table 2A.4 respectively. The estimates continue to give support for Schumpeterian growth models and no support for semi-endogenous growth theory. Not surprisingly, in the industrial production regressions the estimated coefficients of research intensity are larger and the estimated coefficients of population growth are smaller than those of the other estimates because per capita industrial production has increased more than real wages and per capita income before 1830.

Table 2A.3: Estimates Eq. 2.9 using real wages for labour productivity

Period	$\Delta\ln X_t$	$\ln (X/Q)_t$	$as_t\Delta\ln L_t$	$\Delta\ln TO_t$	$\Delta\ln (M/Y)_t$	$\ln UNC_t$	$\Delta\ln (I/K)_t$
	0.012		-4.147**				
1620-		1.928*	-4.567**				
1850	0.008	1.582	-5.089***				
	0.010	1.291	-3.670*	-0.224**	-0.391***	3.960	-0.295
	-0.157		6.463				
1760-		7.145	-3.219				
1850	-0.172	7.756*	-4.188				
	-0.120	7.832**	3.952	0.179	-0.469***	-4.129	-1.256
	0.013		-4.562**				
1620-		1.486**	-4.820***				
1915	0.006	1.458**	-4.869***				
	0.007	1.670*	-4.577**	0.080	-0.183	1.702	-0.031
	-0.082		-6.968*				
1760-		3.192	-2.034				
1915	-0.067	2.868	-2.685				
	-0.039	3.730	-0.787	-0.004	-0.179	1.895	-0.048
	0.011		-5.387***				
1620-		1.306***	-4.585***				
2005	0.004	1.295***	-4.626***				
	0.006	1.330**	-4.387***	0.011	-0.205*	0.157	-0.071
	-0.084		-6.375**				
1760-		2.791	-17.24				
2005	-0.069	2.360	-2.145				
	-0.045	2.720	-0.757	-0.054	-0.201	-0.255	-0.067

Table 2A.4: Estimates Eq. 2.9 using industrial production for labour productivity

Period	$\Delta\ln X_t$	$\ln (X/Q)_t$	$as_t\Delta\ln L_t$	$\Delta\ln TO_t$	$\Delta\ln (M/Y)_t$	$\ln UNC_t$	$\Delta\ln (I/K)_t$
	0.033		1.089				
1700-		2.699***	0.560				
1850	0.018	2.431**	-0.222				
	0.047	1.081	-1.491	0.123	-0.377**	2.487	-0.651
	0.125**		-1.808				
1760-		6.879***	-0.543				
1850	0.113***	6.478***	0.092				
	-0.120	7.832**	3.952	0.179	-0.469***	-4.129	-1.256
	0.024		0.395				
1700-		1.167***	0.678				
1915	0.019	1.105***	0.858				
	0.036	1.757*	-3.512	-0.039	-0.161	0.873	-0.025
	0.037		-1.567				
1760-		0.574	-0.813				
1915	0.041	0.772	-0.413				
	-0.039	3.730	-0.787	0.004	-0.179	1.895	-0.048
	0.014		-0.799				
1700-		1.14***	0.71				
2005	0.013	1.134***	0.753				
	0.03 3	1.554**	-3.394	-0.076	-0.176	-0.252	-0.059
	0.012		-1.755				
1760-		0.504	-0.774				
2005	0.016	0.605	-0.670				
	-0.045	2.720	-0.757	-0.054	-0.201	-0.255	-0.067

2A.2. Data Appendix and Measurement Issues

Patent applications: Different sources are considered to compile the complete annual series of 'patents applied to residents only' for the period 1620-2006 Britain. Patents applied to foreign residents were not taken into account as generally they are duplicates of the domestic patents applied and same patents are applied in many countries (see Madsen, 2008a). The most reliable data for patents issued during Industrial Revolution Britain is the Sullivan (1989) paper. But Sullivan (1989) does not cover any data before 1661 and after 1851. Hence different sources are taken into account. The sources are: *1620-1660*: 'England patents issued' from Mitchell (1988), page 438; *1661-1851*: 'patents issued in England' from Sullivan (1989), Table A1, page-448; *1852-1882*: 'total patents applied to UK' from Mitchell (1988), page 439; *1883-2006*: 'patents applied to residents' from World Intellectual Property Organisation (WIPO) data base (updated July 2008), patents application by patent office (1883-2006) to residents and non-residents on an annual basis. The online source of WIPO is: http://www.wipo.int/ipstats/en/statistics/patents. Lastly, the WIPO series from 1883-2006 is spliced upward using the earlier years' data sources to get the number of 'patents applied to residents only' on an annual basis for the whole period 1620 to 2006.

GDP: Both Nominal GDP and GDP price deflator series for the period 1620-1829 are from Clark (2001), Table 3, pages 19-20 and Table 7, page 30. The data points in Clark (2001) are for every decade starting from 1259/60 to 1869/70. The benchmark years are geometrically interpolated to get a complete series on an annual basis in the period 1620-1830. Nominal GDP is divided by the GDP price deflator to get real GDP. Real GDP series of Angus Maddison is used for the period 1830-2003 which is available online at: http://www.ggdc.net/maddison/. Maddison data is only up to 2003, so the last few years from 2003-2006, the real GDP series is updated from the data base of World Development Indicators (WDI) of World Bank: http://publications.worldbank.org/WDI/. GDP data of Maddison for the United Kingdom includes England and Wales, Scotland and Ireland from 1830-1921 and for 1922 onwards it only includes Northern Ireland instead of Ireland. Alternative measures of real GDP like real wages and industrial production are used in our empirical estimates for additional robustness check, the results of which are in Appendix 1.

Real Wages: Real wages are from Robert Allen, The World Historical Perspective. 1870-1919, http://www.economics.ox.ac.uk/members/robert.allen/WagesPrices.htm. The data are unweighted averages for London and Oxford. They are also the unweighted average of skilled and unskilled labour.

Industrial Production: Crafts and Harley (1992), Table A3.1, pages 725-727.

Financial Deepening (M): *1750-1871*: sum of notes in circulation and deposits in commercial banks and savings banks, Mitchell (1988). *1871-1983*: F. Capie and A. Webber, 1985, *A monetary History of the United Kingdom*. *1870-1982*: George Allen & Unwin, Boston. *1983-2006*: *M*4, IMF, *International Financial Statistics*, Washington: IMF.

Share of agriculture in total income: Nominal net agricultural output divided by nominal net GDP, measures the share of agriculture in total income. Nominal net farm output for the period 1620-1870 is taken from Clark (2002), Table 4, page 14. Nominal GDP is from Clark (2001) Table 3, page 19-20. The data points are again for every decade in which the benchmark years are geometrically interpolated to get series on an annual basis. 1870-1960. Mitchell (1988) "British Historical Statistics", Cambridge University Press and C.H. Feinstein: "Statistical Tables of National Income, Expenditure and Output of the U.K. 1855-1965", Cambridge University Press. 1960-2006. OECD, *National Accounts*, Vil. 2. Paris.

Population: In the period 1801-1921 population includes England and Wales, Scotland and Ireland and from 1922 onwards it includes England and Wales, Scotland and Northern Ireland, excluding the Republic of Ireland. The population series is spliced with the population of England only in the period 1620-1801 due to unavailability of data. The sources are: *1620-1829*: Mitchell (1988), pages 7-14, compiled from Wrigley and Schofield (1981); *1830-2006*: online database of Angus Maddison: http://www.ggdc.net/maddison/.

Investment and capital stock: Investment is measured as the sum of investments in non-residential structures and in machinery and equipment. The sources are: *1780-1969*: Maddison (1995); *1970-2006*: UK database of National Statistics Online (NSO): http://www.statistics.gov.uk/. The capital stock is constructed using the inventory perpetual method with a 3% depreciation rate for non-residential construction and structures and 10% for machinery and equipment. The initial capital stock is obtained by using the Solow model steady-state value of $I_0/(\delta+g)$, where I_0 is initial real investment, δ is the rate of depreciation and g is the growth rate in real investment over the period from 1780 to 2006.

Trade openness: Trade openness is measured as the ratio of the sum of total exports and imports to nominal GDP. Before 1697, the trade openness series is kept constant due to unavailability of data on exports and imports. Total imports and exports data are found in the years *1697-1771* for England and Wales, for Great Britain in the years *1772-1795* and for UK in the years *1796-1944*. The later series is spliced upward to get the whole series from *1697-1944*. The source is from Mitchell (1988), pages 448-454. For *1945-2006*: National Statistics Online (NSO) database for UK: http://www.statistics.gov.uk/default.asp.

Macroeconomic uncertainty: Five years' standard deviation of the inflation series is measured as macroeconomic uncertainty. Inflation is constructed as the annual growth rate of consumer price index (CPI) series. CPI data for the whole period 1620-1870 is collected from London Wages, Prices & Living Standards: The World Historical Perspective (average of London and Oxford). 1870-1960: Mitchell (1988). 1960-2006. International Monetary Fund, *International Financial Statistics*.

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Chapter 3

SECOND GENERATION INNOVATION-BASED GROWTH MODELS AND THE BRITISH AGRICULTURAL REVOLUTION

Findings from this chapter have been submitted as a journal article to *"European Economic Review"* (since February 2010), where the article is currently under review. The paper titled *"Innovation, Technological Change and the British Agricultural Revolution"* is coauthored with my thesis supervisors A/Prof James B. Ang and Prof Jakob B. Madsen. The working paper version can be obtained at CAMA Working Papers 11/2010, Australian National University, Centre for Applied Macroeconomic Analysis.

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"Students of economic growth in today's underdeveloped countries are well aware of the fact that the route to sustained economic growth lies through an industrial revolution. What is still a matter of controversy in connection with the strategy of industrialization is the role that agriculture should play in the process... In this controversy the historical experience of the first country to undergo an industrial revolution assumes a special topical interest."

- *Deane, 1969, page 36.*

3.1. Introduction

The ongoing debate on the possible causes of the British Industrial Revolution has been accompanied by another important dispute among economic historians and growth economists about the simultaneous existence of an Agricultural Revolution in Great Britain. If the two movements accompanied each other, can we explain the agricultural revolution using the second generation innovation-based growth models? Did technology play any substantial role in the agricultural sector in eighteenth and early nineteenth century Britain? What are the contributions of innovative activity in advancing agricultural productivity growth in Britain at the time of the First Industrial Revolution? We don't know these answers yet. In the light of the historical evolution of Great Britain, this chapter will seek to analyse the role of technology and population in advancing British agricultural growth in the period 1620-1850, considering both the theoretical and empirical backgrounds of economic growth.

In the current empirical growth literature, since the refutation of the scale effects of first generation endogenous growth models of Romer (1990), Grossman and Helpman (1991) and Aghion and Howitt (1992) by Jones (1995), the second generation endogenous growth models have acquired a lot of attention in explaining the growth paths of economies in the long run (Jones, 1995; 2001; Ha and Howitt, 2007; Madsen, 2008; Madsen *et al.*, 2010). As regards British historical growth during industrialization periods, three main kinds of theories have been proposed by various growth economists[1]: the *exogenous growth theories*, supported by North and Weingast (1989), Crafts (1995); the *multiple equilibrium theories*, supported by Becker *et al.* (1990); and lastly the *endogenous growth theories*, supported by Greasley and Oxley (1997). In chapter 2 of this dissertation it is shown that the second generation endogenous growth models, particularly the Schumpeterian Growth model, can sufficiently explain British historical growth over time, once population growth is allowed for in the model. However, growth in agriculture should be the first step towards industrialization of an economy (Rostow, 1959). Thus the theoretical explanation behind the sectoral growth in Britain is still missing in the literature, particularly for the agricultural sector in the eighteenth and early nineteenth centuries.

'Agricultural Revolution' was included in the titles of at least in eleven books written during the period 1560 to 1850 about English agriculture. Different contrasting opinions can be found in the literature concerning the periods of its occurrence. The range of time periods under much discussion are 1550-1650, 1650-1750 and 1750-1850, each of which has its own support (Clark, 2002, page 42). More detailed discussion of various views of Agricultural Revolution is included in section 3.2. For the British Industrial Revolution there are minor discrepancies regarding the exact start and end dates of this event. Most historians and growth theorists generally agree on 1750 – 1780 as the beginning of industrial progress in Britain. Ashton (1964) describes the period 1760-1830 as the First Industrial Revolution for Britain, while Williamson (1984) argues that British growth was slow during 1760-1820 due to the enormous debt issues to finance the French wars. On the other hand Sullivan (1989) claims the period 1762-1851 as the 'Age of Inventions' for England which marked the First Industrial Revolution. His claims are further supported by Greasley and Oxley (1996; 1998a; 1998b) who employ more advanced empirical techniques on industrial production data and show that the period 1780-1850 was the period of industrial growth for Britain.

However a common period of overlap can be identified between the so-called 'Agricultural Revolution' and the 'Industrial Revolution' after 1700, which

[1] See Clark (2007) for a discussion of different theories put forward in regards to the occurrence of the Industrial Revolution in Britain.

is the period 1760-1850, where these events may coincide and substantial links may exist between the two. For a long time these two events were much in discussion among various economic historians and growth economists, but very few tried to explain the sectoral growth in Britain. [2] The primary objectives of this chapter are as follows: 1) to examine the roles of innovative activity in explaining British agricultural growth from 1620 to 1850; 2) to discriminate between the innovation-based growth models, namely semi-endogenous growth models of Jones (1995), Kortum (1997) and Segerstrom (1998) and the Schumpeterian growth model of Aghion and Howitt (1998), Peretto (1998), Howitt (1999), Peretto and Smulders (2002) and Hansen and Prescott (2002), using data from the agricultural sector of Britain in the period 1620-1850; and 3) to examine the effects of population growth on agriculture in the historical evolution of Britain. For the first time in literature this chapter empirically examines the relationships among growth, technological progress and population growth at the sectoral level during the onset of British industrialization.

The chapter is organized as follows. The next section will review the literature by contrasting different views of economic historians and growth theorists regarding the existence of an Agricultural Revolution in Britain. This section will also give an overview of the conditions of the agricultural working class during eighteenth and early nineteenth century Britain. Section 3.3 will present an extended innovation-based growth model of the agricultural sector with land as a fixed factor of production, similar to one presented in chapter 2 of this thesis. In addition, this section will describe the empirical methodology followed here. While section 3.4 will discuss the measurement issues, section 3.5 graphically analyses the agricultural sector following the second generation innovation-based growth models. Section 3.6 will discuss the empirical results and finally section 3.7 will conclude the discussion.

[2] Clark (2002) addresses this problem but concludes that, in his view, agriculture did not have a role in British productivity growth during Industrial Revolution.

3.2. British Agricultural Revolution: A Myth or a Mystery?

Although there are fewer doubts about 'Industrial Revolution' having its start between 1760 and 1780 in Britain, [3] there are two main strong contrasting views as regards to the onset of 'Agricultural Revolution'. The first view comes from historians such as Havinden (1961), Jones (1965), Kerridge (1967) and others who argue that agricultural productivity and output only rose significantly in the sixteenth and seventeenth centuries. This is further reformulated and extended by Allen (1999) and Clark (2002) who raise doubt about the coincidence of the two revolutions and argue more in favour of naming them as disjoint events. Allen (1999), rejecting the views of Overton (1996a), describes two periods as revolutionary in English agricultural history: the first preceded the parliamentary enclosures[4] and was accomplished (between 1700-1750) by small-scale farmers before the occurrence of First Industrial Revolution, and the second occurred during the first half of the nineteenth century in Britain. This implies that the rapid productivity growth starting around 1760 in Britain is the result of industrial growth only, not much of which comes from the agricultural sector.

The second view emphasizes that the Agricultural Revolution accompanied the First Industrial Revolution, and is supported by the views of Mingay (1963), Chambers and Mingay (1966), Deane (1969), Campbell and Overton (1993), Martins (1993) and Overton (1996a; 1996b). Chambers and Mingay (1966) describe the period 1750-1880 as the period of 'Agricultural Revolution', and argue that the gradual build up of English agriculture since the Middle Ages came to maturity and permitted the early development of farming systems to meet the new demand of both farming unit sizes and methods of cultivation. This flexibility and responsiveness took English agriculture to the leadership of the world in farming practice during this period[5]. Overton (1996a; 1996b) provide two key indicators, firstly an unprecedented increase in

[3] See Deane and Cole (1962), Ashton (1964), Hobsbawm (1968), Crafts (1985), Sullivan (1989), Clark (2007) etc. for supporting the view of the start of industrialization in Britain in the period 1760-1780. But historians like Williamson (1984; 1987) do not support acceleration in British growth in the last decade of eighteenth century and first few decades of nineteenth century.
[4] An enclosure of land is defined as privatization of land owernership.
[5] Chambers and Mingay, 1966, page 199-210.

agricultural output with an equally unprecedented increase in land productivity and secondly, an unprecedented increase in labour productivity in the period 1750-1850, which he argued was necessary for the Industrial Revolution to occur.

By 1800 in the British economy, only one third of the total population was engaged in the agricultural sector, hitherto this sector acted as the *indispensable foundation* for industrial progress. British farmers at that time were feeding a vastly growing population which was almost double in 1830s as compared to 1750s (Hobsbawm, 1968, page 77). In the mid eighteenth and early nineteenth centuries, 'landed interest' still dominated social and political life, where, for the upper class to have control over the public life of others, required at least owning an estate and/or obtaining a 'seat' in politics. From 1760 onwards, privatization of land ownership or enclosures of land was very common in most parts of England. While on the one hand this practice enabled uncultivated land to be brought into use and farms grew larger, on the other hand, due to this practice, more villagers were landless as landlords started to exploit the small scale farmers. This accounted for further degradation of the poor in villages and the surplus labour was then transferred into the industrial sector of the urban areas at the onset of Industrial Revolution. But enclosure of land was needed to increase the efficiency and productivity made possible by larger farms.

Chambers and Mingay (1966) argue that the farmers themselves recognized the usefulness of enclosure and they were ready to pay high rents for land in enclosures as compared to open-fields. Although the growing luxury of landlords prevented competitiveness in the sector, protection of British farming from abroad was strengthened in 1815 (at the end of Napoleonic wars) with the imposition of the 'Corn Laws'. Both commercial farming and industrial progress were visible in the first half of nineteenth century Britain, when 'high farming'[6] and relative mechanization of industries were predominant in agriculture. The progress of technology in agriculture was even more striking in the 1830s, which was marked by the foundation of Royal Agricultural Society in 1838 and Rothamsted experimental station in 1843 (Hobsbawm, 1968, page 85).

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[6] High farming is defined as a farming technique associated with buoyant farm prices, stimulating new techniques, such as enclosures and scientific breeding. It also encouraged the owners of estates to engage in cultivation themselves rather than to let farms for a fixed return from their tenants.

In explaining the different stages of economic growth, Rostow (1959) claims that one of the essential conditions for successful take-off of the British economy is a technological revolution in agriculture. He argues that at the onset of industrial progress, the British economy was characterized by a rise in population and also a disproportionate rise in urban population. Only technological progress in the agricultural sector could prevent a debacle of modernization by maintaining this greater population pool in the economy. This view is further supported by Deane (1969), who acknowledges three different ways by which the Agricultural Revolution was associated with Industrial Revolution in England[7]: 1) agriculture was the sole means of feeding the growing population along the industrial centres; 2) agriculture inflated the purchasing power for British industrial products; and 3) agriculture provided substantial amounts of financial capital required for industrialization and it was only because of its contribution that the industrialization process went on even in the periods of wars. Moreover, Overton (1996a) sets three criteria that mainly marked the period 1750-1850 as the 'Agricultural Revolution': 1) a series of wide variety of changes in farming techniques; 2) English agriculture was successful in feeding a growing population; and 3) increase in input productivities – all of which indicated a solution in favour of a revolution in English agriculture from the eighteenth century onwards.

Crafts (1985) argues that the main contributors to the agricultural growth rate around the 1790s were input efficiencies rather than input volumes.[8] According to his estimates, the significant rise in investment in agriculture was sustained at least to the 1830s, where land inputs rose slowly due to the French wars in the first half of the nineteenth century and labour inputs were never fast growing, when measured in terms of number of persons in agriculture. Feinstein (1981) places the figure of real investment in the agricultural sector around the 1790s at around twice the level of that of the 1760s. This indicates that agriculture in the first 30 years of the nineteenth century became more capital intensive on the one hand and released labour to the industrial sector on the other. Crafts (1985) calculates the labour force participation rate in the agricultural sector to be only

[7] See Deane, 1969, page 50.

[8] Crafts (1985) also argued that it seemed more probable that hours worked per agricultural worker rose during 1700-1831 by a substantial amount which helped the sectoral output to grow in the later years of eighteenth century (page 48, footnote 8).

0.06% per annum in the period 1759-1801, while in the industrial sector it was around 1.36% per annum. He states that agriculture's loss was industry's gain.

Table 3.1 below shows the average annual growth rate of output and labour productivity in different sample periods between 1620 and 1850, considering two different sources of agricultural output. The two different sources of agricultural output data that are considered here are: agricultural output data of Clark (2002) and Deane and Cole (1962).

Table 3.1: Output and labour productivity growth in English agriculture (% per annum)

Period	Output		Labour Productivity	
	Clark	Deane & Cole	Clark	Deane & Cole
1620-1700	0.12	----	0.07	----
1620-1850	0.32	----	0.19	----
1700-1850	0.43	1.14	0.26	0.88
1760-1850	0.40	1.72	0.21	1.41
1800-1850	0.86	2.65	0.51	2.13

Note: Average annual growth rates over the period are considered for each variable. Data for Deane and Cole is only available in the period 1700 onwards.

The trends of output and labour productivity growth rates of British agriculture presented in Table 3.1 shows that growth rates were minuscule before 1700. The average annual growth rate is always higher for Deane and Cole as compared to Clark. Limitations and differences of these data sources are discussed in details in section 3.4 under measurement issues. After 1700, considering the period 1700-1850, both output and labour productivity grew at a higher rate, ranging from 0.43% to 1.14% for output and 0.26% to 0.88% for labour productivity, respectively. Although the period 1760-1850 showed positive growth in agriculture for both sources of data, the most productive period is identified in the second half of the revolution period from 1800-1850, when output grew at a rate of 0.86% to 2.65% and labour productivity grew at 0.51% to 2.13%, respectively. Overall, compared to 1620-1700, the average annual growth rates of output and labour productivity in the period 1700-1850 are more than triple, and the growth rates are even higher in the period 1800-1850.

Evidence presented in Table 3.1 supports the claims of Overton (1996b) who also shows that input productivity figures were almost doubled in 1850 as compared to 1700. This indeed suggests that the output growth was accompanied by increased labour productivity growth in the period 1700-1850. Keeping in mind that addition of land input was sluggish and proportion of labour in agriculture was falling, input productivity of land and labour were increasing. With diminishing returns to factor inputs, this increase in labour productivity can only be sustained by successful technological progress. The next section models the agriculture sector with land as a fixed factor of production and shows that in the absence of capital, labour productivity growth in the agricultural sector is a race between growth in technological progress and growth in the agricultural labour force.

3.3. The Agricultural Sector with Land as a Fixed Factor of Production

Consider a homogenous Cobb-Douglas production function:

$$Y = A.\overline{T}^{\alpha}.L^{1-\alpha}, \tag{3.1}$$

where Y is the real output in agricultural sector, A is total factor productivity in agricultural sector, $\overline{T}$ is fixed amount of land, L is agricultural labour, α is the share of income going to land and (1- α) is the share of income going to labour. The production function exhibits constant returns to scale in $\overline{T}$ and L, but increasing returns to scale in A, $\overline{T}$ and L altogether.

Taking logs of eq. (3.1),

$$\ln Y = \ln A + \alpha.\ln \overline{T} + (1-\alpha)\ln L$$

or, $$\ln\left(\frac{Y}{L}\right) = \ln A + \alpha.\ln \overline{T} - \alpha.\ln L \qquad (3.2)$$

Total differentiating eq. (3.2) and rearranging,

$$d\ln\left(\frac{Y}{L}\right) = d\ln A - \alpha.d\ln L \qquad (3.3)$$

$d\ln \overline{T} = 0,$ as $\overline{T}$ is constant in the long run along the balanced growth path.

$$\Rightarrow \; g_y = g_A - \alpha.g_L \qquad (3.4)$$

Eq. (3.4) shows the growth equation in the agricultural sector, where the labour productivity growth in the agricultural sector is defined by g_y, g_A is growth in total factor productivity and g_L is growth in the labour force in the agricultural sector. The second term on the right side of eq. (3.4) shows the negative effect of growth of labour on productivity growth in the long run. The negative effect of labour growth originates because of the presence of land as a fixed factor of production in the agricultural sector.

This model differs slightly from the model presented in chapter 2. In chapter 2 the analysis was based on the overall economy, where land, labour and capital were all considered as factors of production. As this analysis is concentrated on the agricultural sector in the seventeenth and eighteenth century Britain, only land and labour are considered as factors of production. Keeping capital separate in the production function does not provide any additional insight in this model because ultimately the (K/Y) ratio remains constant in the long run and disappears from the labour productivity growth equation (3.4). [9] In the modern growth equation of standard neoclassical models, labour productivity is entirely driven by

[9] See the model presented in chapter 2, page 21-22 for more a detailed discussion on this issue.

technological progress. This is because, in presence of capital stock and in absence of land as a fixed factor of production, capital stock endogenously adjusts, where following a labour shock, (*K/L*) ratio gets back to its original position in the long run. Thus in absence of land as a factor of production, the above model reduces to the standard neoclassical model where labour productivity growth will be entirely driven by growth in technological progress. But with land as a fixed input of production, growth in labour reduces productivity growth. Hence, in the agricultural sector the second term on the right hand side of eq. (3.4) is acting as a growth drag in the long run.

Following Ha and Howitt (2007) and Madsen (2008), to discriminate between the innovation-based growth models, the growth of ideas can be written as:

$$g_A = \frac{\dot{A}}{A} = \lambda \left(\frac{X}{Q} \right)^{\sigma} A^{\phi - 1} \text{ and } 0 < \sigma \leq 1, \phi < 1, Q \propto L^{\kappa} \qquad (3.5)$$

where A is technology, λ is the research productivity parameter, X is R&D, Q is product proliferation in the Schumpeterian model, which can be measured as any variable that grows at the same rate as population in the long run, which is approximated by labour (L), σ is the duplication parameter (zero if all innovations are duplications and 1 if there are no duplicating innovations) and ϕ is returns to knowledge. The Schumpeterian model predicts σ =1 for the constant returns to scale to knowledge assumption, and σ < 1for semi-endogenous models as they assume diminishing returns to knowledge. Q is absent in the semi-endogenous models, for which κ =0 in semi-endogenous model and κ =1 in Schumpeterian model.

Assuming that shocks, e_t, are identically and normally distributed with zero mean, Eq. (3.5) forms the following testable model:

$$\Delta \ln A_t = \ln \lambda + \sigma [\ln X_t - \ln Q_t + (\frac{\phi - 1}{\sigma}) \ln A_t] + e_t , \qquad (3.6)$$

Given that $\Delta \ln A_t$ is stationary, it follows that variables in the square bracket are co-integrated. In terms of second generation growth models, the following equations can be tested:

For the Schumpeterian growth model:

$$\psi_t = \ln X_t - \ln Q_t \tag{3.7}$$

For semi-endogenous growth model:

$$\omega_t = \ln X_t + \left(\frac{\phi - 1}{\sigma}\right) \ln A_t \tag{3.8}$$

where, according to the Schumpeterian growth model, in eq. (3.7), ln *(X/Q)* should be stationary and ln *X* and ln *Q* should be co-integrated with a co-integrating vector [1, -1]. *Q* can be approximated to the size of any variable in the sector that grows at the same rate as population in the long run. Although the predicted coefficient of ln *Q* in eq. (3.7) is -1, values less than -1 do not necessarily invalidate the theory because it only indicates that the product proliferation effects are not being captured perfectly by the proxy variable (Madsen, 2008). According to the semi-endogenous model, in eq. (3.8), both ln *X* and ln *A* should be non stationary in levels and they should be co-integrated in the long run with a co-integrating vector $\left[1, \frac{\phi - 1}{\sigma}\right]$, where the second term should come out to be negative.

In the agricultural sector, with land as a fixed factor of production, combining and rearranging eq. (3.2) and eq. (3.8) generates:

$$\ln\left(\frac{Y}{L}\right)_t = c + \frac{\sigma}{(1-\phi)} \ln X_t - \alpha . \ln L_t + \frac{\sigma}{\phi - 1} \omega_t \tag{3.9}$$

where $c = \alpha . \ln \overline{T}$, a constant. In eq. (3.9), α, the share of income going to land, is allowed to vary over time. Thus, co-integration among ln (*Y/L*), ln *X* and ln *L* will validate the semi-endogenous growth model for the British agricultural sector. Co-integration tests for eq. (3.7) and eq. (3.9) will examine the validity of whether the second generation innovation-based growth models are consistent with agricultural productivity growth of Britain in the period 1620-1850. Although co-integration estimates provide the necessary conditions to be satisfied, they are not sufficient to prove the consistency of the growth models (Madsen, 2008). The sufficiency condition can only be met once these models can explain the long run growth in that particular sector. Hence an equation is required that can sufficiently distinguish between the innovation-based growth-models explaining the labour productivity growth in agricultural sector in the period 1620-1850. Combining equation (4) and the predictions of the two theories yields the following stochastic model for growth in agricultural labour productivity:

$$\Delta \ln\left(\frac{Y}{L}\right)_t = \alpha_0 + \beta_1 \ln(X/Q)_t + \beta_2 \Delta \ln X_t + \beta_3 \Delta \ln POP_t + e_t \qquad (3.10)$$

where $\left(\frac{Y}{L}\right)$ is the labour productivity growth in the agricultural sector, measured as real output (*Y*) divided by the agricultural labour force (*L*), *X* is the innovative activity in the agricultural sector, (*X/Q*) is the research intensity variable in the sector following the Schumpeterian model, where *Q* is the product proliferation variable measured by agricultural labour (*L*) in the long run. The third term signifies the population growth drag (POP) on labour productivity growth following equation (4) above.

Extending Eq. (3.10) to allow for control variables, the following growth model is regressed to examine the importance of innovative activity during the British Agricultural Revolution, and to discriminate between semi-endogenous and Schumpeterian growth models:

$$\Delta \ln\left(\frac{Y}{L}\right)_t = \alpha_0 + \beta_1 \ln(X/Q)_t + \beta_2 \Delta \ln X_t + \beta_3 \Delta \ln POP_t + \beta_4 \Delta \ln TO_t$$
$$+ \beta_5 \ln UNC_t + \beta_6 \Delta \ln(M/Y)_t + \beta_7 \Delta \ln LE_t + e_t \qquad (3.11)$$

In equation (3.11) the population of the whole economy is taken instead of the size of the agricultural labour force for two reasons. First, the labour term is there in the denominator of the dependent variable (*Y/L*) and also in the denominator of the independent variable (*X/Q*), where *Q* is approximated by *L* in the long run. Hence, putting labour (*L*) as an additional independent variable in the estimation equation can cause severe serial correlation problems in the results. In the long run, the growth rate of labour is the same as the population growth rate and thus, to avoid the serial correlation problems, population is used instead of labour as the indicator of productivity growth drag in the agricultural sector. Second, in the period 1620-1850, agriculture was the sole sector feeding the whole population of Britain (Deane, 1969; Overton, 1996a). In spite of the growth in industries around the 1760s, the growth could not be sustained without the contribution from agricultural output. Thus population growth of the overall economy would be a more appropriate indicator of productivity growth drag than agricultural labour growth in the sector.[10]

In eq. (3.11), if β_1 is greater than zero, then the Schumpeterian model can sufficiently explain the productivity growth in the agricultural sector, if β_2 is greater than zero, then semi-endogenous theory can sufficiently explain the long run growth in agricultural sector and β_3 is expected to be negative following the population growth drag of the innovation based growth models with land as a fixed factor of production. To reduce the effect of business cycles, all variables in eq. (3.11) are estimated using 5-year non-overlapping first differences, except ln (*X/Q*), which is estimated at 5-year non-overlapping average of level variables.

The different control variables that were included in equation (3.11) are: trade openness (*TO*), macroeconomic uncertainty (*UNC*), money supply to nominal GDP (*M/Y*) and life expectancy at birth (*LE*). While trade openness is measured as the sum of exports and imports over nominal GDP, macroeconomic uncertainty is measured as five-year standard deviation of the annual growth of the consumer price index. The relation between growth and trade openness is discussed by Vamvakidis (2002), Lucas (2007), Madsen (2009) and in chapter 2 above. Although authors have found mixed results in finding the relationship

[10] The labor growth variable was also tried instead of population growth in the estimations and the main conclusions from the estimations remained the same.

between openness and growth, trade openness does not measure openness in an absolute sense. But other indicators such as tariff and non-tariff trade barriers are not available for the period 1620-1850 for Britain. The ratio of broad money to GDP is used here as a proxy for financial development, which is standard in the literature on financial development and growth (see, e.g., Rousseau and Sylla, 2005; Ang and Mckibbin, 2007; Ang, 2010). A positive relationship between financial deepening and economic growth is predicted due to the fact that economic resources are more efficiently used with easy access to credit.

Macroeconomic uncertainty is included as another control variable which is expected to affect growth negatively with mismanagement of fiscal policies. Macroeconomic uncertainty is measured as the standard deviation of the inflation series. Per capita income is often assumed to be a positive function of life expectancy because the incentive to invest in the future is a positive function of the number of years in which an individual is expected to be productive (Cervellati and Sunde, 2005). The longer an individual is expected to live, the larger is the expected returns to schooling. Furthermore, since a long life often goes hand-in-hand with a healthy life, an individual who is expected to live longer is likely to be more productive during his or her adult years. The above evidence justifies taking life expectancy as a control variable in the growth estimation model.

3.4. Measurement Issues

3.4.1. Real GDP

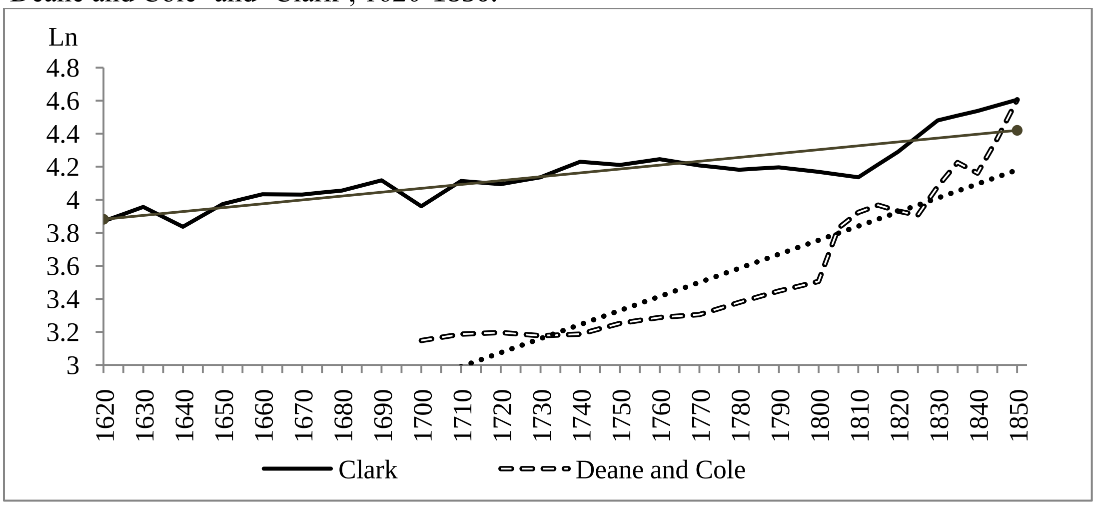
According to Gregory King, the contemporary economic statistician of England, at the beginning of eighteenth century, half of the country's income was accounted for by landlords' rent and farmers' profits. [11] It was agriculture that induced the needs of a variety of markets and specialized demands in England. At the same time, enclosure of land and advanced farming techniques made the best use of these lands and influenced positively the input productivity growth and efficiency of the farming systems. But the bigger challenges faced by the

[11] Chambers and Mingay, 1966, page 15.

historians were to chart this agricultural development in numerical terms. There were no comprehensive statistics for Great Britain before 1851. Using different complex methods of calculation, a few researchers attempted to compile data from various sources. Although there are several doubtful factors involved in their calculations, and one source might look quite different from the other, the relevant task should be to draw common conclusions from them and check the robustness of the empirical estimates for higher reliability of the results.

In the agricultural sector, output data from two relevant sources are used: Deane and Cole (1962) and Clark (2002) (henceforth, DC and GC, respectively in this text). While GC provides real output for England for each decade in the period 1520-1913, DC provides real output from 1700 onwards. Hence, the period 1620-1850 is chosen from GC and 1700-1850 is chosen from DC. Figure 3.1 plots the real output of the agricultural sector in Britain for the period 1620-1850, from the above mentioned sources.

Figure 3.1: Trends in real agricultural output in Britain, comparison between estimates of 'Deane and Cole' and 'Clark', 1620-1850.



Notes: data for real agricultural output from two different sources are in natural logs of level variables.
Sources: Clark (2002) and Deane and Cole (1962). For details see data appendix.

Comparing the two sources of agricultural output data, although both of them have an increasing linear trend over time, the agricultural real output of DC has a much steeper slope as compared to the alternative source of agricultural real output. Clark (2002) criticizes the calculations of Deane and Cole (1962) on the grounds that it was deflated by the Rousseaux index of prices, which counted many goods that were not produced domestically and that were often heavily taxed in those years. Nevertheless, both of them show high growth rates after 1810 until 1850. This high growth rate in agriculture was associated with an increase in labour productivity in the presence of decreasing growth in the labour force and a fixed amount of arable land as predicted by Crafts (1985). According to the calculations done in Clark (2002), Figure 3.1 shows a steady increase in real GDP, which declined in the latter half of the eighteenth century. This decline in output growth in the last few decades of the eighteenth century, as argued by Clark (2002), was due to the fact that English agriculture never had an increase in labour productivity before 1860. There was no sign of revolution in English agriculture, where gains in yields was the primary driver of agricultural productivity until 1860 (1500-1860) and only in the late nineteenth century onwards did labour productivity gains take over.

However, proponents of the 'Agricultural Revolution' would like to argue otherwise. Chambers and Mingay (1966), in describing the new farming techniques, mention the late eighteenth century as a time of improvements in soil fertility, artificial fertilizers, enclosure of lands, which provided better condition for cropping both cereal and fodder crops, and also a time for adopting alternative ways of husbandry, otherwise well known as the '*Norfolk System*' of farming. Ashton (1964) (more appropriately according to an American called Naomi Riches) called the '*Norfolk System*' a series of interrelated technical, economic and legal processes combined on an enclosed farm.[12] "*But the* '*Norfolk System*', *like every major innovation, was the work of many hands and brains*" (page 22).

Ashton (1964) describes the eighteenth century and early nineteenth century English agriculture as the period of introduction of new farming systems and also spreading of the four-course rotation system to almost all parts of Britain

[12] The '*Norfolk System*' includes the introduction of sandy soils of marl and clay, various rotations of crops, importance of growing new types of cereals and fodder crops and cattle rather than sheep, cultivation by tenants under the land enclosure system and long term leases (Ashton, 1964, page 21).

which had a three-course rotation in their old Midlands system.[13] On the other hand, Campbell (1983) shows evidence of the case of the use of '*Norfolk Farming*' around Norfolk in rural England even in the early thirteenth and fourteenth centuries. According to him, a number of similarities can be seen in the farming systems of Norfolk between the thirteenth and fourteenth centuries and in eighteenth and early nineteenth centuries in England. In Figure 3.1, the trends in real agricultural output from both sources show a positive trend in output in the first half of the nineteenth century, which indicates developments in the agricultural sector until 1850.

3.4.2. Innovative Activity

The discussion in section 3.2 shows that there was steady growth in output and labour productivity in the agricultural sector in the period 1760-1850 when industrial output also increased unprecedentedly due to various technological breakthroughs, naming this nation, for the first time in world history, as an industrial nation. Industrial Revolution cannot be restricted to the 'Age of Textiles' or 'Age of Railways', it was an age of overall improvement in every major sector in Britain. Inventions lead to innovations which alter the different forms of production and this in turn augments efficiency in the form of new improved technology.

[13] "Crop rotation is commonly defined as the practice of growing different crops in different years on the same land, in order to prevent the soil's nutrients from being exhausted and to reduce the risk of a build-up of diseases and pests specific to one crop. Crop rotation was widespread in Europe from the time of the Roman Empire. Two-field rotation was practised by the ancient Greeks: one half of a farmer's land was planted in the spring or autumn of each year, while the other half was left fallow (i.e. not planted with crops), to allow the soil to 'rest'. The Romans developed the three-course rotation, which was in use from the Middle Ages until the 18th century. A three-year cycle was followed on each of three fields, with an autumn-sown crop such as rye or winter wheat, a spring-sown crop such as oats or beans, and a year of lying fallow. Two out of three fields were thus in cultivation every year. The three-field system succeeded only in countries with mild climates, such as England. With the Agricultural Revolution and the acceleration of Enclosures in the 18th century, more scientific methods were applied to crop rotation. A four-course rotation was adopted based on turnips, clover, barley, and wheat. The introduction of root-crops (such as turnips) improved the soil and hence the quality of harvest and livestock; they also smother the weeds that have grown between plants of the previous crop. The replacement of the fallow with a leguminous crop, such as clover, peas, beans, or lentils, boosts the fertility of the soil since leguminous plants are able to 'fix' atmospheric nitrogen, which enriches the soil when they die" (*A Dictionary of World History*, 2000, Encyclopedia.com).

Although there is little doubt that there was a great deal of technological progress between 1760 and 1850, the main problems originate when initiatives are taken to measure technological progress in eighteenth and early nineteenth century Britain as we do not have much choice available for our measurement variables. This study uses three measures of innovative activity in agriculture: agricultural patents issued, number of first published titles of farming technical books and number of total published titles of farming technical books in the period 1620-1850, collected from Sullivan (1984; 1985).

Using ‘patent counts’ as an indicator of technological progress has got both positive and negative support. While Boehm and Silberston (1967) and Khan and Sokoloff (2006) argue against using patents as a measure of innovations during Industrial Revolution, Dutton (1984) and Sullivan (1989) put forward arguments in favour of patent counts as an indicator for technological progress. Boehm and Silberston (1967), Griliches (1990) and Khan and Sokoloff (2006) criticize the British patent system on the ground that all inventions were not patented and the cost of obtaining a patent was so excessive, which influenced many inventors to keep their inventions secret. Bound *et al.* (1984) argue that patenting is more common among small firms than large ones, regardless of large firms having higher shares of R&D. Despite these criticisms, Dutton (1984) argues that these arguments are unlikely to hold in early periods of industrialization in Britain. Comparing the cost of acquiring a patent for any new invention with the cost of keeping it a secret at that time, it might not be the case that secrecy was the better option (Dutton, 1984). Sullivan (1989) argues that there was least or fewer chance of inferior quality inventions to be patented during revolutionary periods. Though there still much debate about measuring technology by ‘patent counts’, it is quite commonly used in the present literature.[14]

Sullivan (1984) suggests another method of measuring agricultural innovations by *number of titles of technical farming books published* in the period 1521-1900. He argues that literacy rates were high enough in early modern England such that there were a good number of farmers who used to follow those

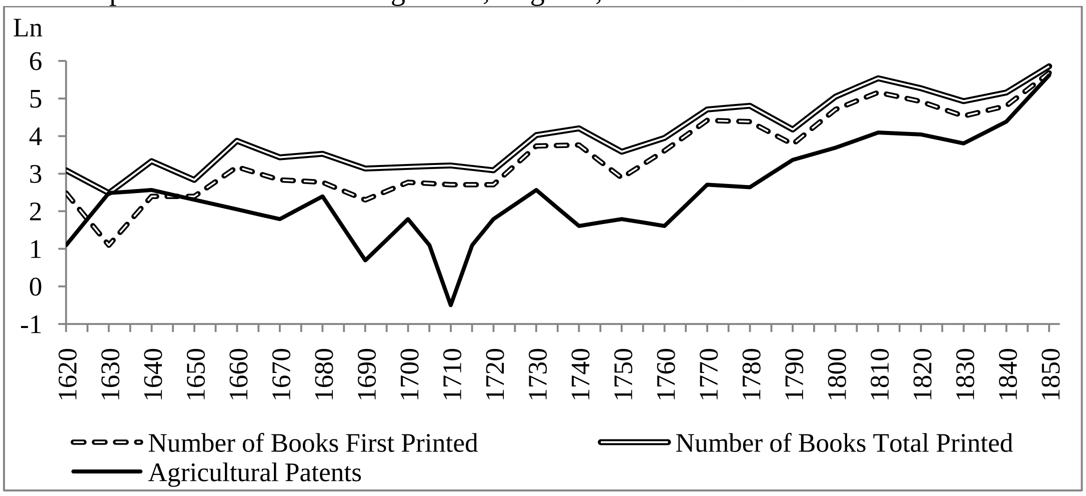
[14] See Greasley and Oxley (1998b; 2007), Madsen (2008) for arguments in favor of using ‘patent counts’ as an indicator of innovations and technology.

books in farming. To address the criticism that all inventions are not patented, Sullivan (1984) points out those often new crops, which could not be patented at that time, were promoted in agricultural books. Books can cover many more productive ideas compared to patents which mainly describe the implementation and mechanical devices of technologies. For example, a new technique for ploughing may be patented, but how to use the technique is not explained by that patent. This is better explained in a book, which describes the use of the ploughing technique in fields by local farmers. Thus the book pushes the use of this new technology among local people more widely than an agricultural patent does. Lastly, Sullivan (1984) shows that the fluctuations of agricultural book data and patent data are highly correlated until 1850. Hence, Sullivan argues that books are at least as good as and perhaps better than patents as a reflection of innovations.

Moreover, in seventeenth and early eighteenth century Britain, perhaps agricultural books were better indicators than agricultural patents due to the fact that, in agriculture, it is hard to acquire monopoly profits/rents on new agricultural farming techniques. Lands were cultivated not by landlords, but by common peasants under those landlords on a temporary basis. Hence, once a new technique was in practice by one farmer, it was hard to restrict another farmer or the same farmer from using that technology on a different farm, provided it generated higher productivity. Gradually it would become common knowledge to all farmers in the area or society. Thus, agricultural technical books and manuals spread this technological progress better among farmers, once the technique came into practice. All this evidence justifies the use of number of titles of technical farming books published as an alternative measure of agricultural technological progress rather than using agricultural patent counts as the sole indicator of technological progress.

Figure 3.2 below shows the number of agricultural patents issued, number of first printed titles of technical farming books and number of total printed titles of technical farming books in England for the period 1620-1850. The first printed title is different from total printed as a number of reprints might have occurred for the same book in each year. While the first printed titles shows the breakthrough of technological innovations in the agricultural sector, the total or reprinted number shows the distribution of this technological knowledge among the farm holders. More volumes of these books indicate the increased demand and the extent of practice of technological advancements in farming systems among farmers in different levels. Sullivan (1984) collects the data from Perkins' bibliography (Perkins, 1932), who was fairly careful in listing exactly what he covers in his bibliography. So it is not impossible to identify the books whose subject matters were responsible for only technological advancement in agriculture. The details of the subject matters are given in the data appendix 3A.

Figure 3.2: Number of agricultural patent counts, first printed technical farming books and total printed technical farming books, England, 1620-1850.



Notes: data for different measures of R&D variable are in natural logarithm of level variables.
Sources: Sullivan (1984), table 1. For details see data appendix.

The trend of fluctuations in first printed books and in total printed books overall matches in the period 1620-1850 (see Figure 3.2), which could reasonably be expected as total number of printed books should differ from first printed books only in volume due to repetition of printing of the same books, but not in growth rates. Comparing the trends of number of printed agricultural books (both first and total printed) with the number of agricultural patent counts, similar trends of fluctuations are observable in most of the years under consideration, except a slight fall in the agricultural patent counts in the period 1700-1710. Indeed this shows a high positive correlation among the different technological measures in the agricultural sector, as indicated by Sullivan (1984), who argues in favour of farming books as a measure of technological progress in the sector. There is a slight fluctuation in the technological progress in the period 1815-1830 for both types of measures and the period can be identified as an unstable period with a series of wars being fought at that time, most prominent of which were French Revolutionary Wars (1803-1814) and the Anglo-Burmese War (1823-1826). The aftermath of these combats might have adversely affected the advancement of technology in the sector.

Overall the agricultural technological indicators have an upward trend in the period 1620-1850, especially after 1760 until 1850, which is otherwise known as the period of the First Industrial Revolution. The upward trend of published technical agricultural books circa 1750 and agricultural patent counts circa 1760 indicate evidence supporting the view of Overton (1996a; 1996b) of an 'Agricultural Revolution' in 1750-1850, but more detailed empirical examination of data is required before reaching any conclusion.

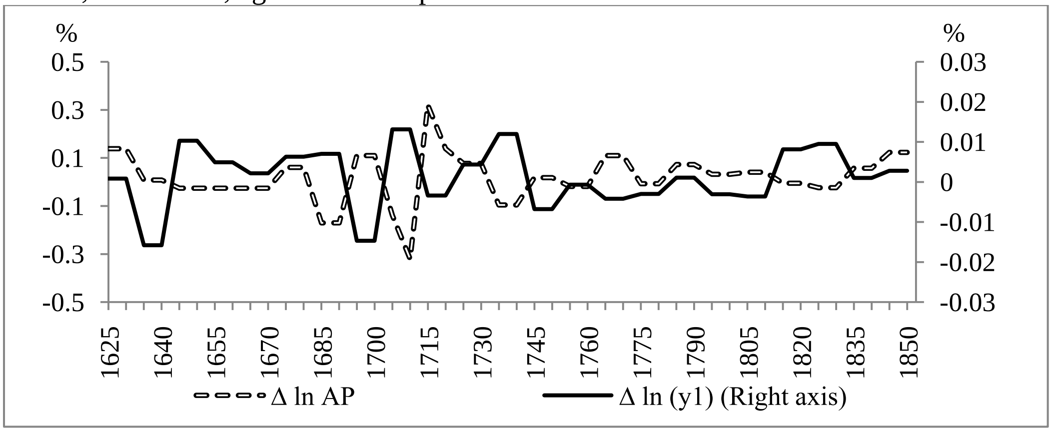
3.5. Data Analysis following Second Generation Innovation-based Growth Models

This section graphically tests the validity of the Schumpeterian growth model and semi-endogenous growth models using data on the British agricultural sector in the period 1620-1850. The models are briefly discussed in the introduction chapter of this dissertation and also in section 3.3 of this chapter.

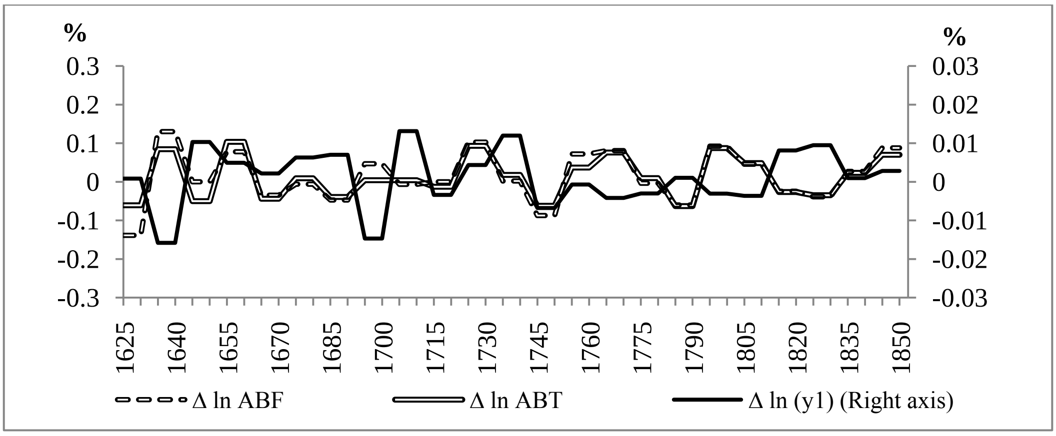
3.5.1. Semi-endogenous model

Figure 3.3 and Figure 3.4 follows the semi-endogenous model of economic growth, which in terms of the British agricultural sector predicts positive growth in innovative activity for sustained positive growth in labour productivity. While Figure 3.3 corresponds to the agricultural output data of GC in the period 1620-1850, Figure 3.4 corresponds to the agricultural output data of DC in the period 1700-1850. The relationship between labour productivity growth ($\Delta \ln y_1$, $\Delta \ln y_2$) and agricultural patent growth ($\Delta \ln AP$) is shown in Figure 3.3 (a) and Figure 3.4 (a) respectively and the relationship between labour productivity growth ($\Delta \ln y_1$, Δ ln y_2) and growth in the number of agricultural technical books published (Δ ln *ABF* and Δ ln *ABT)* are shown in Figure 3.3 (a) and Figure 3.4 (b) respectively.

Figure 3.3: Annual growth rates of agricultural labour productivity and research activity, Britain, 1620-1850; agricultural output data of GC.



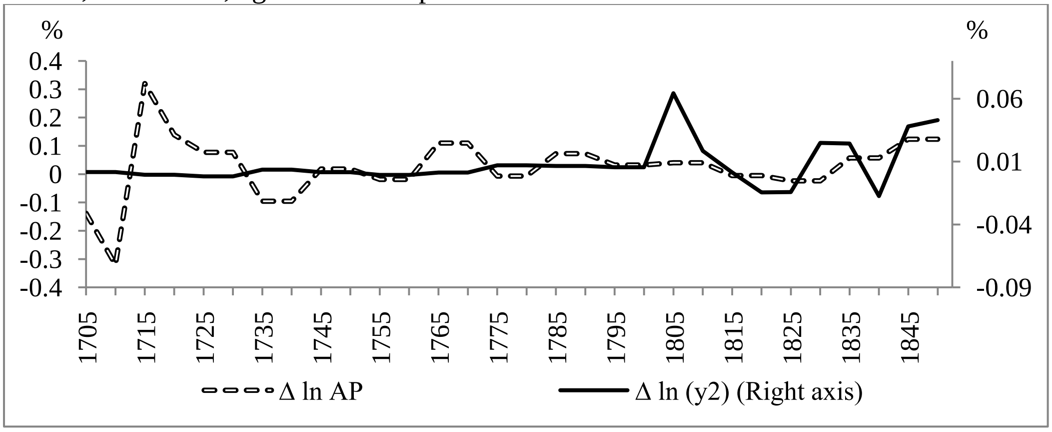
(a)



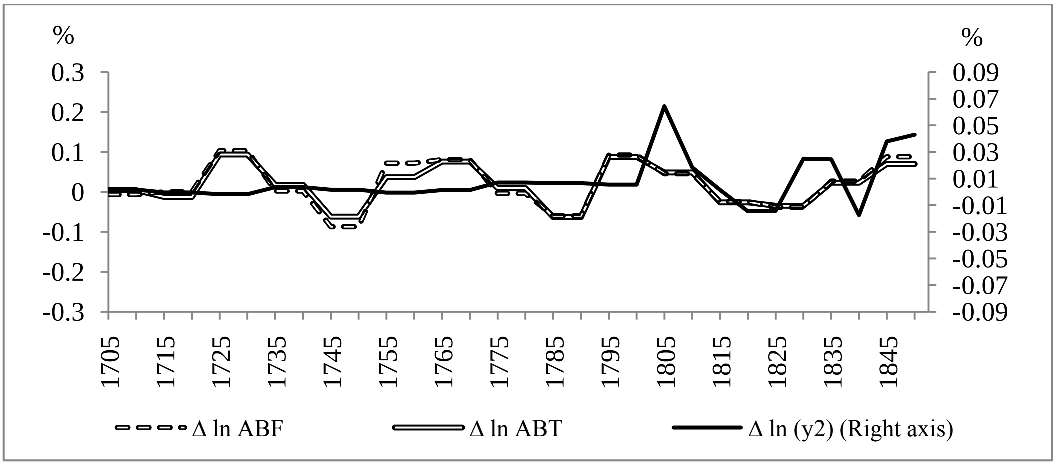
(b)

Note: Figure 3.3 corrosponds to agricultural output data of Clark (2002). In Figure 3.3 (a), agricultural labour productivity (Δ ln *y*1) (right axis) is plotted against agricultural patent growth (Δ ln *AP*) (left axis) for the period 1620-1850. In Figure 3.3 (b), agricultural labour productivity (Δ ln *y*1) (right axis) is plotted against technical agricultural books published (both first and total published) (Δ ln *ABF* and Δ ln *ABT*) (left axis) for the period 1620-1850 respectively. All the variables are measured in non-overlapping annualized five years differences of level variables.

Figure 3.4: Annual growth rates of agricultural labour productivity and research activity, Britain, 1700-1850; agricultural output data of DC.



(a)



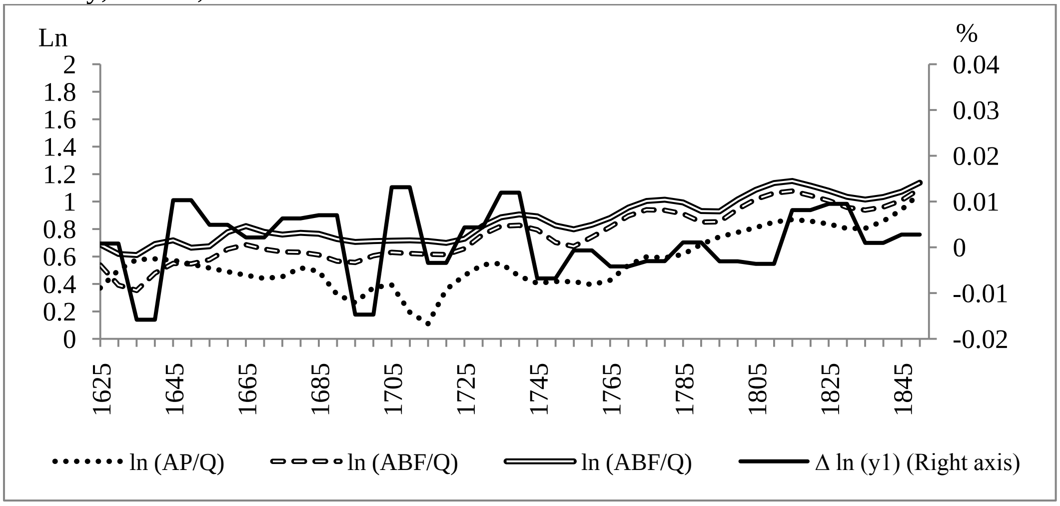
(b)

Note: Figure 3.4 corresponds to agricultural output data of Deane and Cole (1962). In Figure 3.4 (a), agricultural labour productivity (Δ ln *y*2) (right axis) is plotted against agricultural patent growth (Δ ln *AP*) (left axis) for the period 1700-1850. In Figure 3.4 (b), agricultural labour productivity (Δ ln *y*2) (right axis) is plotted against technical agricultural books published (both first and total published) (Δ ln *ABF* and Δ ln *ABT*) (left axis) for the period 1700-1850 respectively. All the variables are measured in non-overlapping annualized five years differences of level variables.

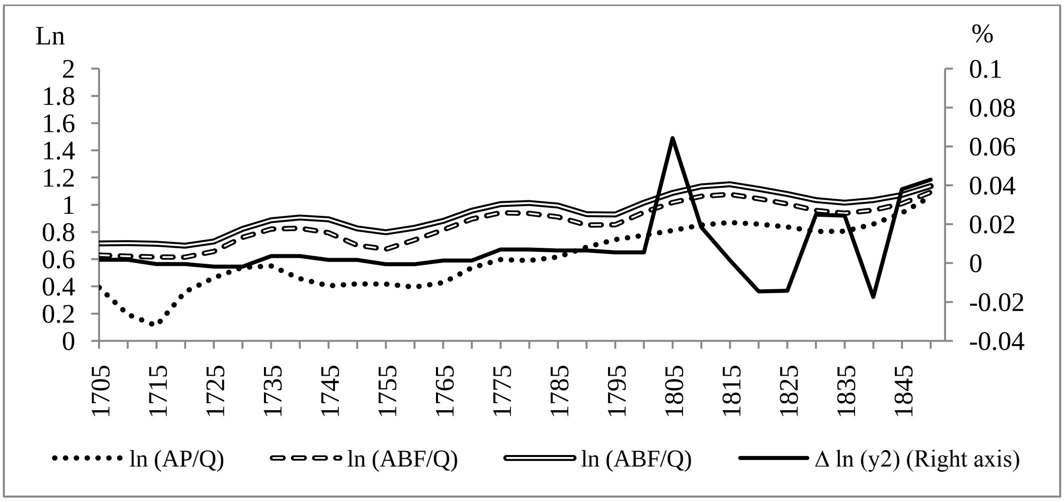
No distinct relation is found between the growth fluctuations of labour productivity and innovative activity in the agricultural sector in the period 1620-1850 (Figure 3.3) and 1700-1850 (Figure 3.4) respectively. This shows no support for semi-endogenous model in explaining the labour productivity growth in the agricultural sector Britain.

3.5.2. Schumpeterian model

Figure 3.5: Annual growth rates of agricultural labour productivity and research intensity, Britain, 1620-1850.



(a)



(b)

Notes: Figure 3.5 (a) corresponds to the agricultural output data of Clark (2002) and Figure 3.5(b) corresponds to the agricultural output data of Deane and Cole (1962). While the period under consideration for Clark (2002) in Figure 3.5(a) is 1620-1850, the period under consideration for Deane and Cole (1962) in Figure 3.5(b) is 1700-1850. Agricultural labour productivity (y1 and y2) in Figures 3.5(a) and 3.5(b), respectively, are measured in non-overlapping annualized five years differences of level variables and all measures of research intensities, where the R&D variable is measured as agricultural patents (*AP*), tittles of first printed technical farming books (*ABF*) and titles of total printed technical farming books (*ABT*), are in non-overlapping annualized five years average of level variables.

Following the Schumpeterian model, in Figure 3.5, labour productivity growth in the agricultural sector (right axis) in the period 1620-1850 is plotted against the three measures of research intensities (left axis), ln (*X/Q*). Figure 3.5 (a) plots the labour productivity growth using the agricultural real output data of GC (Δ ln *y*1) and Figure 3.5 (b) plots the agricultural labour productivity growth (right axis) in the period 1700-1850, using agricultural real output data of DC (Δ ln *y*2). *X* is innovative activity measured as agricultural patents (*AP*), titles of first printed technical farming books (*ABF*) and titles of total printed technical farming books (*ABT*), respectively. *Q* is approximated by the labour force (*L*) in the agricultural sector.

Schumpeterian theory predicts that productivity growth should be well explained by the level of research intensity in the economy. Comparing the two different sources of data for agricultural real output graphically, more support is obtained for GC (Figure 3.5 (a)) compared to DC (Figure 3.5 (b)). Consistent with the proposition of the Schumpeterian model, the graphical evidence presented in Figure 3.5 (a) suggests that the trend in labour productivity growth moves quite closely with various indicators of research intensity, except for a few fluctuations in labour productivity growth in the initial years before 1750. In Figure 3.5 (b), there is less support for the theory where trend in labour productivity is stable until the first quarter of nineteenth century and fluctuates widely in the second half.

Overall, from the viewpoint of second generation innovation based growth models, there is some support in favour of the Schumpeterian growth model as against the semi-endogenous model of economic growth. However empirical testing of the two theories is certainly required before reaching any conclusion.

3.6. Empirical Results

3.6.1. Unit root tests results

Before the co-integration test results are presented to test the validity of the two second generation growth models for the British agricultural sector in the period 1620-1850, the unit roots in levels and first differences of selected variables are checked. The null hypothesis of a unit root in the series is tested against the alternative of trend stationary in levels and/or differenced stationary in first or higher order differences of the variables.

Table 3.2: Unit root results of agricultural variables, 1620-1850.

Variables	ADF		PP		ZA		Result
	Levels	1st Differenced	Levels	1st Differenced	Levels	1st Differenced	
ln Y_1/L	-2.71 (0.23)	-3.44*** (0.01)	-2.09 (0.55)	-4.41*** (0.00)	-4.77 (BP=1760)	-4.61* (BP=1741)	I(1)
ln Y_2/L	-1.19 (0.91)	-4.88*** (0.00)	-1.65 (0.77)	-13.40*** (0.00)	-4.49 (BP=1802)	-11.54*** (BP=1808)	I(1)
ln *AP*	-1.46 (0.84)	-6.77*** (0.00)	-1.44 (0.85)	-5.94*** (0.00)	-4.70 (BP=1701)	-7.71*** (BP=1710)	I(1)
ln *ABF*	-1.46 (0.55)	-4.04*** (0.00)	-0.36 (0.91)	-4.28*** (0.00)	-5.93*** (BP=1681)	-5.25*** (BP=1811)	I(0)/I(1)
ln *ABT*	-1.32 (0.95)	-3.43*** (0.01)	-2.78 (0.21)	-4.37*** (0.00)	-5.96*** (BP=1681)	-6.16*** (BP=1811)	I(0)/I(1)
ln *L*	-1.77 (0.71)	-2.47* (0.12)	0.06 (0.10)	-2.70* (0.08)	-3.92 (BP=1784)	-5.15*** (BP=1811)	I(1)
ln (AP/L)	-1.64 (0.77)	-6.80*** (0.00)	-1.60 (0.79)	-5.96*** (0.00)	-4.81* (BP=1701)	-7.73*** (BP=1710)	I(0)/I(1)
Ln (ABF/L)	-5.28*** (0.00)	-4.06*** (0.00)	-3.58 (0.03)	-4.30*** (0.00)	-5.90*** (BP=1681)	-4.60* (BP=1751)	I(0)
ln (ABT/L)	-3.57** (0.04)	-3.48*** (0.01)	3.07* (0.11)	-4.37*** (0.00)	-5.84*** (BP=1681)	-4.61* (BP=1661)	I(0)

Note: 'ln' refers to natural logarithm. Y_1 corresponds to the agricultural real output data of Clark and Y_2 corresponds to the agricultural real output data computed from Deane and Cole. For the latter case, the period of estimation is 1700-1850. *AP*, *ABF* and *ABT*, *L* stand for agricultural patents, titles of technical farming books first published and titles of technical farming books total published and agricultural labour force, respectively. Although the *p*-values of the ADF test statistics in first differences with a constant term included for ln *L* were 0.12, they are very close to 10% critical levels and hence concluded as I(1) under ADF test. ZA refers to Zibot-Andrews test. BP refers to the break-point year in the test.

The variables under consideration following the semi-endogenous theory are: real GDP per labour (*Y/L*), considering two sources of real GDP as calculated by Clark (2002) and Deane and Cole (1962), the later is deflated by the agricultural component of the Rousseaux index, agricultural patent counts (*AP*), titles of first farming technical books published (*ABF*), titles of total farming technical books published (*ABT*) and labour force in the agricultural sector (*L*). The theory predicts that the above variables will contain a unit root in levels and be stationary in first differenced. The different research intensity variables following the Schumpeterian theory are: patents per worker (P/L), first printed books per worker (ABF/L) and total printed books per worker (ABT/L). The theory predicts the research intensity variables to be stationary in levels.

Unit root tests are performed using the conventional Augmented Dickey Fuller test (ADF), Phillips-Perron test (PP) and Zibot-Andrews test (ZA), where the last test takes into account one structural break over time. In Table 3.2, although ABT and ABL came out to be I(0) under the ZA test, combining the results from three tests of output per worker, measures of innovative activity and labour force are I(1) following the predictions of semi-endogenous growth theory and measures of research intensity are I(0) following the Schumpeterian growth theory. The section tests the co-integration among variables following eq. (3.7) and eq. (3.9) for the two second-generation innovation based growth models.

3.6.2. Co-integration analyses

Turning our focus towards long run growth theories that can explain the British agricultural growth in the period 1620-1850, co-integration tests follow eq. (3.7) for the Schumpeterian growth model and eq. (3.9) for semi-endogenous growth model from section 3.4. The regression results follow Johansen (1988) methodology. Table 3.3 shows the co-integrating relationship between technology variables (ln *X*) and product variety (ln *Q*) in British agriculture in the periods 1620-1850 and 1760-1850, respectively.

In Table 3.3, following eq. (3.7), in both periods 1620-1850 and 1760-1850, it is observed that the null of no co-integration between ln *X* and ln *Q* cannot be rejected in any of the cases. In the agricultural sector, all the different technological variables (*X*), namely agricultural patents (*AP*), first printed titles of technical farming books (*ABF*) and total printed titles of technical farming books (*ABT*) are all co-integrated in the long run with product variety (*Q*), measured as labour force engaged in the agricultural sector, especially in the period 1760-1850, i.e. during the First Industrial Revolution. The ECT term associated with Δ ln *X* is highly significant in each case and also has the right sign. This indicates that a significant long run relationship exists between the variables.

Table 3.3: Johansen co-integration test for Schumpeterian growth theory; eq. (3.7).

VECM variables	Hypothesis	Trace Statistic	Max-eigenvalue statistic	Co-integrating vector	ECT
Period: 1620-1850					
[ln *AP*, ln *Q*]	$r = 0$	16.85**	15.47**	[1, -10.90***]	-0.03***
	$r \leq 1$	1.38	1.38	(-5.94)	(-3.33)
[ln *ABF*, ln *Q*]	$r = 0$	16.22**	15.78**	[1, -10.12***]	-0.01***
	$r \leq 1$	0.44	0.44	(-5.37)	(-3.64)
[ln *ABT*, ln *Q*]	$r = 0$	17.57**	16.81**	[1, -8.38***]	-0.01***
	$r \leq 1$	0.76	0.76	(-5.64)	(-3.55)
Period: 1760-1850					
[ln *AP*, ln *Q*]	$r = 0$	16.18**	13.33*	[1, -11.34***]	-0.01***
	$r \leq 1$	2.85	2.85	(-3.87)	(-3.40)
[ln *ABF*, ln *Q*]	$r = 0$	17.18**	14.07**	[1, -3.00**]	-0.02***
	$r \leq 1$	3.11	3.11	(-2.07)	(-2.85)
[ln *ABT*, ln *Q*]	$r = 0$	16.62**	15.04**	[1, -2.57*]	-0.02***
	$r \leq 1$	1.58	1.58	(-1.94)	(-3.06)

Notes: AP, ABF and ABT stand for agricultural patents issued, titles of first printed books on farming and titles of the total printed books on farming, respectively. Figures in parenthesis are *t*-statistics. The null hypothesis is there are *r* co-integrating relationships between the variables. A constant but no trend is included in the tests. The optimal lag length is chosen according to minimum AIC criteria. Critical values are from Mackinnon *et al.* (1999). ECT is the error correction term associated with Δ ln *X* equation.

Table 3.4: Johansen co-integration test for semi-endogenous growth theory; eq. (3.9); output data of GC.

VECM variables	Hypothesis	Trace Statistic	Max-eigenvalue statistic	Co-integrating vector	ECT
Period: 1620-1850					
[ln (Y_1/L), ln AP, ln L]	$r = 0$	24.99	14.20	[1, 0.22***, -3.15***]	-0.00
	$r \leq 1$	10.79	7.74	(3.71, -4.48)	(-0.45)
	$r \leq 2$	3.05	3.05		
[ln (Y_1/L), ln ABF, ln L]	$r = 0$	26.46	17.86	[1, -0.25***, 1.81**]	-0.00**
	$r \leq 1$	8.59	7.44	(-4.51, 2.65)	(-2.48)
	$r \leq 2$	1.15	1.15		
[ln (Y_1/L), ln ABT, ln L]	$r = 0$	28.84*	18.06	[1, -1.02***, 7.68***]	-0.00
	$r \leq 1$	10.78	9.00	(-4.44, 3.35)	(-1.06)
	$r \leq 2$	1.78	1.78		
Period: 1760-1850					
[ln (Y_1/L), ln AP, ln L]	$r = 0$	28.76*	17.17	[1, 0.01, -0.53***]	0.00
	$r \leq 1$	11.59	8.80	(0.89, -3.91)	(0.06)
	$r \leq 2$	2.79	2.79		
[ln (Y_1/L), ln ABF, ln L]	$r = 0$	27.82*	18.67	[1, 0.52***, -2.02***]	-0.00
	$r \leq 1$	9.15	9.11	(4.95, -3.54)	(-0.49)
	$r \leq 2$	0.04	0.04		
[ln (Y_1/L), ln ABT, ln L]	$r = 0$	26.57	19.36*	[1, 0.31***, -1.33***]	-0.00
	$r \leq 1$	7.22	7.09	(5.71, -4.90)	(-0.45)
	$r \leq 2$	0.13	0.13		

Notes: Here Y_1 refers to the agricultural real output calculated by Clark (2002). AP, ABF and ABT stand for agricultural patents issued, titles of first printed books on farming and titles of the total printed books on farming, respectively. Figures in parenthesis are *t*-statistics. The null hypothesis is there are *r* co-integrating relationships among the variables. A constant but no trend is included in the tests. The optimal lag length is chosen according to minimum AIC criteria. Critical values are from Mackinnon *et al.* (1999). ECT is the error correction term associated with Δ ln (Y_1/L) equation.

Table 3.5: Johansen co-integration test for semi-endogenous growth theory, eq. (3.9); output data of DC.

VECM variables	Hypothesis	Trace Statistic	Max-eigenvalue statistic	Co-integrating vector	ECT
Period: 1700-1850					
[ln (Y_2/L), ln *AP*, ln *L*]	$r = 0$	32.05*	14.08	[1, 0.01, -2.18***]	0.04
	$r \leq 1$	17.97**	9.61	(0.20, -2.77)	(1.07)
	$r \leq 2$	8.36	8.36		
[ln (Y_2/L), ln *ABF*, ln *L*]	$r = 0$	31.99**	15.00	[1, 0.11, -3.83***]	-0.04
	$r \leq 1$	16.99**	11.99	(1.20, -4.45)	(-1.57)
	$r \leq 2$	4.99	4.99		
[ln (Y_2/L), ln *ABT*, ln *L*]	$r = 0$	30.43**	15.35	[1, 0.09, -3.56***]	-0.04
	$r \leq 1$	15.08*	10.14	(1.0, -4.56)	(-1.61)
	$r \leq 2$	4.94	4.94		
Period: 1760-1850					
[ln (Y_2/L), ln *AP*, ln *L*]	$r = 0$	33.36**	15.27	[1, -0.25***, -0.60]	-0.23***
	$r \leq 1$	18.08**	13.38*	(-5.70, -1.08)	(-3.05)
	$r \leq 2$	4.70	4.70		
[ln (Y_2/L), ln *ABF*, ln *L*]	$r = 0$	35.02***	17.07	[1,-0.51***, -0.86*]	-0.16**
	$r \leq 1$	17.95**	13.01*	(-6.53, -1.89)	(-2.57)
	$r \leq 2$	4.93	4.93		
[ln (Y_2/L), ln *ABT*, ln *L*]	$r = 0$	36.32***	19.81*	[1,-0.55***,-1.06**]	-0.17***
	$r \leq 1$	16.50**	13.08*	(-7.46, -2.64)	(-2.76)
	$r \leq 2$	3.43	3.43		

Notes: Here Y_2 refers to the agricultural real output calculated by Deane and Cole (1962). AP, ABF and ABT stands for agricultural patents issued, titles of first printed books on farming and titles of the total printed books on farming, respectively. Figures in parenthesis are *t*-statistics. The null hypothesis is there are *r* co-integrating relationships among the variables. A constant but no trend is included in the tests. The optimal lag length is chosen according to minimum AIC criteria. Critical values are from Mackinnon *et al.* (1999). ECT is the error correction term associated with Δ ln (Y_2/L) equation.

Following eq. (3.9) for the semi-endogenous growth model, the co-integration relationships among labour productivity (*Y/L*) in the agricultural sector, different technological variables (*X*) and agricultural labour force (*L*) are considered. Table 3.4 corresponds to real output from GC and Table 3.5 corresponds to real output from DC. In Table 3.4, for both periods 1620-1850 and 1760-1850, no support was found for semi-endogenous theory. The trace statistic and maximum eigenvalue statistic show no co-integration relationship exists among variables ln (Y_1/L), different measures of ln X and ln L in most cases. The results show, where the trace statistic was found to be significant, the error correction term (ECT) associated with Δ (Y_1/L) came out to be insignificant and hence the results are not satisfactory.

Next in Table 3.5, following equation (3.9) the co-integration test is done using the real output data of DC. In the period 1700-1850, no support for semi-endogenous growth model was found either, where the ECT term associated with the Δ ln (Y_2/L) equation came out to be insignificant in all of the three cases. In the subsequent period of the First Industrial Revolution during 1760-1850, there was weak support in the co-integration relationship among labour productivity, innovative activity and labour, where the trace statistic shows two co-integration relationships exist among variables and the ECT term associated with the Δ ln (Y_2/L) equation came out significant. However the max-eigenvalue statistic did not come out significant in those cases. Only in the last case, using total published books (ln ABT) as the indicator of technological progress, there is some support in favour of semi-endogenous theory. Overall, aggregating the results from the two sample periods in Table 3.5, not much support is obtained for semi-endogenous theory using the real output data of Deane and Cole (1962) either.

Summing up the co-integration test results in this section, a significant co-integration relationship exists between the technology variable and the product variety variable in the agricultural sector of Britain in the period 1620-1850 and also in the period of the First Industrial Revolution i.e. 1760-1850. The co-integrating vector shows the coefficients for ln Q are all significant for different measures of agricultural technological progress. This shows full support for Schumpeterian theory in explaining British labour productivity growth in the agricultural sector. However, there is no support for the semi-endogenous growth model in the specified periods. The results are found to be robust to two different sources of data for agricultural output. In either case, no support for the semi-endogenous growth model is found for the agricultural sector in Britain during the period of early industrialization. This finding is very important in the literature of economic growth and economic history, which shows, for the first time, that second generation innovation-based growth models can successfully explain the sectoral growth in Britain during the Industrial Revolution. Further, the sufficiency condition is tested in the next section where growth regressions are run incorporating the predictions of both versions of the endogenous growth models to explain the long run labour productivity growth in the agricultural sector in the period 1620-1850.

3.6.3. Estimates of Labour productivity growth

This section shows the labour productivity growth estimations for English agriculture in the period 1620-1850, following eq. (3.10) and (3.11) in section 3.4.3. This also tests the sufficiency condition for validity of the two growth models in explaining the long run sectoral growth of Britain in the periods 1620-1850 and 1760-1850. Table 3.6 – Table 3.8 corresponds to real GDP of the agricultural sector computed from GC and Table 3.9 – Table 3.11 corresponds to real GDP of the agricultural sector computed from DC. Each table shows the results of labour productivity growth estimations in the agricultural sector in the two specified sample periods, from 1620-1850 and 1760-1850. Agricultural output data of Deane and Cole begins at 1700, whereas in Clark's calculations, it begins from sixteenth century onwards. Hence the estimation periods are 1700-1850 using data of Deane and Cole and that of 1620-1850 using data of Clark. The First Industrial Revolution period of 1760-1850 is common from both sources.

Table 3.6: Estimates of labour productivity growth in the agricultural sector, (eq.3.10 & 3.11); output data corresponds GC and X= patents.

	$\ln (X/Q)_t$	$\Delta\ln X_t$	$\Delta\ln POP_t$	$\Delta\ln (M/Y)_t$	$\Delta\ln TO_t$	$\ln UNC_t$	$\ln LE_t$
Period 1620-1850							
(1)	0.66*	-2.99***	-0.02				
	(0.06)	(0.00)	(0.32)				
(2)	0.65*	-2.99***	-0.02	-0.00			
	(0.07)	(0.00)	(0.33)	(0.58)			
(3)	0.66*	-3.02***	-0.02		0.00		
	(0.06)	(0.00)	(0.32)		(0.85)		
(4)	0.69**	-3.05***	-0.03			-0.63	
	(0.05)	(0.00)	(0.22)			(0.32)	
(5)	1.32***	-2.88***	0.05*				-4.48**
	(0.01)	(0.00)	(0.09)				(0.03)
(6)	1.32***	-3.00***	0.06*	-0.01	-0.00	-0.14	-4.79***
	(0.01)	(0.00)	(0.10)	(0.16)	(0.59)	(0.81)	(0.01)
Period 1760-1850							
(1)	0.76**	-2.33	-0.00				
	(0.04)	(0.16)	(0.98)				
(2)	0.75**	-2.28	0.01	-0.01			
	(0.05)	(0.19)	(0.90)	(0.33)			
(3)	0.70**	-2.29*	0.01		0.03**		
	(0.03)	(0.09)	(0.89)		(0.02)		
(4)	0.80**	-2.55	-0.02			-0.18	
	(0.02)	(0.18)	(0.88)			(0.82)	
(5)	0.89**	-2.50	0.04				-5.17
	(0.05)	(0.19)	(0.59)				(0.59)
(6)	0.83*	-1.95*	0.24	-0.03	0.05***	0.44	-11.77
	(0.09)	(0.08)	(0.50)	(0.15)	(0.00)	(0.75)	(0.55)

Note: the dependent variable is labour productivity (real output per unit of labour) growth in the agricultural sector calculated using agricultural output data of Clark (2002). Newey-West procedure was used to obtain heteroskedasticity consistent robust estimates. A constant was included in the test. Nominal GDP used to calculate *TO* and (*M/Y*) corresponds to the GDP of the overall economy. Values in square brackets are *p*-values. *, ** and *** indicates significance levels at 10%, 5% and 1%, respectively.

Table 3.7: Estimates of labour productivity growth in the agricultural sector (eq. 3.10 & 3.11); output data corresponds GC and X= First printed books.

	$\ln (X/Q)_t$	$\Delta\ln X_t$	$\Delta\ln POP_t$	$\Delta\ln (M/Y)_t$	$\Delta\ln TO_t$	$\ln UNC_t$	$\ln LE_t$
Period 1620-1850							
(1)	0.92^{*}	-3.36^{**}	-0.26^{*}				
	(0.07)	(0.05)	(0.09)				
(2)	0.92^{*}	-3.36^{*}	-0.26^{*}	0.00			
	(0.07)	(0.06)	(0.10)	(0.99)			
(3)	0.97^{*}	-3.38^{**}	-0.26^{*}		-0.01		
	(0.06)	(0.05)	(0.09)		(0.37)		
(4)	0.93^{*}	-3.41^{*}	-0.25			0.20	
	(0.06)	(0.06)	(0.16)			(0.77)	
(5)	1.49^{**}	-3.10^{*}	0.07				-4.13^{**}
	(0.02)	(0.09)	(0.73)				(0.07)
(6)	1.61^{**}	-3.22^{*}	0.13	-0.00	-0.02	0.54	-4.53^{*}
	(0.02)	(0.07)	(0.60)	(0.93)	(0.56)	(0.37)	(0.06)
Period 1760-1850							
(1)	1.27^{*}	-2.73^{**}	-0.01				
	(0.07)	(0.02)	(0.67)				
(2)	1.34^{*}	-2.79^{**}	-0.01	0.01			
	(0.07)	(0.03)	(0.55)	(0.43)			
(3)	1.31^{**}	-2.28^{*}	0.00		0.01^{***}		
	(0.04)	(0.06)	(0.94)		(0.01)		
(4)	1.47^{*}	-2.24	0.02			0.14	
	(0.08)	(0.23)	(0.65)			(0.85)	
(5)	1.66^{*}	0.11	0.07				-4.15
	(0.10)	(0.96)	(0.32)				(0.26)
(6)	3.40^{**}	-1.50	0.11^{*}	-0.00	0.04	0.83	-5.43
	(0.03)	(0.30)	(0.08)	(0.76)	(0.34)	(0.34)	(0.14)

Table 3.8: Estimates of labour productivity growth in the agricultural sector (eq. 3.10 & 3.11); output data corresponds GC and X= Total printed books.

	ln $(X/Q)_t$	Δln X_t	Δln POP_t	Δln $(M/Y)_t$	Δln TO_t	ln UNC_t	ln LE_t
Period 1620-1850							
(1)	1.74**	-2.75	0.11				
	(0.05)	(0.25)	(0.63)				
(2)	1.72*	-2.74	0.13	-0.01			
	(0.02)	(0.26)	(0.63)	(0.77)			
(3)	1.75*	-2.94	0.10		-0.01		
	(0.06)	(0.22)	(0.69)		(0.40)		
(4)	1.88**	-2.89	0.19			0.60	
	(0.04)	(0.22)	(0.48)			(0.31)	
(5)	1.74**	-2.75	0.12				-4.44*
	(0.05)	(0.25)	(0.63)				(0.09)
(6)	1.85**	-3.02	0.14	0.01	0.38	-0.03	-4.54*
	(0.05)	(0.22)	(0.62)	(0.85)	(0.55)	(0.49)	(0.10)
Period 1760-1850							
(1)	1.67**	-4.53**	-0.06				
	(0.04)	(0.05)	(0.60)				
(2)	1.70**	-4.55*	-0.07	0.00			
	(0.04)	(0.06)	(0.61)	(0.83)			
(3)	1.67**	-3.98	-0.03		0.02		
	(0.04)	(0.12)	(0.82)		(0.23)		
(4)	1.69*	-4.47*	-0.06			-0.06	
	(0.06)	(0.07)	(0.61)			(0.92)	
(5)	0.95*	-4.02***	-0.19*				2.23
	(0.06)	(0.01)	(0.10)				(0.23)
(6)	1.23*	-3.25	0.08	-0.00	0.03*	0.96	-0.89
	(0.06)	(0.03)	(0.61)	(0.78)	(0.09)	(0.27)	(0.70)

Table 3.9: Estimates of labour productivity growth in the agricultural sector (eq. 3.10 & 3.11); output data corresponds DC and X= Patents.

	$\ln (X/Q)_t$	$\Delta\ln X_t$	$\Delta\ln POP_t$	$\Delta\ln (M/Y)_t$	$\Delta\ln TO_t$	$\ln UNC_t$	$\ln LE_t$
Period 1700-1850							
(1)	0.04***	0.01	-0.01				
	(0.00)	(0.51)	(0.25)				
(2)	0.03***	0.01	-0.01	-0.00			
	(0.00)	(0.53)	(0.29)	(0.45)			
(3)	0.04***	0.01	-0.01		-0.00		
	(0.00)	(0.37)	(0.23)		(0.37)		
(4)	0.03***	0.01	-0.01			0.02	
	(0.00)	(0.34)	(0.40)			(0.38)	
(5)	0.02*	0.01	-0.01*				0.07
	(0.06)	(0.56)	(0.06)				(0.26)
(6)	0.03**	0.02	-0.01	0.00	-0.00	0.01	0.07
	(0.04)	(0.37)	(0.14)	(0.71)	(0.38)	(0.68)	(0.24)
Period 1760-1850							
(1)	0.04***	0.09	-0.01				
	(0.00)	(0.28)	(0.30)				
(2)	0.04***	0.09	-0.01	-0.00			
	(0.01)	(0.31)	(0.52)	(0.66)			
(3)	0.04**	0.08	-0.01		-0.00		
	(0.03)	(0.29)	(0.21)		(0.48)		
(4)	0.04**	0.12	-0.00			0.04	
	(0.02)	(0.29)	(0.75)			(0.43)	
(5)	0.03*	0.11	-0.03***				0.67**
	(0.10)	(0.21)	(0.01)				(0.05)
(6)	0.05***	0.11	-0.00	-0.00	-0.00	0.04	-0.05
	(0.01)	(0.34)	(0.75)	(0.97)	(0.57)	(0.44)	(0.65)

Note: the dependent variable is labour productivity (real output per unit of labour) growth in the agricultural sector calculated using agricultural output data of Deane and Cole (1962). Newey-West procedure was used to obtain heteroskedasticity consistent robust estimates. A constant was included in the test. Nominal GDP used to calculate *TO* and (*M/Y*) correspond to the GDP of the overall economy. Values in square brackets are *p*-values. *, ** and *** indicates significance levels at 10%, 5% and 1%, respectively.

Table 3.10: Estimates of labour productivity growth in the agricultural sector (eq. 3.10 & 3.11); output data corresponds DC and X= First printed books.

	$\ln(X/Q)_t$	$\Delta\ln X_t$	$\Delta\ln POP_t$	$\Delta\ln(M/Y)_t$	$\Delta\ln TO_t$	$\ln UNC_t$	$\ln LE_t$
Period 1700-1850							
(1)	0.05***	0.05	-0.01				
	(0.01)	(0.23)	(0.27)				
(2)	0.05***	0.05	-0.01	-0.00			
	(0.01)	(0.26)	(0.31)	(0.64)			
(3)	0.05***	0.04	-0.01		-0.00		
	(0.01)	(0.27)	(0.22)		(0.55)		
(4)	0.05***	0.04	-0.01			0.00	
	(0.01)	(0.30)	(0.33)			(0.86)	
(5)	0.04*	0.03	-0.01**				0.06
	(0.06)	(0.37)	(0.04)				(0.18)
(6)	0.04*	0.03	-0.01*	0.00	-0.00	-0.01	0.08
	(0.07)	(0.54)	(0.07)	(0.60)	(0.45)	(0.70)	(0.18)
Period 1760-1850							
(1)	0.08*	0.10	-0.01				
	(0.07)	(0.22)	(0.24)				
(2)	0.08*	0.10	-0.01	-0.00			
	(0.06)	(0.26)	(0.44)	(0.87)			
(3)	0.08*	0.08	-0.01		-0.00		
	(0.07)	(0.28)	(0.11)		(0.69)		
(4)	0.08**	0.10	-0.01			-0.01	
	(0.02)	(0.21)	(0.26)			(0.91)	
(5)	0.09**	0.13	-0.04**				0.70**
	(0.04)	(0.89)	(0.05)				(0.05)
(6)	0.10**	0.04	-0.05**	-0.00	-0.00	-0.07*	1.03**
	(0.04)	(0.74)	(0.03)	(0.33)	(0.83)	(0.08)	(0.03)

Table 3.11: Estimates of labour productivity growth in the agricultural sector (eq. 3.10 & 3.11); output data corresponds DC and X= Total printed books.

	$\ln (X/Q)_t$	$\Delta \ln X_t$	$\Delta \ln POP_t$	$\Delta \ln (M/Y)_t$	$\Delta \ln TO_t$	$\ln UNC_t$	$\ln LE_t$
Period 1700-1850							
(1)	0.06***	0.06	-0.01				
	(0.01)	(0.21)	(0.24)				
(2)	0.06***	0.06	-0.01	-0.00			
	(0.01)	(0.22)	(0.30)	(0.68)			
(3)	0.06***	0.05	-0.01		-0.00		
	(0.01)	(0.26)	(0.18)		(0.57)		
(4)	0.06***	0.06	-0.01			0.00	
	(0.01)	(0.26)	(0.30)			(0.86)	
(5)	0.04*	0.05	-0.01**				0.06
	(0.08)	(0.26)	(0.05)				(0.22)
(6)	0.04*	0.04	-0.01*	0.00	-0.00	-0.01	0.08
	(0.09)	(0.44)	(0.08)	(0.61)	(0.47)	(0.71)	(0.20)
Period 1760-1850							
(1)	0.08*	0.11	-0.01				
	(0.06)	(0.22)	(0.11)				
(2)	0.08**	0.11	-0.01	-0.00			
	(0.05)	(0.27)	(0.29)	(0.92)			
(3)	0.08*	0.09	-0.01**		-0.00		
	(0.07)	(0.30)	(0.02)		(0.71)		
(4)	0.08**	0.11	-0.01			-0.01	
	(0.02)	(0.20)	(0.16)			(0.91)	
(5)	1.00**	0.03	-0.04**				0.67**
	(0.03)	(0.73)	(0.02)				(0.04)
(6)	1.00**	0.06	-0.05**	-0.00	-0.00	-0.07*	1.02**
	(0.02)	(0.66)	(0.02)	(0.35)	(0.84)	(0.09)	(0.03)

Table 3.6 to Table 3.8 show the estimates of labour productivity growth in the agricultural sector using agricultural output data of Clark, which is tested against different measures of innovative activity (*X*), population growth and other control variables. The first half of each table shows the estimation results for the period 1620-1850 and latter half shows for 1760-1850 which covers the period of

the First Industrial Revolution. Following the estimation results, it is observed that in all above cases, the coefficient of the research intensity (*X/Q*) variable (column 2) is highly significant for the agricultural sector. Population growth, however, shows a negative sign in a few cases, and came out insignificant in the estimation results using GC's output data. As far as the control variables are concerned, in all cases research intensity is highly significant indicating the results are robust to different control variables. The coefficient of growth in innovative activity ($\Delta ln\ X$) came out negative in all estimation results in Table 3.6 to Table 3.8, which shows no support for semi-endogenous growth theory.

With DC output data, which is shown in Table 3.9 to Table 3.11, the research intensity variable (*X/Q*) is again found to be significant in all cases for both sample periods 1620-1850 and 1760-1850. This supports the Schumpeterian model in explaining the labour productivity growth in the agricultural sector. But growth in innovative activity ($\Delta ln\ X$) is insignificant, which shows no support for the semi-endogenous growth model. Although the coefficient of population growth is insignificant in a few cases, population growth drag is clearly visible on labour productivity growth, which carries a negative sign in front of the coefficients in both sample periods for different measures of technological progress. The results are robust to the estimation results of the research intensity variable in both sample periods with respect to the addition of control variables.

Overall results from Table 3.5 – Table 3.10 offer some important insights: 1) the importance of innovations in the labour productivity growth of the agricultural sector in 1620-1850 Britain, supporting the claim of Overton (1996a; 1996b); 2) Schumpeterian growth theory can explain agricultural labour productivity growth sufficiently well in the period 1620-1850 and also in the period of the First Industrial Revolution of 1760-1850. This is quite consistent with the findings of the second chapter of this thesis, where it has been shown that among modern endogenous growth theories, the Schumpeterian model can provide better explanations of British growth in the period 1620-2006; 3) The results are robust in regard to different data sources available for that period. Using two different sources of agricultural output data to measure the labour productivity (GC and DC), in both cases the Schumpeterian model was found to be consistent with the developments in the agricultural sector in the period 1760-

1850. 4) Lastly, the presence of population growth drag is visible to some extent in the agricultural sector, with a consistent negative sign in front of the coefficient in the estimation results of DC. Clark (2002) himself does not give much weight to the importance of innovative activity in the agricultural sector during the First Industrial Revolution period. Thus these results are really important because for the first time it is being shown that his agricultural output data itself is sensitive to the research intensity variable, following the Schumpeterian model, not only at the onset of the First Industrial Revolution around 1760s, but also in the period 1620-1850 for British agriculture.

3.7. Conclusion

The findings of this chapter are important in the literature of economic growth and also in the history of the British economy. First, results show that technological progress was a determining factor in improving the labour productivity growth in British agriculture during the period 1620-1850.

Second, within the confines of second generation endogenous growth models, the results show that the Schumpeterian growth model is better able to explain the technological progress as compared to the semi-endogenous growth model. The results are robust to different control variables and also to two different sources of data available for that time. These findings are consistent with Mingay (1963), Chambers and Mingay (1966), Deane (1969) and Overton (1996a; 1996b) who argue that an Agricultural Revolution and an Industrial Revolution occurred simultaneously. Third, this chapter empirically tests the demographic transition in sectoral levels at the time of industrial revolution period and found more support in favour of domestic factors, such as technology, in expanding the growth process in the agricultural sector. These results are consistent with the findings of Greasley and Oxley (1998b) where they show that domestic factors played a major role in forming the Industrial Revolution.

Fourth, in the labour productivity growth estimation results, although the coefficient of population growth did not come out significant, the sign of the coefficients is consistently negative in the estimation results of agricultural output calculated by Deane and Cole, in both sample ranges of 1700-1850 and 1760-1850. This indeed shows support in favour of the theoretical predictions made in section 3.3 that diminishing returns to land can act as a growth drag for labour productivity growth when land is a fixed factor of production. This is again consistent with the findings of the second chapter of this dissertation where it has been shown that, in presence of land as a fixed factor of production, population affected growth negatively while innovative activities influenced growth positively throughout the period of British growth from the seventeenth century onwards.

Finally, another major contribution of this study is the use of 'number of technical farming books published' as an alternative measure of innovative activity in agriculture other than 'patent counts'. Empirical results in section 3.5 are consistent with the use of agricultural patent counts and also with the use of number of technical farming books published. In fact, the values of the coefficients of the research intensity variable using number of technical farming books are higher and close to one as compared to patent counts in the productivity growth estimations in Tables 3.6 – Table 3.11. This shows the effect of technical farming books as a measure of innovative activity is bigger and hence perhaps a superior indicator to patent counts.

Although by the end of 1850 more people in Great Britain were engaged in manufacturing industries than in agriculture, the role of innovative activities cannot be ignored in expanding the labour productivity growth in the agricultural sector. When there is technological advancement in one major sector in the economy, it has positive spillover effects in other major sectors as well. Technological advancements in agriculture, transport, manufacture, trade and finance, all jointly made the period 1760-1850 difficult to match with any other time periods in history. This was not only a period of higher output but also a period of higher returns from investing in R&D. Ashton (1964) comments on '*innovation*' that it is a process, which once gets started, tends to accelerate. This further attracts more people to the market, bringing higher profits for everyone who is a part of this new liberal system. List of new patents, higher farming techniques with enclosure of land, higher output and productivity are evidence that show agriculture was not much lagging behind industries in adopting this new pace of development along time.

Compared to sixteenth or seventeenth century Britain, by the end of 1850 the standard of living associated with higher productivity has increased in the overall economy. Deane (1969) describes this event as *"Over the century that ended in the 1850's product per head is estimated to have multiplied nearly two and half times in Britain, and this brought with it more than doubling of the national standard of living (pp-266)."* Thus the role of agriculture during the First Industrial Revolution was significant. By 1850, intensive farming was already introduced in various regions of Britain and new artificial fertilizers were coming into the market. Overton (1996a) in the concluding chapter of his book mentions that both economic integrity and diversity were present in British agriculture by the mid-nineteenth century and better opportunities for innovation and enterprise led to the Agricultural Revolution. While better farming techniques helped the farmers to be less dependent on soil characteristics and created fewer regional differences, economic integration and commercialization encouraged diversity in the economy. Certainly the underlying force was innovations in both small and large farms that helped in advancing the integrity in farming and also gave the initiative for commercialized agriculture. Thus, these events are neither myths nor mysteries in the history of mankind, but were influenced largely by simultaneous increases in research intensity in all major sectors in the economy.

3A. Data Appendix

Patents issued: data on the number of agricultural patents issued over the period 1620-1850 are taken from Sullivan (1984, Table 1, p 274). The data points are given for every decade starting from 1611 to 1850. All the benchmark years (10-year data) have been interpolated to obtain a complete annual series for the period 1620-1850. Sullivan (1984) compiles this series from a subject index of patents issued in Britain provided by Woodcroft (1857). All patents given in Woodcroft (1857) under the heading ‘Agriculture’ were included in his series and the data were carefully checked so that each patent is counted only once. The following patents were included under agriculture: ‘Cutting Vegetable Substances’, ‘Grinding’, ‘Cutting’, ‘Crushing Corn and other grain’, ‘Manure’, ‘Farm and Dairy Process Apparatus’, ‘Farriery’ and ‘Medical treatment of Animals’. Patents under the heading ‘Water and other Fluids – Draining Land and Mines’ were included unless the patent referred was specifically used for other than draining land, for example, used for draining mines instead of land.

Technical books on English farming: ‘number of titles of technical farming books published’ in the period 1620-1850 is taken as an additional measure of innovative activity in the agricultural sector. This is taken from Sullivan (1984), Table 1, page 274. The data points are again for every decade starting from 1521 to 1913. The benchmark years are interpolated to get the annual series in the period 1620-1850. The number of titles of technical manuals published was divided into First printed and total printed numbers, where the later shows the reprinting but updated versions of the earlier books. Sullivan (1984) compiles this data from Perkin’s bibliography (Perkin's, 1932). Subjects that were included as technical farming books were agricultural chemistry, botany, grasses and weeds, drainage, improvements, weights and measures, entomology, and biography. Excluded are manuscripts, books on foreign and colonial agriculture, translations, serials, journals, catalogs, books on general chemistry and botany, forestry and timber, gardening and horticulture, surveying and land management, farriery and veterinary, law, cider, orchards, poultry, bees, goats, farm architecture, and agricultural politics and economics (Sullivan, 1984, page 282).

GDP: Two sources of real GDP are considered in the period 1700-1850. The first source of real agricultural output is Clark (2002), Table 5, page 16. Clark (2002) deflates the nominal GDP with agricultural price index compiled by him in Clark (2004).The whole series was rebased to 1850 to maintain consistency with the other series. The second source is Deane and Cole (1962), Table 19, page 78, where index number of real output of Britain is calculated in the period 1700-1800 for every decade. For 1800-1850, the nominal agricultural income of Deane and Cole (1962), Table 37, page 166 is used and then the series is deflated using agricultural part of the Rousseaux index, collected from Mitchell (1988), Table ‘*prices 3*’, page 722. The later series is spliced up with the earlier one and is rebased to 1850 to get a complete annual series in the period 1700-1850.

Labour: Agricultural labour force for 1620-1850 is taken from Clark (2002), Table 3, page 12, measured as number of males in agriculture (preferred estimates). The data points are given in Clark (2002) for every decade in the period 1521-1913. The benchmark years are interpolated to get a complete series in annual basis.

Population: In the period 1801-1850 population includes England and Wales, Scotland and Ireland. The population series is spliced with the population of England in the period 1620-1801 due to unavailability of data for the whole UK. The sources are Mitchell (1988, pp 7-14), for the period 1620-1829, which are compiled from Wrigley and Schofield (1981), and the online database of Maddison (available at http://www.ggdc.net/maddison/) for the period 1830-1850.

Trade Openness: Trade openness is measured as the sum of exports and imports over nominal GDP. Before 1697, the series is kept constant at the 1697 level due to data unavailability. Trade data are available for the years 1697-1771 for England and Wales, 1772-1795 for the Great Britain and 1796-1944 for the UK. The latter series is spliced upward to obtain a complete series from 1697-1850. The source is from Mitchell (1988), pp 448-454). The nominal GDP data for Britain are obtained from Clark (2001), Table 3, pp. 19-20), which are available on a decennial basis from 1259/60 to 1869/70. Missing data are interpolated to derive an annual series over the period 1620-1830. For the period 1830-1850, Maddison's data are used (available online at: http://www.ggdc.net/maddison/).

Life Expectancy: data on life expectancy at birth are compiled from Wrigley *et al.* (1997) for the period 1620-1837 and from the Human mortality database (available at: http://www.mortality.org/) for the period 1837-1850.

Macro uncertainty: Five years' standard deviation of inflation. Inflation is constructed as the annual growth rate of consumer price index (CPI) series. CPI data for the whole period 1700-1850 is collected from London Wages, Prices & Living Standards: The World Historical Perspective (average of London and Oxford) compiled by Robert Allen. This can be found online in: http://www.economics.ox.ac.uk/Members/robert.allen/WagesPrices.htm

Financial Deepening (M/Y): financial deepening is measured as the sum of notes in circulation and deposits in commercial banks and savings banks divided by economy-wide nominal GDP. Monetary aggregate data are available from 1750 onwards in Mitchell (1988). Data for the period 1620-1749 are geometrically extrapolated backward using the available data. The source for nominal output is as mentioned before (see trade openness).

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Chapter 4

AMERICAN TAKE-OFF AND THE BRITISH FALL, PRODUCTIVITY GROWTH RECONSIDERED

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"After take-off there follows, then, what might be called the drive to maturity. There are a variety of ways a stage of economic maturity might be defined; but for these purposes it is defined as the period when a society has effectively applied the range of (then) modern technology to the bulk of its resources."

- Rostow, 1959, page 8.

4.1. Introduction

Following the industrial revolutions and the Victorian era of prosperity, Britain was termed the *'workshop of the world'*, yet by the end of the nineteenth century the technological leadership had passed on to the US. Consequently, this raises the question, why in America. What helped this economy to flourish so quickly? What went wrong that the British productivity lead could not be maintained? Although the questions have been of much interest to economists for many decades, the nature, timing and causes of the American economic triumph over Europe have remained open issues.

In the seminal work of Habakkuk (1962) it is argued that labour-saving technology was the key to American leadership from the early twentieth century. Labour supply was scarce and inelastic in the US in the late eighteenth century; hence an American entrepreneur with a given amount of capital had a greater incentive than entrepreneurs in Britain to replace labour with capital. Although a mechanized method justifies the saving of capital and labour per unit of output in both economies, American labour was saved at the expense of an increase in capital per unit of output. This worked as a greater incentive in the US compared to their English counterparts. Habakkuk (1962) defines this mechanism that the US adopted at the start of the twentieth century as capital-intensive technology.

However this still does not make clear why British manufacturing industries, which had already experienced industrial revolutions in the eighteenth and nineteenth centuries, lagged behind the US in terms of technological progress in the twentieth century. The general argument put forward by Habakkuk (1962) was that in Britain there was a deeply entrenched social system that limited social mobility and worked against its own entrepreneurs. Although there were desires to adopt new technologies, the differences came in the ability to do so, because of power and prestige and less incentives towards business. Moreover, slow growth in demand of British exports in the last three decades of the nineteenth century gave few opportunities for growth in new technologies, whereas America, in addition to its large domestic market, had already started to take over Britain in the export market with new and advanced manufactured goods.

Rosenberg (1981), Nelson and Wright (1992), Abramovitz and David (1996) also support the arguments of large domestic market and abundant natural resources in the US were the main factors behind the take-off. Rosenberg (1981) argues that America, which was initially an importer of technology from Europe, was a rapid adopter of technologies that suited their economic needs and moreover they were highly skilled at improving upon the old technologies to meet their own domestic requirements. In the nineteenth century the American economy was pushed in a different direction as compared to the economies of Western Europe, by their resource endowment and demand conditions. Rosenberg (1981) proposes that the principal demand factor behind this high growth was the rapid rate of population growth, both naturally and due to immigration. This was further enhanced by a richer transportation system and an abundance of natural resources with pre-dominance of the agricultural sector. From the supply side, technology from Europe and a plentiful supply of natural resources helped the economy to grow at a faster rate than Europe.

Abramovitz (1986) and Abramovitz and David (1996) gave a broad picture of the US leadership in terms of *technological gap* and *social capability* which defines the potentiality of a country to catch-up in productivity growth rates. Social capability of a country covers general education, technical competence in commercial, industrial and financial institutions, and political and social characteristics influencing risk and rewards from economic activities. In the convergence mechanism of the US and Europe, Feinstein (1988) stresses that technical progress of an economy is not confined only to mechanical innovations, but innovations in corporate structures, management techniques, the developments of capital markets and systems of industrial remuneration are equally important. In the same light, in more recent studies, Gordon (2002, 2004) emphasize political unity, greater material intensive manufacturing goods, and a set of marketing innovations as the main factors leading to the US to rise after 1870. After 1913, with the First World War, Europe lagged further behind because of larger negative effects from wars and economic chaos. Then after 1950, the European catch up was rapid with late exploitations of inventions and erosion of America’s early advantage.

To explain these events through the lens of economic growth theories, Romer (1996) claims that resource abundance interacted with scale to create the endogenous technological lead in manufacturing in the US that continued in the twentieth century. Kocherlakota and Yi (1997) empirically test the features of exogenous and endogenous growth models, with data spanning over more than hundred years for the US and the UK and found that policy implications can affect growth rates in the long run, favouring the characteristics of the endogenous growth models. Conversely Crafts *et al.* (1992) emphasize that the catch-up events are not automatic, rather institutional factors, rent seeking, bargaining and politics play the key roles. Their paper suggests that the evidence points away from the new growth theories where much concentration is on factor accumulation. Crafts (1998) further argues that the overtaking was due to differences in natural resources and non-transferable technology, rather than coming from knowledge-based investments that the modern growth theories suggest.

Although economists have tried to explain the productivity lead of the US from various angles, not much attention has been given to sectoral decomposition of the two economies in the catch up period. Broadberry (1993) shows that the US was already enjoying a lead in the manufacturing sector over the UK from the early nineteenth century and labour productivity in agriculture at that time was almost same in both countries. In a more recent paper, Broadberry and Irwin (2006) using benchmark data from 1850 and 1910, show that labour productivity and per-capita income were higher in the UK in the mid-nineteenth century where they had a lead in the service sector. But in the later period UK passed this lead to the US, when a significant percentage of labour from the agricultural sector had shifted to the service sector in the twentieth century.

Temin (2002) reconsiders the rapid European growth in terms of catching-up with the American frontier after the Second World War, which he called '*The Golden Age of European Growth*'. Supporting Broadberry's view, Temin (2002) argues that catching-up is mainly the result of transferring economic resources from low-productive sectors such as agriculture to high productive sectors such as manufacturing. The rapid catch up in the Golden period after the 1950s by the European countries again signifies the transfer of labours from agriculture to the industrial sector, similar to what happened in the US at the start of the century. The normal catch-up worked thereafter and the equilibrium was restored around the 1970s, where the major advanced economies converged and marking the end of the rapid growth of the European nations.

Nevertheless the sources of growth in the advanced sectors that helped the US to take off and later forge ahead of the UK are still not clear. How important were innovations in the US sectors in this period? Is there any modern growth theory that can explain this technological shift? To answer these questions, ideally the aim should be to investigate the productivity gap and the gap in technological inputs between the two economies on a sectoral basis, where the latter is a positive function of the former. In each sector the following function should be examined $A_i^{US} - A_i^{UK} = \beta(X_i^{US} - X_i^{UK})$, where A_i is the productivity in sector i and X_i is the technology augmented input in the corresponding sector. But due to insufficient sectoral data, particularly for the UK before 1950s, the above equation cannot be empirically tested. Hence, the conclusions are based on examining the sources of productivity advancements in the twentieth century in the leading sectors of the US and corresponding sectors of the UK, where data is available.

In this study, two hypotheses are proposed that could potentially explain the phenomenon of 'America's catching-up and forging ahead of Britain': (1) US agricultural productivity increased to a greater extent due to increasing returns to land coming from enormous land resources and greater investment in technology augmented equipments; and (2) the US transport sector went through major transformations, for example there was intensive use of highways and trucking, which increased the productivity in the service sector. While the agricultural miracle intensified the take-off process, revolution in the service sector sustained the lead until 1970. Inadequate land resources in the UK as compared to the US, along with low investment in technology could not generate any advantage for the former. The hypotheses are discussed in more detail in section 4.3.

In this study, the year 1840 is chosen as the starting point, which marks two distinctive features: first, Britain was at the peak of industrialisation, and the American economy was not the technological leader; second, from circa 1840 the American economy started to experience a labour productivity lead in the manufacturing sector (Broadberry and Irwin, 2006). Moreover, except Broadberry and Irwin (2006), no other study has tried to analyse the event 'the US takeover' on a sectoral basis. However this study differs from Broadberry and Irwin (2006) because this is the first attempt to explain the technological sources behind the American economic surge through the lens of sectoral productivity growth comparison.

The next section provides a broad picture of the sectoral comparison of the two economies in the period 1840 to 2008. Section 4.3 will discuss the hypotheses, theoretical model and empirical methodology. Section 4.4 will discuss the data measurement issues and section 4.5 will present the results. Section 4.6 will throw some further light on the structure of the American agricultural growth to pin down the role of technology, equipment investments and labour growth over the period 1840-2008. Finally section 4.7 concludes.

4.2. Aftermaths of the British Industrial Revolution

The chronology of events for the UK and the US are as follows: the *'First Industrial Revolution'* in Great Britain, which most historians and growth theorists agree started somewhere between 1750 and 1780 and continued until 1850.[1] The subsequent period, 1850-1913, (until the emergence of the First World War in 1914), is called the *'Second Industrial Revolution'*.[2] These events were

[1] Refer to Ashton (1964), Hobsbawm (1968), Deane (1969) and Clark (2007) for discussions of the timing and source of the First and Second Industrial Revolutions in Britain.
[2] See footnote 1.

examined in more detail in earlier chapters of this thesis.[3] The period of industrialisation was interrupted by the First World War, which ended in 1918 (1914-1918), followed by Irish Independence War (1919-1921), the Great Depression (1930s) and later World War Two (1939-1945). All these events placed the UK and the whole of Europe in a position of severe economic down-turn. Historians recognize this period as the *'Second thirty-year War'* (1913-1945), as a result of series of wars in different location in Europe within this thirty years of time.[4] On the other-hand, from the start of the twentieth century, the US gradually leapfrogged the UK and other European economies to become the world economic leader. In spite of the world wars, the US managed to stimulate its own economy towards higher productivity growth.

This section provides a comparative sectoral analysis between the US and the UK in the period 1840 to 2008. Furthermore, this section introduces the relative importance of each sector that helped the US to catch-up and finally forge ahead of the UK. The contributions from agriculture and services in the take-off period are particularly important for the following reasons. The reasons behind the agricultural sector are: 1) the US had huge land resources compared to the UK, which signifies a greater importance of agriculture in the US; and 2) revolutionary impacts from technological innovations in the US agriculture, such as tractors, and other machinery and fertilizers that might have influenced agricultural productivity to rise at a faster rate than its counterpart in Britain. The role of tractors in US productivity growth has been put forward recently by White (2001), Olmstead and Rhode (2001) and Thirtle *et al.* (2002), who reached the same conclusion, that tractors were one of the most important innovations in the twentieth century that revolutionized the American rural economy.

The high productivity growth of the US service sector in the twentieth century has already been discussed by Field (2003, 2006) and Broadberry and Irwin (2006). The period between 1948 and 1973 is termed as the '*Golden Age*' of the US productivity growth where the private nonfarm economy grew at a

[3] Chapter 2 examines the roles of innovative activity and population growth during the British Industrial Revolution and also in the modern growth period (1620-2006) and Chapter 3 examines them for the British agricultural sector in the period 1620-1850.

[4] Feinstein *et al.* (2008), page 184.

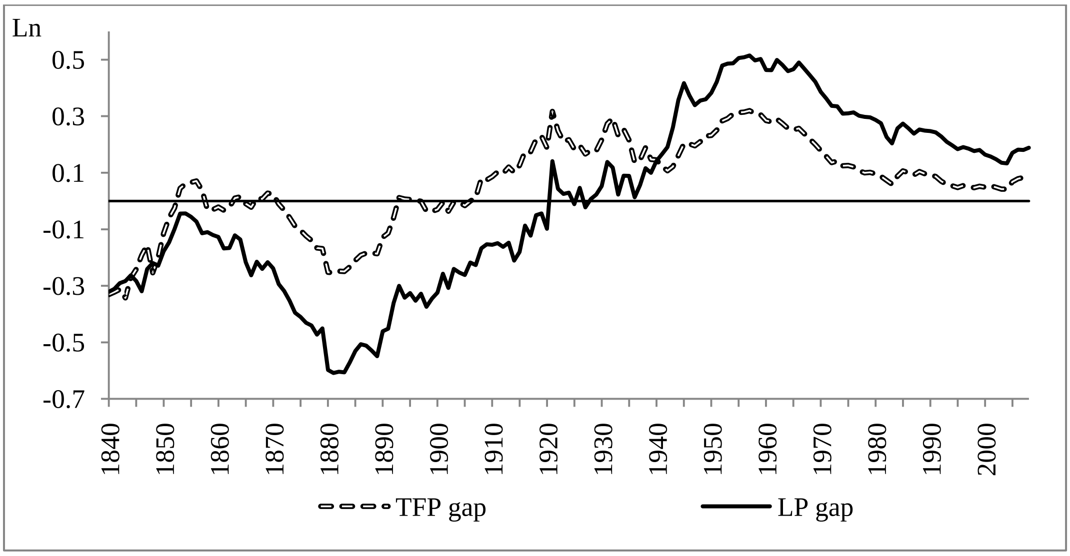
compound annual average rate of 2.88 percent per year (Field, 2007), with lower growth rates in manufacturing and higher growth rates in transportation, communications, and public utilities and, to a lesser degree, in retail distribution. Within this group, the transportation sector is noteworthy in the *Golden age period*, and accounted for around 6.4 percent of the private nonfarm TFP growth (Field, 2007).

Figure 4.1 below shows the comparative total factor productivity (TFP) and labour productivity (LP) of the US and the UK in the period 1840 to 2008. LP is measured using real annual GDP divided by employment times average annual hours worked for the whole economy. TFP is calculated following Chapter 2 of this dissertation, with land as a factor of production to capture the importance of the agricultural sector in the nineteenth century.[5] A more detailed discussion of how TFP is measured is in data measurement section 4.4. In figure 4.1 the vertical axis measures the differences in logarithmic values of TFP and LP of the two economies. In terms of catching up and convergence, when UK is the productivity leader, the series are negative and falling. Furthermore, when the series are still negative but rising, it means that the US has started to catch-up to the UK or the gap between the two economies is reducing. However, if the series are positive and rising, it implies that the UK has higher productivity growth than the US.[6]

[5] The share of the working population in agriculture was almost 96% in 1840 and 28% in 1913 in the US (US Historical Statistics), while in the UK it was 35% in 1840 and 13% in 1913 (Mitchell, 1988).

[6] Zero on the vertical axis implies that the productivities of the two economies have converged at that point in time. If at any point of time, both countries have the same productivities, then the ratio (US/UK) becomes 1. In other words, log (US/UK) =0.

Figure 4. 1: Comparative Total Factor Productivity gap and Labour productivity gap in the US and in the UK; 1840-2008



Note: The TFP gap is calculated as ln (TFP_{US}/TFP_{UK}) and the LP gap is calculated as ln (LP_{US}/LP_{UK}) on an annual basis. The sources are detailed in the data appendix.

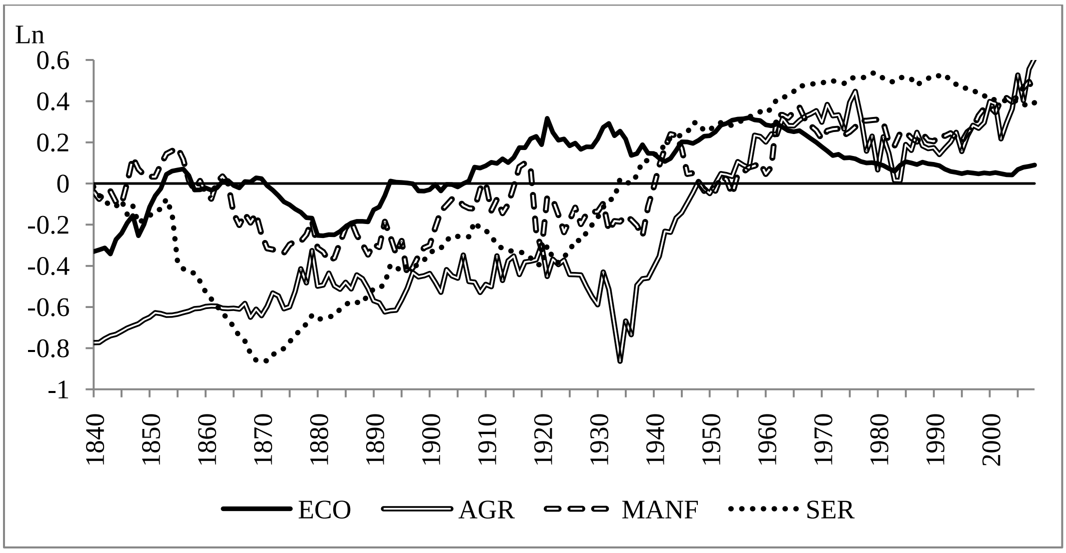
From figure 4.1 it is evident that America converged to Britain in the mid-nineteenth century, but could not maintain the lead due to the industrial revolutions that Britain was experiencing at that time. The LPs and TFPs of these two economies were almost the same around the 1860s and thereafter Britain lead for the next thirty years due to the industrial revolution it was experiencing in this period. Around 1880 and more prominently in the last decade of the nineteenth century, labour productivity growth in America began to increase at a faster rate than in Britain. This is demonstrated by the consistently increasing trend in the labour productivity gap in Figure 4.1 from 1890 that converged around 1920. Thereafter, the US maintained the lead over Britain until 1970. The period 1890-1920 can be termed the early take-off period for the US, as it led the foundation for America's dominance of the world economy in the twentieth century.

Comparing the TFP gap to the labour productivity gap in Figure 4.1, the US economy took the lead in TFP much faster than in labour productivity. In the First World War period (1914-1918), while the British economy lagged behind, Americans took the lead in terms of TFP growth. Thereafter, American TFP growth was constantly higher than Britain until 1970. In post World War II, due to technological catch-up by Europe, the TFP lead of the US slowed down and dropped below the labour productivity lead. Finally in the post 1970 period both LP and TFP gaps show a declining trend in favour of the UK, but they are still positive in the current decade.

In Figure 4.2 the sectoral TFP gap between the two economies in the period 1840-2008 is examined. While the service sector had a continuously increasing trend in favour of the US in the periods 1870-1910 and 1920-1970, the US agricultural sector shows a fluctuating but increasing trend in the periods 1840-1920 and 1935-1970. In the 1920s, the sharp decline in America's agricultural TFP lead was due to it being hit early by depression that hit the world in 1930s (Feinstein *et al.*, 2008, page 64). The US was one of the major agricultural exporters before and during World War I, when farmers used to borrow freely to expand their markets. However in the 1920s, debts of the farmers emerged ever larger as the agricultural prices fell and consequently the agricultural sector was caught by early depression.

The manufacturing sector TFP gap, on the other hand, had the early lead from the 1840s, but does not show any trend in the long run. Around 1915 manufacturing the lead was lowered due to World War One; however in the next decade the higher growth rate was again restored by the US. Field (2006, 2007) show that between 1919 and 1941, overall productivity for the US was high with a remarkable growth in the manufacturing sector in the period 1919-1929. In these ten years, TFP in the sector grew at a continuous compound rate of 5.12 percent per year, which accounted for around 84 percent of the growth of the residual in the private non-farm economy. Hence, in this decade, while US agriculture was already hit by depression, the manufacturing and service sectors continued to sustain the US productivity lead. Figure 4.2 shows that the US productivity lead in manufacturing increased sharply in the period 1915-1929, thus supporting the claims of Field (2006, 2007).

Figure 4. 2: Comparative Sectoral Total Factor Productivity Gap in the US and in the UK; 1840-2008

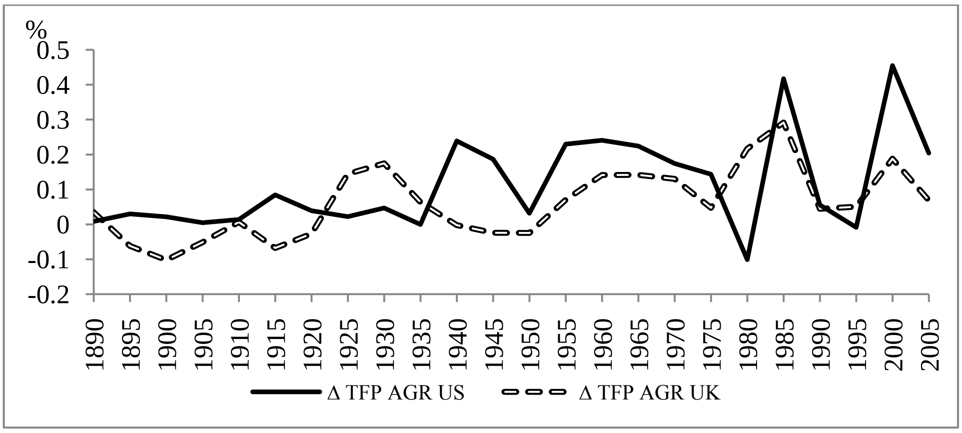


Note: Productivity gaps are measured as ln (TFP_{US}/TFP_{UK}) in each sector and for the overall economy. 'Agr', 'Manf' and Ser' denote the labour productivity gap in agriculture, manufacturing and service sector, respectively. 'Economy' shows the overall labour productivity gap in the economy.

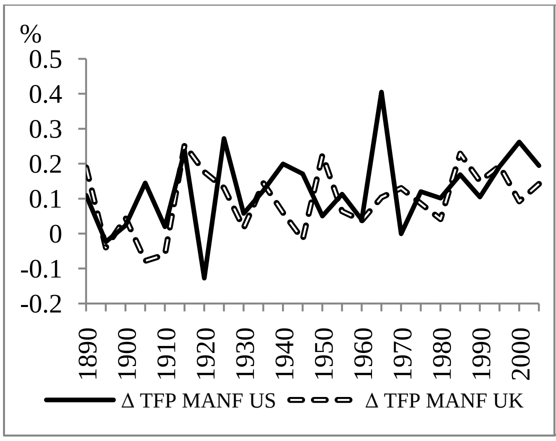
The first half of twentieth century can be identified from figure 4.2 as being more productive for both the agricultural and service sectors in the US, when the manufacturing sector gap was roughly constant. Oxley and Greasley (1995) and Greasley and Oxley (1998) compare the industrial production of these two economies on the basis of the catching-up hypothesis, focusing on the industrial gap in terms of per-capita income, real wages and industrial output per worker. They find no convergence in industrial output per worker between these economies. Their results support Figure 4.2, where the manufacturing TFP gap shows no sign of convergence between the economies.

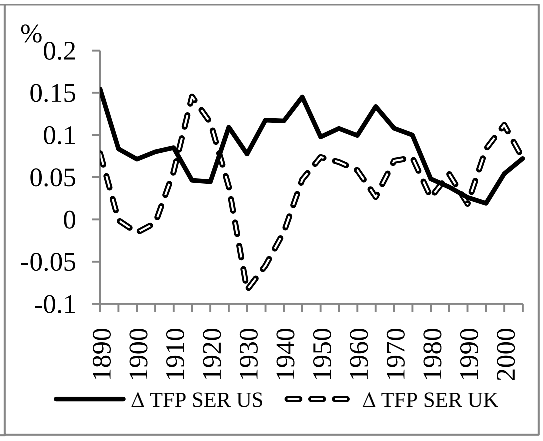
The similarity of the trends between the economy wide and agricultural sector TFP gaps at the start of the twentieth century shows that there was indeed a positive role played by agriculture in the catching up period. The claim of this study is further supported by the fact that the American economy always had the added advantage of vast land resources and technological advancement in farming as compared to Britain. Although these findings support Broadberry and Irwin (2006), who argue that the US manufacturing lead was maintained from the early mid nineteenth century and a more important role was played by the service sector, in addition to their claims, this study identifies that there was a positive role played by agriculture in the period 1840 to 2008. The gap was reduced steadily in the period 1840 to 1920 and also in the period 1935-1970. Since the start of the 1990s, while neither the manufacturing nor the service sector shows any high growth in favour of the US, only the agricultural sector has a lead, showing an upward trend in Figure 4.2.

Figure 4. 3: Sectoral TFP growth in the US and in the UK; 1890-2008



(a) Agricultural sector





(b) Manufacturing sector (c) Service sector

Note: The series are constructed in five year non-overlapping growth rates of annual data.

To examine further how the agriculture and service sectors influenced these two economies in the twentieth century, Figure 4.3 shows the US and the UK sectoral TFP growth in the period 1890 to 2008. For the agricultural sector (see Figure 4.3(a)) apart from the depression years of 1930s and in 1980, agricultural TFP growth is always higher in the US compared to the UK.

Although TFP growth in the US agricultural sector is high but fluctuating in the recent years, the growth rate remained mostly positive after 1910, which was further augmented from mid 1930s to 1970. Comparing the TFP growth in the service sectors in Figure 4.3(c), it is found that before 1970, TFP growth in the US is always higher than the UK, except in the decade 1910-1920. This shows that the service sector pushed the gap up in favour of the US in the middle years of the twentieth century. Finally, comparing the manufacturing sector TFP growth in Figure 4.3(b), in the first half of the twentieth century, not much can be concluded about the productivity lead for any particular economy. Combining the productivity growth rates of these three sectors in the two economies, it can certainly be argued that, in the first half of twentieth century, growth was higher in the agriculture and service sectors in the US compared to the UK, which helped in not only reducing the gap, but also put the American economy at the technological frontier.

The evidence above indicates that the productivity growth rates in the US were higher than those of the UK in all three sectors during most of the period 1890-1970. However, from the early twentieth century when the manufacturing lead was maintained at an almost constant level by the US, the agriculture and service sector leads were increasing in the first half of the twentieth century (see Figure 4.2 and Figure 4.3). Thus manufacturing productivity lead uphold the overall productivity growth at a higher level when in some periods there were negative shocks in agriculture and service sectors. This finding strengthens the claim in this study that it is agriculture and services that helped the US to takeover Britain at a faster rate. In the next section, based on the observations in this section, the sources of higher productivity growth are examined for the agricultural sector in the period 1840-2008 and for the service sector in the period 1910-2008. This section will also provide the theoretical backgrounds behind each of the hypotheses formed.

4.3. Model and Empirical Methodology

On the basis of the discussion in the previous section the following testable hypotheses are formulated:

H_1: In the first half of the twentieth century, US agriculture experienced increasing returns (IRS) to land together with technological progress in the form of R&D expenditure and various equipment investments. The UK failed to take any advantage in this sector due to the absence of adequate land resources as compared to the US and because of slow technological progress in agriculture.

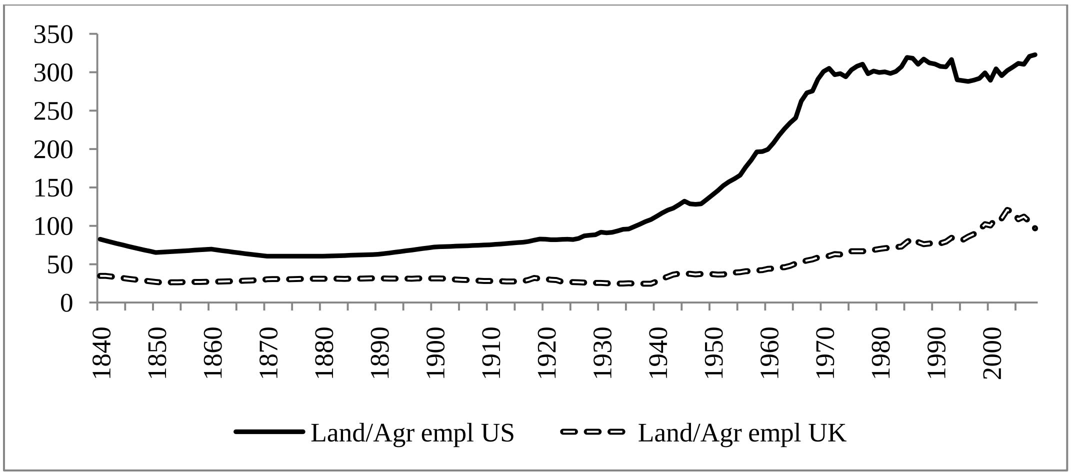
H_2: Before circa 1970, productivity growth in the US service sector was enhanced by various transformations in the transport system. The transport system was widened from a rail/water system to a rail/road/water system (Field, 2006; 2007).

4.3.1. The Role of the Agricultural Sector

As already discussed in the introduction, one of the main reasons behind high growth in the US in the late nineteenth and early twentieth centuries was abundant endowments of natural resources which were not present in Europe (Nelson and Wright, 1992). Rich and fertile agricultural land contributed to high fertility levels and hence to rapid growth of the domestic market. Additionally low food prices were generated due to this abundant supply, which resulted in a larger margin left over for the purchase of non-food products at any given income level (Rosenberg, 1981). The immense supply of agricultural land when employed with resource intensive methods of production, favourable to technological progress, would eventually increase the productivity in that sector (Nelson and Wright, 1992; Abramovitz, 1986).

Figure 4.4 below shows the land under cultivation per agricultural worker for the US and the UK in the period 1840-2008. While land per worker increased from 100 to almost above 300 in the US over the whole sample period, it only increased from 40 to 100 for the UK. This suggests that the US had more to gain from the mechanization of agriculture than the UK. Ruttan (2002) claims that progress in mechanical technologies in agriculture have been closely associated with the industrial revolution. In most developed countries, advancements in mechanical technology are a primary source of growth in labour productivity and advancements in biological technology are a primary source of growth in land productivity. He suggests that development of an economy comes with more emphasis on the research resource allocation of advanced biological and mechanical technology in agriculture.

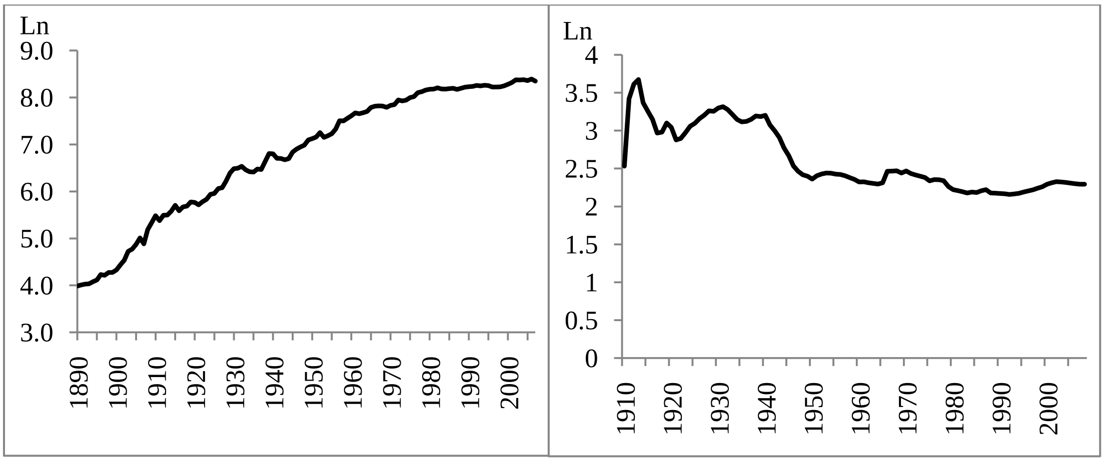
Figure 4. 4: Land under cultivation per worker; 1890-2008



Note: Land is measured as agricultural land in '000 acres. Agricultural employment measures total number of agricultural workers measured in '000.

This study argues that endogenous technological progress is generated in the agricultural sector through two different sources: (a) direct research resource allocation to agriculture, measured as real R&D expenditure and (b) technology augmented equipment investments such as in tractors and other farm machinery. The relationship between equipment investment and economic growth is tested by a series of works by De Long and Summers (1991), De Long *et al.* (1992), Auerbach *et al.* (1994), Greenwood *et al.* (1997), Temple (1998) and more recently by Gordon (2003) and Madsen (2005). The central argument behind the works of De long and Summers is that technology embodied machinery is a prime determinant of productivity growth of advanced nations in the post World War Two era. Their results are challenged by Auerbach *et al.* (1994) who argue that the long run growth effect of investment is not consistent in De long and Summers because of model misspecifications and biased sample selection. In contrast, Greenwood *et al.* (1997) establish that in the post war period, US productivity is advanced by technology embodied in capital goods. Along the same line, this study proposes that technology augmented capital goods started to influence US productivity growth in agriculture and services from late nineteenth century, long before the world wars started.

Figure 4. 5: Technology and number of tractors in agriculture



(a) US Real R&D expenditure; 1890-2008 *(b) Number of Tractors (US/UK), 1910-2008*

Note: Figure 4.5(a) and 4.5(b) are represented in natural logs of annual data. Figure 4.5(b) measures the logarithm of the ratio of absolute numbers of tractors in the US and the UK.

Figure 4.5(a) shows the real R&D expenditure in the US agricultural sector in the period 1890-2008 and 4.5(b) shows the logarithm of the ratio of number of tractors in the US and in the UK in the period 1910-2008. Figure 4.5(a) shows that the trend in real R&D expenditure in US agriculture is sharply increasing over time. The growth is more apparent in the period 1890-1980, after which it slowed down. On the other hand, in Figure 4.5(b) the ratio of number of tractors in the US and the UK is increasing in the first four decades of the twentieth century and is almost constant in the second half. This illustrates that the agricultural miracle is short lived and gradually growth in other sectors outpaces growth in the agricultural sector. Overall, Figure 4.5(a) and 4.5(b) demonstrate that in the first half of the century there is rapid growth in technological progress in US agriculture, both in R&D inputs and R&D augmented investments in farming. This evidently supports the hypothesis that, because of vast land resources and technological progress in the agricultural sector, the US achieved an additional advantage over the UK in the initial years.

The structural transformation in US agriculture in the mid nineteenth and early twentieth centuries can be best described with the help of a simple model by extending Gollin *et al.* (2007) and the model presented in chapter 2 of this dissertation. However unlike Gollin *et al.* (2007), technology is assumed to be endogenous in this model. Four stages of neoclassical production functions are defined in the agricultural sector following different technological processes, starting from the Malthusian world to the modern growth period:

$$Y_0 = T_0^{\alpha} L_0^{1-\alpha} \tag{4.1}$$

$$Y_1 = A_1 T_1^{\alpha} L_1^{1-\alpha} \tag{4.2}$$

$$Y_2 = A_2 K_2^{\beta} T_2^{\alpha} L_2^{\gamma} \tag{4.3}$$

$$Y_3 = A_3 K_3^{\beta} T_3^{\alpha} L_3^{1-\alpha-\beta} \tag{4.4}$$

Equation (4.1) can be best described as a Malthusian version of production in the agricultural sector when there is no effect of endogenous technological change. Here output at time ‘0’ (Y_0) is only a function of land (T) and labour (L). Due to lack of technological progress (normalized to unity), agricultural output cannot grow over time. Consequently, in the long run, agricultural output cannot sustain the growing population in the economy. Each unit of labour and capital will produce one unit of output to be consumed. This economy can be best described as the eighteenth and early nineteenth century US, when a large domestic market was not available and the only source of food was small domestic farming by each household. Considering land to be an input of production, which imposes diminishing returns, further slows down the growth process if no technological progress occurs.

In the next step, at period 1, agricultural output is responsive to endogenous technological progress. This is essentially an intensification of the traditional technology during early development in the agricultural sector, when a single farm produces more than its members can consume. At period 1, output is still only a function of land and labour, but reflects the introduction of farm equipment, chemical fertilizers or better irrigation systems. While equation (4.2) exhibits constant returns to scale in *T* and *L*, keeping the stock of TFP (*A*) constant, it shows increasing returns to scale in *T*, *L* and *A* together.

Following equation (4.3), the economy then experiences a growth miracle due to large increase in agricultural efficiency over a short period of time. The key difference between equation (4.2) and (4.3) is that the latter considers capital from the manufacturing sector as an additional input of production. Equation (4.2) is needed for this structural transformation to occur from the Malthusian world to the modern growth period (Gollin *et al.*, 2007). Hence, in period 2 due to technology augmented investment in agriculture, the efficiency of the agricultural sector at that point of time increases sharply. Further, these investments create increasing returns to land, once land is associated with higher technology augmented capital stock. Here it should be noted that the increasing returns to land are not due to spillover effects from other sectors, but due to technology induced capital investment in farming. Hence, while equation (4.3) exhibits increasing returns to scale in *K*, *T* and *L* keeping the stock of TFP (*A*) constant, i.e. $\alpha+\beta+\gamma>1$, it shows increasing returns to scale in K, *T*, *L* and *A* together.

An agricultural growth miracle can be richer than non-agricultural miracle, but only for a short period of time (Gollin, *et al.*, 2007). An agricultural revolution should be accompanied with advancement in other sectors, which later outpace the growth in that sector by moving its resources out of agriculture. Hence, after the short-lived agricultural growth miracle, the economy transforms into a normal neoclassical growth model in equation (4.4) with constant returns to scale in *K*, *T* and *L*, but exhibits increasing returns in *K*, *T*, *L* and *A* altogether. At this period of time (period 3), population growth drag will be present due to land as a fixed factor of production and then the growth of output per worker in the sector will be a race between endogenous technological progress and the growth rate of population. This can be further shown in the equations below:

Keeping land as a fixed factor of production, eq. (4.4) can be rewritten as

$$Y_3 = A_3 K_3^{\beta} \bar{T}_3^{\alpha} L_3^{1-\alpha-\beta} \tag{4.4a}$$

In per capita terms:

$$\frac{Y_3}{L_3} = A_3^{1/(1-\alpha)} \left[\frac{K_3}{Y_3}\right]^{\alpha/(1-\alpha)} \bar{T}_3^{\beta/(1-\alpha)} L_3^{-\beta/(1-\alpha)} \tag{4.5}$$

Taking logs and differentiating yields labour productivity growth along the balanced growth path:

$$g_y = 1/(1-\alpha) g_A - \beta/(1-\alpha) g_L \tag{4.6}$$

where g_y is the labour productivity growth in the agricultural sector, g_A is the growth in technology and g_L is the growth in the labour force in the agricultural sector. Here, the first derivative of the *K*-*Y* ratio is set to zero because the *K*-*Y* ratio is constant along the balanced growth path. However, if investment is embodied with technological progress, for example R&D augmented machinery, it generates positive effects on productivity growth, associated with the first term in equation (4.6). The second term in equation (4.6) is the population growth drag introduced by land as a fixed factor of production imposing diminishing returns in the long run. As long as the rate of technological progress outpaces the population growth drag, there is positive productivity growth in the sector. Assuming endogenous technological progress and following the second generation Schumpeterian growth model (Aghion and Howitt, 1998; Peretto, 1998; Howitt, 1999; Peretto and Smulders, 2002; Ha and Howitt, 2007; Madsen, 2008b; Madsen *et al.*, 2010), productivity is positively affected by increased levels of research intensity in the sector. The growth of ideas is a function of R&D inputs and other variables:

$$g_A = \frac{\dot{A}_t}{A_t}\lambda\left(\frac{X_t}{Q_t}\right)^{\sigma}, \; 0 < \sigma \leq 1 \qquad (4.7)$$

$$Q_t \propto L_t^{\kappa} \text{ in steady state}$$

where g_A is the growth of knowledge, λ is the research productivity parameter, X is the R&D input, σ is the duplication parameter which is 0 if all innovations are duplications and 1 if none are duplications, Q is the product proliferation variable which is assumed to grow at the same rate as population (L) in the long run and κ is the coefficient of product proliferation. $\kappa = 1$ in the second generation Schumpeterian growth model and $\kappa = 0$ in the first generation Schumpeterian growth model.

In the agricultural sector, the following growth model is regressed to examine: 1) the importance of innovations, 2) the importance of R&D augmented investment and 3) the role of population or labour growth in the US agricultural sector in the period 1840-2008:

$$\Delta \ln A_t^A = a_0 + a_1 \Delta \ln I_t^{EQ} + a_2 \Delta \ln\left(\frac{I_t}{S_t}\right)^{EQ} + a_3 \ln\left(\frac{X_t}{Q_t}\right)^{A} + a_4 \Delta \ln L_t^A + e_{1t} \qquad (4.8)$$

$$\Delta \ln y_t^A = b_0 + b_1 \Delta \ln I_t^{EQ} + b_2 \Delta \ln\left(\frac{I_t}{S_t}\right)^{EQ} + b_3 \ln\left(\frac{X_t}{Q_t}\right)^{A} + b_4 \Delta \ln L_t^A + e_{2t} \qquad (4.9)$$

where A_t^A represents the TFP in the US agricultural sector, I^{EQ} represents the R&D augmented investment in machinery and equipment and S^{EQ} represents the stock of machinery and equipment in the US agricultural sector. The second term in equations (4.8) and (4.9) deals with the importance of equipment investment as put forward by De Long and Summers (1991) and De Long *et al.* (1992) and later on by a series of authors mentioned in section 4.3. Although in empirical specification, De Long and Summers regress real gross investment in equipment divided by real output on productivity growth, Madsen (2005) shows that their specification could generate biased estimates and is sensitive to regression periods and countries included.

In addition to real gross investment in agriculture, equipment investment (I^{EQ}) is approximated by investment in tractors and investment in farm machinery in the US agricultural sector. Hence three types of investment were considered: tractors (I^{TRA}), machinery and equipment (I^{M}) and real gross investment in agriculture (I^{A}). Tractors were considered as a separate indicator in the study because it is believed that investment in tractors significantly changed the returns from agriculture in terms of increasing returns to land. Moreover, the data for tractors are available for the US from the early twentieth century, which gave the chance to exploit this data separately. In farm tractors and machinery both change in investment and change in investment to stock of farm machinery are considered, where the latter measures the effect of annual turnover of equipment investment on growth.[7]

The third variable predicts the Schumpeterian theory of economic growth where the R&D input (X_t^A) is approximated by real R&D expenditure in the agricultural sector and the product proliferation variable (Q_t^A) is approximated by real GDP (Y_t^A) and labour (L_t^A) times the TFP ($A_t^A.L_t^A$) in the agricultural sector, respectively. Change in R&D input following the semi-endogenous growth model is also tried in the regression estimates; however results for the variable were insignificant. Hence the variable is omitted from the empirical specification and the results are not reported here.[8]

However, while analysing the productivity growth of the agricultural sector, the first generation Schumpeterian growth model is considered in the empirical specification as well. Since the agricultural sector is less imitative in final products, product proliferation effects might not work fully. This allows for consideration of the first generation innovation-based endogenous growth models with constant returns to scale to knowledge but in the absence of product proliferation effects (Aghion and Howitt, 1992). Hence, in equation (4.7), this follows $\kappa = 0$. The fourth variable in equations (4.8) and (4.9) represents the

[7] The empirical specification captures both types of investment possibility (one direct change in investment and the other considering change in investment to stock). To my knowledge to date no other study has tried to see the impact of equipment investment on economic growth in a time series framework.

[8] The author can provide the results for the semi-endogenous growth model upon request.

population growth drag (following equation 4.6), which is measured as the change in employment. It is expected that a_1, a_2, a_3 will be positive and a_4 will be negative in equation (4.8) and b_1, b_2, b_3 will be positive and b_4 will be negative in equation (4.9). Equations (4.8) and (4.9) are estimated in ten year and twenty year overlapping differences of annual data to reduce effects of business cycles over time.

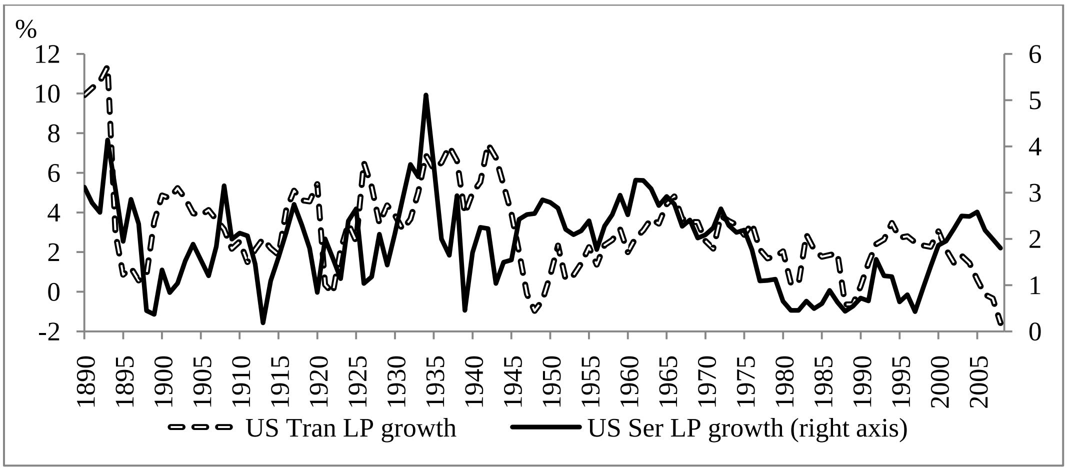
4.3.2. The Role of the Service Sector

In the service sector, a major difficulty lies in measuring the output and also the relevant price deflators. Griliches (1994) stated that economists do not know more about the sources of productivity growth because of certain difficulties arising from the distribution of output in the service sector, an example of which can be put forward as the ‘computer paradox’. Three quarters of computer or related investments in the late twentieth century US went into immeasurable or unobserved sectors and thus remained invisible from the data. Although the figures can show a decline in the US productivity growth in the last quarter of the century, the mismeasurements can underestimate the actual growth in productivity (Griliches, 1994).

One way of addressing this problem is to analyse those sectors within the service sector that are measurable correctly and contribute substantially to the service sector. Twentieth century US, which comprises the ‘*the Golden Age*’ period (1948-1973), persistently has high TFP growth in transportation, communication, public utilities and trade. Of these advanced sectors, growth in the transport sector in the twentieth century is particularly worth mentioning (Field, 2007).

The 1930s saw major development in streets and highway construction, along with a rapid expansion of trucks and automobile production. As a result the US transport system was transformed into a broader integrated system consisting of railroads, highways, waterways and pipelines. A high TFP growth rate in trucking and warehousing, and to a lesser degree, in railroads during the 1930s advanced the growth in this sector. Moreover productivity growth in the transport sector accounted for a large part in the overall productivity growth in the interwar years, about an average of 35% of total TFP in the period 1929-1941 (Field, 2006). Following the discussion in section 4.2, the second hypothesis predicts that, in the twentieth century, a large part of the enormous productivity growth in the US service sector was due to advancement in the transport sector.

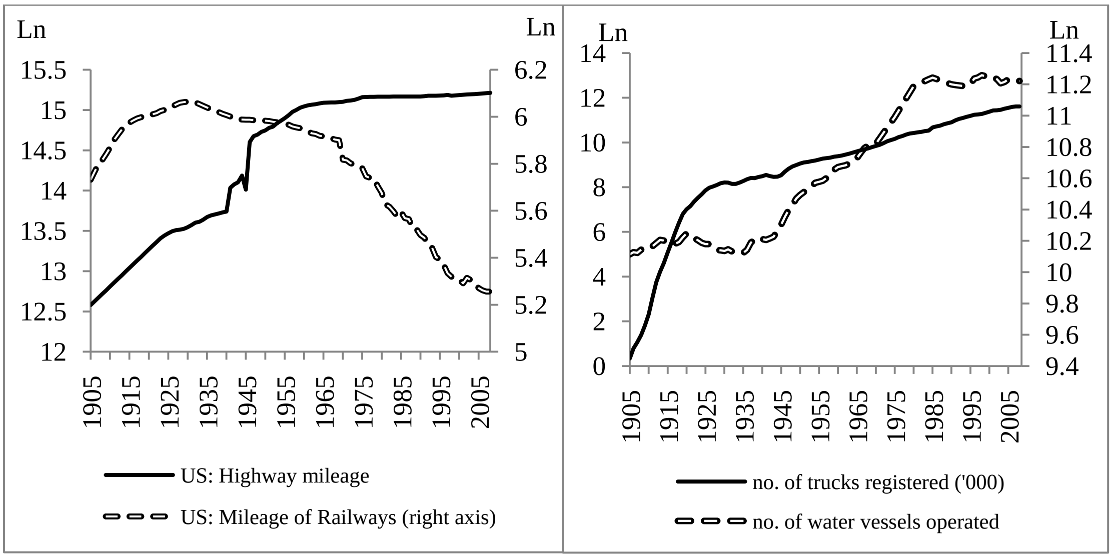
Figure 4. 6: Labour Productivity Growth in the US Service Sector and the US Transport Sector; 1890-2008



Note: The growth rates are computed in annual 5-Year moving averages.

Figure 4.6 shows the labour productivity growth in the service sector and transport sector in the US from 1890-2008. The US labour productivity growth rate in the transport sector in the first half of the twentieth century is always higher than growth in the service sector. The striking period of positive growth in the transport sector can be identified in the years 1910-1945, which includes the interwar years, supporting the view of Field (2006, 2007). In the whole sample period, growth in the transport sector exactly matches the growth rate of the service sector. The positive higher growth in the transport sector gradually slowed down in the second half of the century from circa 1970, reaching almost zero around the 1980s. This evidently shows that the slowdown in the US service sector productivity growth was responsible, to some extent, for the slow growth of the US in the last quarter of the twentieth century.

Figure 4. 7: Developments in the US Transport System; 1900-2008



(a) (b)

Note: Figure 4.7(a) shows development in the mileage of trucks and railroads. Figure 4.7(b) shows the number of trucks registered and number of water vessels operated. The figures are in natural logs of annual data.

Figures 4.7(a) and 4.7(b) show the development in the US transport sector from 1900-2008. Comparing the mileage of trucks and railways in Figure 4.7(a), while mileage of railways is falling steadily after the mid 1930s, mileage of highways is increasing up to 1970. Constructions of new highways and investment in mass production of trucks expanded the transport sector on the one hand and reduced the share of railways on the other. In the first three decades, the production of trucks increased sharply after which the rate dropped, however the numbers continued to go up throughout the century (see Figure 4.7(b)). In comparison, the waterways are more prominent in the latter half of the twentieth century after the 1950s, which became a common mode of transportation only in the recent years.

Overall, comparing the three modes of transport, namely railways, highways and waterways, railways were more effective only at the start of the twentieth century and their share was eaten away by roadways in the middle years with heavy investment in trucks and other motor vehicles. In the latter half of the century, highways were accompanied by waterways, while the share of railways continued to drop at the start of the twenty-first century. Hence, the most prominent and effective mode of transport that ruled the twentieth-century US transport sector was roadways.

To examine the roles played by technology augmented investment in the transport sector, such as trucks and construction of highways, in enhancing service sector productivity growth, the following growth regression model is estimated in the US service sector:

$$\Delta \ln A_t^S = \alpha_0 + \alpha_1 \Delta \ln I_t^{HWV} + \alpha_2 \Delta \ln\left(\frac{I_t^{HWV}}{S_t^{HWV}}\right) + \alpha_3 \Delta \ln I_t^{RW} + \alpha_4 \Delta \ln\left(\frac{I_t^{RW}}{S_t^{RW}}\right) + \alpha_5 \Delta \ln I_t^{WW} + \alpha_6 \Delta \ln\left(\frac{I_t^{ww}}{S_t^{ww}}\right) + \varepsilon_{1t} \qquad (4.10)$$

$$\Delta \ln y_t^S = \alpha_0 + \alpha_1 \Delta \ln I_t^{HW} + \alpha_2 \Delta \ln\left(\frac{I_t^{HWV}}{S_t^{HWV}}\right) + \alpha_3 \Delta \ln I_t^{RW} + \alpha_4 \Delta \ln\left(\frac{I_t^{RW}}{S_t^{RW}}\right) + \alpha_5 \Delta \ln I_t^{WW} + \alpha_6 \Delta \ln\left(\frac{I_t^{ww}}{S_t^{ww}}\right) + \varepsilon_{2t} \qquad (4.11)$$

where $\ln A_t^S$ and $\ln y_t^S$ are the TFP and labour productivity in the service sector, I_t^{HWV} and S_t^{HWV} are the investment in highway vehicles and stocks in highways vehicles, respectively, I^{RW} and S^{RW} are investment in railways and stock in railways, respectively and I_t^{WW} and S_t^{WW} are the investment and stocks of water vessels, respectively. The explanation behind the change in the ratio of investment to stocks variable is same as the measure of equipment investment in tractors in the agricultural sector, which shows the change in annual turnover of vehicles in the transport sector. In other words, this variable shows the actual increase in investment in vehicles, after taking depreciation into account by dividing the investment variable by its stock. If this change is positive over time, the actual investment in vehicles is higher and influences productivity growth in the service sector positively. Two different measures of roadways are considered in this study: trucks (*TRK*) and highways vehicles (*HW*). The reason for taking trucks as a separate indicator is that data on trucks are available separately and trucks are the most commonly used means of long distance transport of goods.

4.4. Data Measurements

4.4.1. TFP

Overall economy wide TFP in both economies was calculated considering the following Cobb-Douglas production function:

$$Y_t = A_t K_t^{\alpha} T_t^{\beta} L_t^{(1-\alpha-\beta)} \tag{4.12}$$

$$\Rightarrow \quad A_t = \frac{Y_t}{K_t^{\alpha} T_t^{\beta} L_t^{(1-\alpha-\beta)}} \tag{4.13}$$

where Y_t is real GDP, A_t is total factor productivity, K_t is capital, T_t is land and L_t is labour. While equation (4.12) exhibits constant returns to scale in *K*, *T* and *L* keeping the stock of TFP (*A*) constant, it shows increasing returns to scale in *K*, *T*, *L* and *A* altogether. Capital stock and real GDP are measured in purchasing power parity (PPP) units. In PPP conversion, 1990 is kept as the base year for real GDP and capital stock was calculated using 1996 prices of output and capital. Labour and capital's income shares are taken as 0.7 and 0.3, respectively following the standard literature and land's share is calculated as the share of agriculture in total output on an annual basis. Labour is measured as total number persons employed times annual number of hours worked on an annual basis, as opposed to population, to correct for changes in the labour force participation rate over time.

In deriving the sectoral TFP, due to the absence of a sectoral conversion rate, the economy wide PPP conversion rate is used to convert real GDP and capital stock in each sector. While capital, labour and land are the inputs of production in the agricultural sector, capital and labour are the inputs of production in the manufacturing and service sectors. In other words, there is no population growth drag present in the manufacturing and service sectors due to the absence of land as a factor of production. Average annual hours worked in the manufacturing and service sectors are assumed to be same as in the overall economy. The variable is kept constant for the agricultural sector since it is reasonable to believe that in agriculture there was no restriction on working hours of farmers unlike manufacturing and services.

Capital stock in TFP is calculated for each sector and in the overall economy for both the US and the UK using the perpetual inventory method. Two types of capital expenditures were considered – structures and capital and equipment with depreciation rates of 3% and 8%, respectively. For those sectors, where gross fixed capital formation is available, 8% depreciation rate is taken for computing the capital stock series from it. The data were collected from different sources and carefully spliced together to get a complete series on an annual basis. The details of the sources are in the data appendix in section 4A.2.

4.4.2. R&D in the US agricultural sector

R&D expenditure in agriculture is measured as total appropriations of research and development funds from federal and state sources to state agricultural research experimental stations and the US department of Agriculture. The nominal value is then deflated by the agricultural R&D deflator with base year 1980 calculated by Pardey *et al.* (1989) for the period 1890-1970. The real series is finally spliced with real agricultural R&D expenditure by public sector for the period 1970-2008, collected from the US department of Agriculture. Finally real R&D expenditure in the agricultural sector before 1890 was constructed by splicing the R&D expenditure series with agricultural patents applied in the period 1840-1890 to build a complete series on an annual basis in the period 1840-2008.

In construction of the US agricultural R&D deflator, Pardey *et al.* (1989) compute a Paasche index for the period 1890-1985, where three separate research inputs are considered: two capital expenditure categories – land and buildings, and capital and equipment, and a non-capital expenditure component which includes research labour and recurrent operating expenses. Labour and non-capital prices are proxied by university teachers' salaries; plant and equipment along with operating expense prices are proxied by the implicit price deflator for state and government purchases of goods and services. Finally land and building prices are proxied by the Handy-Whiteman index of public utility building costs. The authors use the current weighted (Paasche) price index formula, the surrogate price indices and the set of quantity weights derived from value-based factor shares to calculate the final agricultural research deflator for the US in the period 1890-1985.

4.4.3. Equipment Investments in Agriculture and Services

Two kinds of equipment investments are considered in the agricultural sector and three kinds in the service sector, each of which is specific to the corresponding sector only. In the agricultural sector, the investments are in tractors and farm machines. Total farm machinery includes tractors, motor trucks, automobiles, grain combines, corn pickers, pick-up balers, field forage harvesters, cotton pickers and number of milking machines. Production of tractors in the US and in the UK only starts from circa 1910 onwards. Data for total farm machinery is also available from circa 1910 onwards and since tractors are found to have the major share in total farm machinery, the data is assumed to zero before 1910. In addition to tractors and total farm machinery, real gross investment in agriculture is also included in the regression estimates as a separate indicator. In the service sector, three kinds of equipment investments corresponding to three different transport modes are considered. They are trucks and total highway vehicles for roadways, mileage of railways and water vessels for waterways.

To estimate how the change in turnover in investments affects sectoral productivity growth, change in investment to stock series for each of these equipment investments are incorporated separately in equations (4.8) and (4.9) for the agricultural sector and equations (4.10) and (4.11) for the service sector. To calculate the stock series from each flow series, the perpetual inventory method is used with annual 8% depreciation rate in equipment investment.

4.4.4. Measure of Research Intensity in the US Agricultural sector

Two measures of research intensity are constructed in the US agricultural sector following the definitions of Aghion and Howitt (1998), Peretto (1998), Howitt (1999), Peretto and Smulders (2002), Ha and Howitt (2007), Madsen (2008):

$$\frac{X}{Q}=\frac{R\,\&\,D_{\exp}}{Y_A}=\frac{R\,\&\,D_{\exp}}{A_A.L_A}$$

Research intensity is measured as R&D input (X) divided by the product proliferation variable (Q) in the agricultural sector. While real R&D expenditure in US agriculture is considered as the R&D input variable, two measures of product proliferation variable are considered: real GDP in the agricultural sector (Y_A) and agricultural TFP multiplied by the agricultural labour force ($A_A.L_A$).

4.5. Empirical Results

4.5.1. Test Results of hypothesis H_1

This section presents the empirical results from testing the first hypothesis, which states that, in the first half of the twentieth century, US agriculture experienced increasing returns (IRS) to land combined with technological progress in the form of higher R&D expenditure and various forms of R&D augmented investments. Tables 4.1 to 4.4 show the growth estimation results from the US agricultural sector following equations (4.8) and (4.9) in section 4.3. To reduce the effects from business cycles, both equations are estimated in ten year and twenty year overlapping differences of annual data in the period 1840-2008. While the results for twenty year differences are presented in the main text, the results for ten years differences are presented in appendix 4A.1. The main conclusions remain the same under both the ten and twenty year overlapping series.

Nine different models are estimated in each table following equations (4.8) and (4.9). The first three models in each table take into account the effects of population growth drag in the agricultural sector measured by change in agricultural labour force (row 1), change in investment in tractors (row 2), change in the ratio of investment to stock of tractors (row 4), and three different measures of R&D expenditure corresponding to first and second generation Schumpeterian growth theories. Following second generation Schumpeterian growth theories, models 1 and 2 include two different measures of research intensity (X_t/Q_t) [9]: R&D expenditure divided by real GDP in agriculture (row 7) and R&D expenditure divided by labour times TFP in agriculture (row 8). Model 3 follows the first generation Schumpeterian growth model, where the level of R&D expenditure (row 9) is considered in the absence of product proliferation effect. Models four to six estimate the same variables as in the first three models but instead of tractors these models consider change in investment of total farm machinery (rows 3) and change in the ratio of investment to stock of total farm machinery (row 5). Finally, models seven to nine estimate the effects of change in investment to stock of real gross investment in agriculture (row 6) instead of equipment investments. Real gross investment is considered in a separate regression model to avoid multicollinearity problems between equipment investments and real gross investments in agriculture.

[9] See Ha and Howitt (2007) and Madsen (2008b) for different measures of research intensity in an economy following the Schumpeterian model of economic growth.

Table 4. 1: 20-year annual estimates of US agricultural TFP growth

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$\Delta \ln L_t^A$	-0.35*** (0.00)	-0.35*** (0.00)	0.39*** (0.00)	-0.35*** (0.00)	-0.35*** (0.00)	-0.38*** (0.00)	-0.24* (0.08)	-0.22* (0.08)	-0.26** (0.03)
$\Delta \ln I_t^{TRA}$	-0.02* (0.09)	-0.02 (0.24)	-0.02 (0.13)						
$\Delta \ln I_t^M$				-0.04*** (0.01)	-0.03** (0.04)	-0.04** (0.02)			
$\Delta \ln \left(\frac{I_t}{S_t}\right)^{TRA}$	0.14* (0.09)	0.14* (0.09)	0.12 (0.13)						
$\Delta \ln \left(\frac{I_t}{S_t}\right)^{M}$				0.13** (0.03)	0.13** (0.05)	0.12* (0.07)			
$\Delta \ln \left(\frac{I_t}{K_t}\right)^{A}$							0.10** (0.02)	0.10*** (0.01)	0.10*** (0.01)
$\ln \left(\frac{R_t}{Y_t}\right)^{A}$	0.11*** (0.00)			0.11*** (0.00)			0.13*** (0.00)		
$\ln \left(\frac{R_t}{(A.L)_t}\right)^{A}$		0.10*** (0.00)			0.10*** (0.00)			0.12*** (0.00)	
$\ln R_t^A$			0.06*** (0.00)			0.07*** (0.00)			0.08*** (0.00)

Note: I^{TRA}, $(I/S)^{TRA}$, I^M, $(I/S)^M$, L^A, *(I/K)* are, respectively, investment to tractors, investment to stock ratio of tractors, investment to total farm machineries, investment to stock of total farm machinery, agricultural labour force (employment) and investment to stock in agriculture. *R, R/Y* and *R/(A.L)* are respectively R&D expenditure, R&D expenditure to real GDP in agriculture and R&D expenditure to (TFP times labour) in agriculture. The Newey-West corrected test statistic is reported to correct for serial correlation and heteroskedasticity. A constant is included in the regression, but not reported here. ***, ** and * show significance at the 1%, 5% and 10% critical levels respectively. Figures in parenthesis are p-values. The estimation period is 1840-2008.

Table 4. 2: 20-year annual estimates of US agricultural labour productivity growth

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$\Delta \ln L_t^A$	-0.79***	-0.78***	-0.80***	-0.78***	-0.77***	-0.77***	-0.65***	-0.62***	-0.64***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
$\Delta \ln I_t^{TRA}$	-0.02*	-0.02	-0.02*						
	(0.10)	(0.15)	(0.10)						
$\Delta \ln I_t^M$				-0.04***	-0.04**	-0.04***			
				(0.01)	(0.02)	(0.01)			
$\Delta \ln\left(\frac{I_t}{S_t}\right)^{TRA}$	0.17**	0.18**	0.17**						
	(0.04)	(0.04)	(0.04)						
$\Delta \ln\left(\frac{I_t}{S_t}\right)^{M}$				0.18***	0.18***	0.17***			
				(0.00)	(0.01)	(0.01)			
$\Delta \ln\left(\frac{I_t}{K_t}\right)^{A}$							0.10***	0.11***	0.11***
							(0.01)	(0.00)	(0.00)
$\ln\left(\frac{R_t}{Y_t}\right)^{A}$	0.04			0.02			0.06*		
	(0.15)			(0.17)			(0.06)		
$\ln\left(\frac{R_t}{(A.L)_t}\right)^{A}$		0.04*			0.03			0.06**	
		(0.10)			(0.13)			(0.02)	
$\ln R_t^A$			0.02			0.02			0.04**
			(0.17)			(0.20)			(0.03)

Note: see notes to table 4.1

The results in Tables 4.1 and 4.2 (and also in Tables 4A.1 and 4A.2 in appendix section 4A.1) confirm that the coefficients of changes to investment to stock of tractors (row 3) and total machinery and equipment (row 8) in agriculture are consistently positive and highly significant in both TFP and LP growth estimations. In other words, changes in turnover of tractors are positively affecting the productivity growth (both TFP and LP) in the agricultural sector. Furthermore is this turnover, creates increasing returns to land when supplemented with other inputs of production. The empirical findings support hypothesis H_1 of technology augmented investment in the agricultural sector. On the other hand, changes in investment in tractors and total machinery (rows 2 and 7) are either insignificant or have the wrong sign.

The results find support for both versions of Schumpeterian theory of economic growth for TFP growth estimations in tables 4.1 and 4.2. Coefficients corresponding to rows 4 and 5 show support for second generation growth models and coefficients corresponding to row 6 show support for first generation growth models. However, not much support for R&D expenditure in agriculture was found in the LP growth estimates in Table 4.2. Combining the TFP growth estimation results in ten year (see appendix Tables 4A.1 and 4A.2) and twenty year overlapping growth series (see tables 4.1 and 4.2), both measures of research intensity and the level of R&D expenditure are highly significant in all cases, showing technology advancement in the US agricultural sector in the twentieth century. There is strong evidence of negative effects of population growth drag in the US agricultural sector, which shows negative coefficients of labour growth (row 1). Hence, in the long run, land as a factor of production creates a labour growth drag and productivity growth is then sustained only by advancement in technological progress in the form of higher research intensity and technology embodied investments.

These findings support the claims of Schimmelpfennig and Thirtle (1994) of a significant relationship between R&D expenditure and productivity in the US agricultural sector. Using an Error Correction model and Johansen cointegration technique they found that, in the agricultural sector, TFP and R&D expenditure is cointegrated for the US and ten European countries in the period 1973-89 and for the UK in the period 1967-87. In America, as opposed to most of Europe, research intensity flourished more largely due to contributions from American universities from the early nineteenth century (Rosenberg, 2000). Rosenberg (2000) mentioned the Morrill Act of 1862, a system of land-grant colleges, which, together with the later introduction of the agricultural experimental stations, provided not only the basic infrastructure for generating new scientific knowledge but transmitted the knowledge to the local levels.[10] Undoubtedly the structure and performance of the American universities from the early nineteenth century gave the opportunity to do research-oriented work not only in agriculture, but in all sectors of the economy.

[10] Another example is the agricultural development of the Hybrid corn and study of genetics at the University of Connecticut Agricultural Experiment Station in the 1920s and at the Iowa State University in the 1930s.

Table 4. 3: Granger Causality tests between productivity growth and growth in Investment to stock of equipments in US agriculture

Null Hypothesis	F Stat	Null Hypothesis	F Stat
$\Delta\ln\left(\frac{I_t}{S_t}\right)^{TRA}$ does not GC $\Delta\ln A^A$	2.97** (0.05)	$\Delta\ln\left(\frac{I_t}{S_t}\right)^{TRA}$ does not GC $\Delta\ln y^A$	3.50** (0.03)
$\Delta\ln A^A$ does not GC $\Delta\ln\left(\frac{I_t}{S_t}\right)^{TRA}$	0.52 (0.60)	$\Delta\ln y^A$ does not GC $\Delta\ln\left(\frac{I_t}{S_t}\right)^{TRA}$	0.68 (0.51)
$\Delta\ln\left(\frac{I_t}{S_t}\right)^{M}$ does not GC $\Delta\ln A^A$	4.07** (0.02)	$\Delta\ln\left(\frac{I_t}{S_t}\right)^{M}$ does not GC $\Delta\ln y^A$	4.85*** (0.01)
$\Delta\ln A^A$ does not GC $\Delta\ln\left(\frac{I_t}{S_t}\right)^{M}$	0.00 (1.00)	$\Delta\ln y^A$ does not GC $\Delta\ln\left(\frac{I_t}{S_t}\right)^{M}$	0.03 (0.97)

Note: I^{TRA}, S^{TRA}, I^M, S^M, A^A and y^A are, respectively, investment in tractors, stock of tractors, investment in total machinery, and stock of total farm machinery. The series are 20 year overlapping growth series of annual data. Two lags are included in the tests. ***, ** and * show significance at the 1%, 5% and 10% critical levels, respectively. Figures in parenthesis are *p*-values. The estimation period is 1840-2008.

For a further robustness check and to check for any endogeneity bias between investment in equipments and productivity variables, table 4.3 shows the Granger causality tests between change in investment to stock of tractors and machinery and change in TFP and LP in the period 1840-2008 for twenty year overlapping growth of annual series. Results from table 4.3 confirm that only one-way causality exists between the variables and it runs from change in investment to stock of tractors/machinery to TFP and LP growth.[11] Overall, the empirical evidence in this section shows the positive significant effect of technology augmented investment in the US agricultural sector in the twentieth century.

Next, to learn whether similar market mechanisms worked in the UK agricultural sector in the period 1840-2008, comparable growth regressions are run using variables from the UK agricultural sector. Due to unavailability of data, the effects of R&D expenditure on productivity growth could not be examined in UK agriculture. Hence, the effects of change in R&D augmented investment such

[11] Granger causality tests were also performed between change in investment of tractors and machinery and TFP and LP growth, which were insignificant in all cases. This confirms that there is no relationship between change in investment and productivity variables in the case of the US agricultural sector.

as tractors and other farm machinery, real gross investment in agriculture and the effect of population growth with land as a factor of production are examined in Tables 4.4 and 4.5 using twenty year overlapping growth series. The growth estimations are also run using ten year overlapping growth series and the results are presented in appendix tables 4A.3 and 4A.4, the results of which are not different from the tables presented in the main text.

Table 4. 4: 20-year annual estimates of UK agricultural TFP growth

	(1)	(2)	(3)	(4)	(5)
$\Delta \ln L_t^A$	-1.03*** (0.00)	-1.04*** (0.00)	-1.10*** (0.00)	-1.10*** (0.00)	-1.19*** (0.00)
$\Delta \ln I_t^{TRA}$	-0.00 (0.85)	-0.01 (0.61)			
$\Delta \ln I_t^M$			0.08 (0.38)	0.12 (0.24)	
$\Delta \ln \left(\frac{I_t}{S_t}\right)^{TRA}$	-0.30*** (0.00)	-0.29*** (0.00)			
$\Delta \ln \left(\frac{I_t}{S_t}\right)^{M}$			-0.19 (0.71)	-0.18 (0.71)	
$\Delta \ln \left(\frac{I_t}{K_t}\right)^{A}$		-0.03 (0.45)		-0.05 (0.29)	-0.02 (0.70)

Note: I^{TRA}, $(I/S)^{TRA}$, I^M, $(I/S)^M$, L^A, (I/K) are respectively investment to tractors, investment to stock ratio of tractors, investment to total farm machinery, investment to stock of total farm machinery, agricultural labour force (employment) and investment to stock in agriculture. The Newey-West corrected test statistic is reported to correct for serial correlation and heteroskedasticity. A constant is included in the regression, but not reported here. ***, ** and * show significance at the 1%, 5% and 10% critical levels, respectively. Figures in parenthesis are p-values. The estimation period is 1840-2008.

Table 4. 5: 20-year annual estimates of UK agricultural labour productivity growth

	(1)	(2)	(3)	(4)	(5)
$\Delta \ln L_t^A$	-1.59*** (0.00)	-1.58*** (0.00)	-1.04*** (0.00)	-1.04*** (0.00)	-1.61*** (0.00)
$\Delta \ln I_t^{TRA}$	0.02 (0.27)	-0.02 (0.37)			
$\Delta \ln I_t^{M}$			0.27*** (0.00)	0.28*** (0.00)	
$\Delta \ln \left(\frac{I_t}{S_t}\right)^{TRA}$	-0.06 (0.32)	-0.07 (0.23)			
$\Delta \ln \left(\frac{I_t}{S_t}\right)^{M}$			-1.20*** (0.00)	-1.20*** (0.00)	
$\Delta \ln \left(\frac{I_t}{K_t}\right)^{A}$		0.03 (0.22)		-0.02 (0.27)	0.04** (0.05)

Note: see notes to Table 4.4.

The results in Tables 4.4 and 4.5 suggest that there is no support for technology augmented equipment investment in the agricultural sector of the UK when compared with its counterpart in the US. The coefficients of the changes in the ratio of investment to stock of tractors or total agricultural machinery are either insignificant or show the wrong sign (rows 2 to 6). This evidence is quite intuitive because the UK does not have big land or arable areas as in the US; hence, it is less probable that increasing returns to land will work in the agricultural sector of the UK if accompanied with less advancement in technological progress. Schimmelpfennig and Thirtle (1999) compare the technological efficiencies in the United States and ten other European countries including the UK through a comparison of multilateral indices of agricultural TFP in the period 1973-93. While they find the US to have much more advanced research system and to be more active in agricultural R&D, the UK had fewer incentives to innovate and a lower TFP in the agricultural sector. The results of this study support their findings. However, there is strong evidence of population growth drag present in the agricultural sector of the UK with land as a factor of production. All the coefficients in row 1 of Tables 4.4 and 4.5 (and in appendix tables 4A.3 and 4A.4) are negatively significant in the period 1840-2008. Thus, apparently with little or no technological progress and in presence of population growth drag, productivity growth will automatically cease in the long run.

Combining all results in this section it can be concluded that throughout the twentieth century, agricultural productivity was higher in the US compared to its counterpart in the UK because of higher technological progress and R&D embodied investment. Thus, they created increasing returns in US agriculture which further augmented the productivity growth in the first half of the twentieth century. The predominance of the agricultural sector and the presence of abundant land resources gave the US an edge over the UK at the start of the new century, which continued until 1970.

4.5.2. Test results of hypothesis H_2

The second hypothesis in section 4.3 states that, in the twentieth century, the US transport sector had major transformations from the start of the twentieth century, which augmented the productivity growth in the service sector until 1970. Considering three wide ranges of transport systems in the twentieth century US: roadways including trucks (*TRK*) and total highway vehicles (*HW*), railways (*RW*) and waterways (*WW*), tables 4.6 and appendix table 4A.5 show the productivity growth estimation results in the US service sector in the period 1910-2008 following equations (4.10) and (4.11) using twenty year (table 4.6) and ten year (presented in appendix table 4A.5) overlapping growth series.

Table 4. 6: 20-year annual estimates of US Service sector productivity growth

	$\Delta\ln I_t^{TRK}$	$\Delta\ln\left(\frac{I_t^{TRK}}{S_t^{TRK}}\right)$	$\Delta\ln I_t^{HW}$	$\Delta\ln\left(\frac{I_t^{HW}}{S_t^{HW}}\right)$	$\Delta\ln I_t^{RW}$	$\Delta\ln\left(\frac{I_t^{RW}}{S_t^{RW}}\right)$	$\Delta\ln I_t^{WW}$	$\Delta\ln\left(\frac{I_t^{WW}}{S_t^{WW}}\right)$
Dependent variable: $\Delta\ln A_t^S$ (TFP growth)								
(1)	-0.08***	0.11***						
	(0.00)	(0.01)						
(2)			-0.08**	0.11*				
			(0.03)	(0.10)				
(3)					0.61*	-0.56*		
					(0.06)	(0.10)		
(4)							-0.20	0.33
							(0.51)	(0.34)
(5)	-0.07***	0.12***			0.94***	-0.84***	0.06	0.01
	(0.00)	(0.00)			(0.00)	(0.00)	(0.31)	(0.93)
(6)			-0.13***	0.15***	1.09***	-1.05***	0.15	-0.11
			(0.00)	(0.01)	(0.00)	(0.00)	(0.09)	(0.36)
Dependent variable: $\Delta\ln y_t^S$ (LP growth)								
(1)	-0.08**	0.02						
	(0.05)	(0.79)						
(2)			-0.08	0.02				
			(0.27)	(0.85)				
(3)					0.62**	-0.45		
					(0.04)	(0.18)		
(4)							-0.31	0.39
							(0.39)	(0.34)
(5)	-0.07***	0.02			0.83***	-0.59**	0.08	-0.10
	(0.00)	(0.76)			(0.00)	(0.03)	(0.72)	(0.69)
(6)			-0.14***	0.07	1.04***	-0.86***	0.12	-0.19
			(0.01)	(0.47)	(0.00)	(0.01)	(0.61)	(0.50)

Note: I^{TRK}, S^{TRK}, I^{HW}, S^{HW}, I^{RW}, S^{RW}, I^{WW}, S^{WW} are, respectively, investment in number of trucks, stock in number of trucks, investment in number of highway vehicles, stock in number of vehicles, investment in railway tracks, stock in railway tracks, investment in number of water vehicles and stock in number of water vehicles. Natural log of twenty year overlapping difference of annual data is estimated. The Newey-West corrected test statistic is reported to correct for serial correlation and heteroskedasticity. The AR(1) term is included as an additional regressor in a few estimations to correct for serial correlation. A constant is included in the regression, but is not reported here. ***, ** and * show significance at the 1%, 5% and 10% critical levels, respectively. Figures in parenthesis are p-values. The estimation period is 1910-2008.

The first two columns in table 4.6 show the changes in investment in trucks and changes in the ratio of investment to stock of trucks (*TRK*), respectively. The next two columns measure the same variables for total highway vehicles (*HW*), and columns five and six measure them for railways (*RW*) and, finally, the last two columns measure them for water vehicles (*WW*). The results show that the coefficients of change in investment to stock of trucks and highway vehicles are positive and significant in explaining TFP growth in the US service sector. Although for estimating LP growth, the results are not significant under the twenty year overlapping series, the coefficients are significant when estimated with ten year overlapping series (see appendix table 4A.5). Thus the actual increase after considering depreciation (dividing the investment in trucks by stock of trucks) augmented the transport sector growth and thus the service sector growth. Conversely, in the case of railways, the change in the investment variable is positive and significant, while the change in investment to stock variable is negative and significant. Nonetheless, negative significance of the change in investment to stock variable for railways show that the share of railways in the transport sector was gradually decreasing in the twentieth century. Waterways are significant in most of the cases, which is not surprising because this mode of transport has a greater impact only in the recent years, when the US market was more opened to the rest of the world.

In the twentieth century US, mechanization of roadways augmented the process of transportation of goods and services across distant locations. Use of highways became so rapid that it overtook the earlier use of railways in the eighteenth and early nineteenth century. The empirical results suggest that with more capacity utilization of highways and trucking, investment in railroads contributed positively but railways (change in investment to stock) was not so high, showing the coefficient of investment to stock of railways to be negatively significant. One reason behind this failure of railways is that, at the start of the twentieth century, it was predicted that trucks would only be used to fill the gaps between railways and retail outlets of goods and services. However, it was never imagined that much of the railway’s market share would be gradually eaten away by low barriers to entry in trucking and lack of regulations in trucking before 1935. While railways enjoyed much monopoly profit with less incentive to innovate, the trucking industry faced higher competition and more incentive to innovate, which boosted its productivity.[12] Overall, empirical evidence supports hypothesis H_2 and the views of Field (2006, 2007) who argued that in the twentieth century until 1970, the US transport system played a big role in enhancing growth in the US service sector. Due to limitations of data and scope,

[12] For a comparison of the economics of trucking and railways and the reasons behind the failure of railways in the twentieth century, see Field (2007), page 79-81.

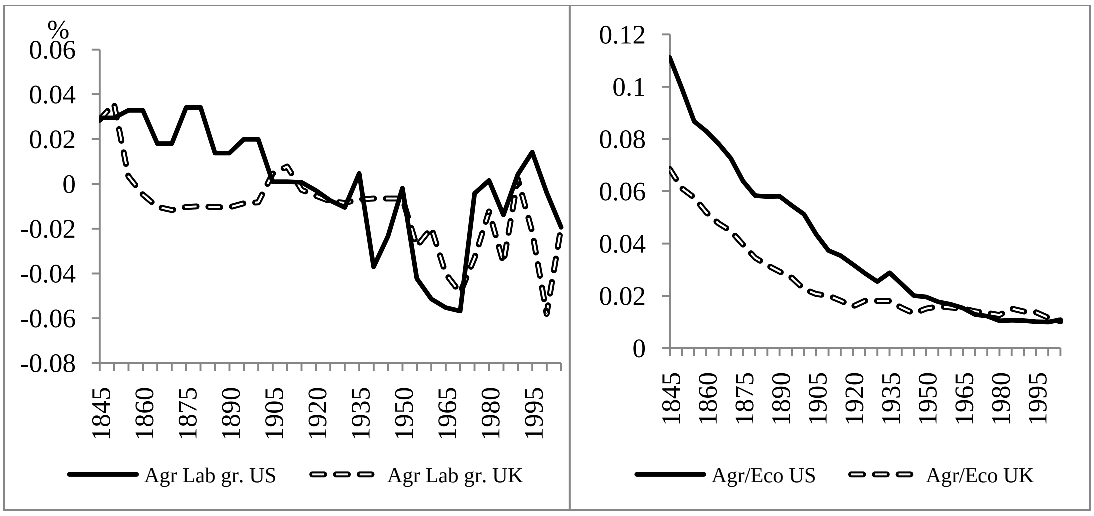
similar regression analysis could not be performed at this stage for the UK service sector. However, the author is currently planning of doing future works focusing only on the service sector of the two economies, which would be helpful in comparing the growth in the twentieth century.

4.6. Structure of Growth in American Agriculture

In this section, to throw further light on the first hypothesis about increased agricultural productivity growth in the US, the structure of American agriculture is decomposed into contributions from equipment investments, R&D expenditure and population growth. The reason the contributions are decomposed in this section, is primarily because of the immense importance of agriculture during the take-off period of the US and secondly to see how, in presence of land as a factor of production, productivity growth is a race between technological progress and population growth.

The growth rate of labour in the agricultural sector of the US was consistently falling from the mid nineteenth century to late twentieth century (see Figure 4.8a). Only in the post 1970 period, did employment in agriculture have a positive growth rate. Thus, while the decreasing growth rate of labour in the pre-1970 phase should have a positive effect on productivity growth in agriculture, the increasing growth rate in the recent years should have a negative effect. Comparing the growth rate in the US to its counterpart in Britain, growth of agricultural labour in Britain decreased in the initial years between 1840 and 1870 in favour of productivity growth, after which it remained almost constant until the 1950s (see Figure 4.8a). Even constant labour growth implies a significant growth drag on productivity in the absence of sufficient technological progress.

Figure 4. 8: Labour Force growth and share of agriculture in total income in the US and in the UK, 1840-2008



(a) (b)

Note: The growth rates of the agricultural labour force are annualized growth rates measured in five year non-overlapping differences (figure 4.8a). The share of agriculture in total income is measured in five year averages (figure 4.8b).

Agriculture always had a greater influence on the American economy than the British in the first hundred years of the sample period. Comparing the share of agriculture in total income in circa 1840, the US had an agricultural share in total income that was almost double the share in the UK (see Figure 4.8b). The share decreased over time, but the gap between the two economies remained significantly positive before the 1950s. Around 1950, the share of agriculture in total income converged in the two economies has remained approximately the same since.

Table 4.7 displays simulation results from the contributions to *changes* in TFP and labour productivity growth in agriculture of the *changes* in R&D augmented investment such as tractors and total farm machinery (measured as change in investment to stock), *level* of R&D expenditure in agriculture and *changes* in agricultural labour growth rates based on the coefficients estimates of tables 4.1 and 4.2. This will shed some light on the forces behind the increasing growth rates in US agriculture in the twentieth century. Since the data for tractors and total farm machinery for the US are available only from 1910 onwards, the model could be simulated in the period 1910-2008. Keeping in mind that in the US, the share of agriculture in total income was significantly greater than the UK before circa 1950 and the population growth rate was decreasing before circa 1970, the following two structural transformations in the US agricultural sector are considered here: (1910-1950) to (1951-2008) and (1910-1970) to (1970-2008). They were considered over both ten and twenty year overlapping growth series.

Table 4. 7: Simulation results

Period	Actual changes in (%) $\Delta ln\, A_t^A$	Contribution from (%) $\Delta \ln\left(\frac{I^{EQ}}{S^{EQ}}\right)_t$	$\ln\left(\frac{X}{Q}\right)_t^A$	$\Delta ln\, L_t^A$
10 year overlapping				
(1910-1950) to (1951-2008)	0.149	0.036	0.045	0.032
(1910-1970) to (1971-2008)	0.056	0.030	0.039	-0.054
20 year overlapping				
(1910-1950) to (1951-2008)	0.327	0.067	0.103	0.054
(1910-1970) to (1971-2008)	0.120	0.035	0.093	-0.035
	$\Delta ln\, y_t^A$	$\Delta \ln\left(\frac{I^{EQ}}{S^{EQ}}\right)_t$	$\ln\left(\frac{X}{Q}\right)_t^A$	$\Delta ln\, L_t^A$
10 year overlapping				
(1910-1950) to (1951-2008)	0.151	0.044	0.019	0.058
(1910-1970) to (1971-2008)	0.043	0.037	0.017	-0.096
20 year overlapping				
(1910-1950) to (1951-2008)	0.363	0.090	0.038	0.128
(1910-1970) to (1971-2008)	0.023	0.047	0.034	-0.082

Note: the average estimated coefficients of change in investment to stock ratio of tractors and machines, level of research intensity and change in labour force in tables 4.1 and 4.2 are used in the simulations. For example, in twenty year overlapping growth series, first the average coefficients of change in investment to stock ratio of tractors and total farm machinery are calculated from table 4.1 (rows 4 and 5). This gives the average estimated coefficient for all farm machinery. This coefficient was then multiplied by the actual change in the growth series of tractors and total farm machinery (average of the actual growth in tractors and actual growth in total farm machinery) to calculate the contributions to the actual growth in TFP. A^A, y^A, I^{EQ}/S^{EQ}, X/Q, L^A are, respectively, TFP in agriculture, labour productivity in agriculture, investment to stock ratio of farm machinery (including tractors and other farm machinery), research intensity and agricultural labour force (employment). *R&D/Y* and *R&D/A.L* are, respectively, measures of research intensities calculated as R&D expenditure divided by real GDP and R&D expenditure divided by TFP multiplied by labour in the agricultural sector. The contribution from *X/Q* is the average of the contribution of research intensity and the level of R&D.

In the first part of Table 4.7, the simulation results correspond to TFP growth and the second part of the results corresponds to labour productivity growth. During the transition from initial take-off to sustained growth of 1910-1950 to 1951-2008, TFP in agriculture grew at 0.15 (ten year overlapping growth) to 0.33 (twenty year overlapping growth) of a percentage point. Increasing research intensity in the economy pushed the growth rate up by 0.04 to 0.07 of a percentage point and R&D augmented investments such as tractors and other farm machinery pushed it further by 0.05 to 0.10 of a percentage point.[13] Since population growth was decreasing in this period, it contributed positively to the TFP growth by 0.03 to 0.05 of a percentage point. In each case the growth impacts on TFP and contributions from each component are larger in twenty year overlapping series compared to ten year overlapping series, because there are fewer impacts from business cycles in the former.

While there were positive growth effects from reduced labour growth in transition from 1910-1950 to 1951-2008, the effect was negative in the transition from 1910-1970 to 1971-2008. This finding is fairly intuitive because of agricultural labour growth was increasing in the years after 1970 (see figure 4.7b). Consequently it has a growth drag on TFP growth of 0.04 (twenty year overlapping) to 0.05 (ten year overlapping) of a percentage point. In spite of the growth drag from labour growth, R&D augmented investments and research intensity contributed positively at 0.03 to 0.04 and 0.04 to 0.09 of a percentage point, respectively. In the transformation between the pre-1970 and the post-1970 period, the productivity growth is much lower compared to the earlier break point, which grew only at a rate of 0.06 to 0.12 of a percentage point (almost half). The reasons behind the lower productivity growth are mostly because of positive growth rate of labour in post-1970 period, which created a growth drag on productivity and also short-lived agricultural miracle, which gradually disappeared in the latter half of the century.

The interpretation of the results in the second part of Table 4.12 corresponding to labour productivity growth in agriculture is similar to the first

[13] The first figure in each range corresponds to ten years overlapping growth series and the second figure corresponds to twenty year overlapping growth series.

part of the table. Thus reduced growth of labour in the agricultural sector contributed positively to the labour productivity growth in transformation from 1910-1950 to 1951-2008 and contributed negatively in transformation from 1910-1970 to 1971-2008. Technological progress through R&D augmented investments and research intensity in agriculture had positive effects in both transformation periods.

The finding, that productivity growth in American agriculture was predominantly driven by research intensity, R&D augmented investments and labour force growth, is important in the context of 'American catching-up and forging ahead'. Technology augmented growth in agriculture sped up the process at the start of the century, which was further pushed up by lower labour or population growth in agriculture. Hansen and Prescott (2002), Lucas (2009) and the first chapter of this dissertation, all pointed out that innovations and population are the principal drivers of economic growth. This analysis suggests that the same story is dominant in the American agricultural sector at the start of the twentieth century.

The invention of tractors made it possible for farms to shift rapidly to a new technology, cultivating greater areas of land in smaller amount of time, and thus complementing the traditional uses of horses and mules. As the quality of tractors and other farm machinery evolved over time with greater contributions from research intensity in the sector, they gradually substituted the traditional use of horses and mules in the latter half of the century (Olmstead and Rhode, 2001). All these factors focus on the underlying causes of the surge in innovative activity in the economy. Once the agricultural miracle began to decline due to diminishing returns from land as a factor of production, the progress was shifted with advancements in the service sector, which continued until 1970.

4.7. Conclusion

In this study, four important characteristics of the American take-off are demonstrated at onset of the twentieth century. First, while the manufacturing sector had an early but constant lead from the mid nineteenth century, agriculture and service sectors boosted the US productivity growth at the beginning of the twentieth century. Second, in the US agricultural sector, new innovations such as tractors and other farm machinery, when applied to vast land resources, created advantages over traditional techniques such as the use of horses and mules. Endogenous R&D augmented investment created increasing returns to land through which agricultural productivity was further enhanced in the period. The UK unlike the US could not take advantage of this mainly due to the absence of natural resources and failing to generate R&D augmented investments in agriculture. Third, in the presence of land as a factor of production, American agricultural productivity growth in the first half of the twentieth century was further augmented due to low labour growth in the agricultural sector, where productivity growth becomes a race between technological progress and population growth drag. Fourth, in the US service sector, the transport sector underwent major transformations in the twentieth century from railways to roadways system. Availability of a greater range of transport mechanisms created flexibility in terms of trading of goods and services.

The findings of this chapter suggest that early technological progress in agriculture and efficient use of land resources can take an economy to a stage of higher growth. Further, these findings support the view of Rostow (1959), who claims that one of the reasons behind successful take-off, for example, in the British economy in the eighteenth century, was considerable developments in agriculture. Once labour saving technology is applied in agriculture, labour is released to other sectors and the economy grows at a higher rate (Gollin *et al.*, 2002). The same mechanism also worked for the US at the start of the twentieth century. Finally technological progress in agriculture played a key role behind successful productivity growth in the US in the period 1840-1920 and later in the period 1935-1970.

Olmstead and Rhode (2001) show that the tractor represented a grand Schumpeterian innovation, which revolutionized the American farming system, creating new opportunities and replacing old farming techniques. The technological diffusion of tractors in the period 1910-1960 replaced about 23 million draft animals and increased the effective cropland base by 79 million acres. A gradual diffusion of tractors in farming made agricultural production more versatile, and reduced the labour requirement by an essential 1.7 million workers relative to the older technology[14]. This study finds support in favour of the Schumpeterian view of technological progress (both first and second generation versions of growth models) where increased levels of R&D in the sector influences higher productivity growth in American agriculture. Economic progress was fostered by a system of privately funded R&D labs that reached its peak during the 1930s and were not affected by wars (Rosenberg, 2000). The simulation results in section 4.6 confirm that decreasing growth of the agricultural labour force further pushed up the productivity growth in the period before 1970. However, at the same time, it has to be kept in mind that agricultural miracles are short lived and thus growth in other sectors are necessary for successful take-off in the economy (Gollin *et al.*, 2007). In the American scenario, the service sector was the fastest growing sector in the twentieth century until 1970, which helped maintain the productivity gap over other developed nations.

The empirical results also confirm that in the US service sector, the advances were high in transportation in the 1930s and in the subsequent period 1948-1973, as the sector strongly benefited from investments in government infrastructure (Field, 2003; 2006, 2007). Public investments in construction of highways complemented by quality improvements in trucking meant that trucks travelled at a higher average speed and over longer distances per day. Uses of longer routes and greater numbers of trucks increased the productivity per unit of labour in the transport sector.

Overall, America took the lead over Britain in the twentieth century because of its resource availability and rich inventive possibilities in all sectors. As opposed to conventional studies that give importance to either manufacturing or service sector growth as the main cause of American economic leadership, this study proposes a role for agriculture as well, for successful take-off of an economy like the US. Short lived agricultural miracles due to advancement in

[14] See Olmstead and Rhode (2001), table 7, page 692.

endogenous technological progress can lift the productivity of an economy when accompanied by long and continued growth in other sectors. Britain could not take advantage of this as it lacked the enormous land resources of the US and furthermore, as it put more importance on maintaining traditional values and attitudes, it could not balance the process of innovating and adopting new technologies equally in all sectors at the same time. Thus the nineteenth century leader lost its position to the Americans in the twentieth century.

4A.1. Appendix tables

Table 4A. 1: 10-year annual estimates of US agricultural TFP growth

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$\Delta \ln L_t^A$	-0.51***	-0.50***	-0.50***	-0.50***	-0.49***	-0.48***	-0.40***	-0.38***	-0.38***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
$\Delta \ln I_t^{TRA}$	-0.02*	-0.02*	-0.02*						
	(0.06)	(0.09)	(0.08)						
$\Delta \ln I_t^{M}$				-0.04***	-0.04***	-0.04***			
				(0.01)	(0.01)	(0.01)			
$\Delta \ln \left(\frac{I_t}{S_t}\right)^{TRA}$	0.19**	0.19**	0.18**						
	(0.02)	(0.02)	(0.02)						
$\Delta \ln \left(\frac{I_t}{S_t}\right)^{M}$				0.17**	0.17**	0.16**			
				(0.03)	(0.04)	(0.04)			
$\Delta \ln \left(\frac{I_t}{K_t}\right)^{A}$							0.07**	0.07**	0.07**
							(0.04)	(0.03)	(0.03)
$\ln \left(\frac{R_t}{Y_t}\right)^{A}$	0.04**			0.03**			0.04**		
	(0.02)			(0.04)			(0.02)		
$\ln \left(\frac{R_t}{(A.L)_t}\right)^{A}$		0.04**			0.04**			0.04**	
		(0.02)			(0.03)			(0.03)	
$\ln R_t^A$			0.03***			0.03**			0.03***
			(0.01)			(0.02)			(0.01)

Note: I^{TRA}, $(I/S)^{TRA}$, I^M, $(I/S)^M$, L^A, (I/K) are, respectively, investment in tractors, investment to stock ratio in tractors, investment to total farm machinery, investment to stock in total farm machinery, agricultural labour force (employment) and investment to stock in agriculture. *R*, *R/Y* and *R/(A.L)* are, respectively, R&D expenditure, R&D expenditure to real GDP in agriculture and R&D expenditure to (TFP times labour) in agriculture. The Newey-West corrected test statistic is reported to correct for serial correlation and heteroskedasticity. A constant is included in the regression, but not reported here. ***, ** and * show significance at the 1%, 5% and 10% critical levels, respectively. Figures in parenthesis are p-values. The estimation period is 1840-2008.

Table 4A. 2: 10-year annual estimates of US agricultural labour productivity growth

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$\Delta \ln L_t^A$	-0.89*** (0.00)	-0.88*** (0.00)	-0.87*** (0.00)	-0.88*** (0.00)	-0.87*** (0.00)	-0.86*** (0.00)	-0.77*** (0.00)	-0.74*** (0.00)	-0.73*** (0.00)
$\Delta \ln I_t^{TRA}$	-0.02* (0.06)	-0.02* (0.07)	-0.02* (0.07)						
$\Delta \ln I_t^{M}$				-0.04*** (0.01)	-0.04*** (0.01)	-0.04*** (0.01)			
$\Delta \ln\left(\frac{I_t}{S_t}\right)^{TRA}$	0.22*** (0.00)	0.22*** (0.00)	0.22*** (0.01)						
$\Delta \ln\left(\frac{I_t}{S_t}\right)^{M}$				0.21*** (0.01)	0.21*** (0.01)	0.21*** (0.01)			
$\Delta \ln\left(\frac{I_t}{K_t}\right)^{A}$							0.08** (0.02)	0.08*** (0.01)	0.08*** (0.01)
$\ln\left(\frac{R_t}{Y_t}\right)^{A}$	0.01 (0.52)			0.01 (0.60)			0.01 (0.41)		
$\ln\left(\frac{R_t}{(A.L)_t}\right)^{A}$		0.01 (0.45)			0.01 (0.54)			0.02 (0.29)	
$\ln R_t^A$			0.01 (0.39)			0.01 (0.45)			0.02 (0.23)

Note: see notes to table 4A.1.

Table 4A. 3: 10-year annual estimates of UK agricultural TFP growth

	(1)	(2)	(3)	(4)	(5)
$\Delta \ln L_t^A$	-0.80*** (0.00)	-0.80*** (0.00)	-0.87*** (0.00)	-0.85*** (0.00)	-0.93*** (0.00)
$\Delta \ln I_t^{TRA}$	-0.00 (0.90)	-0.00 (0.90)			
$\Delta \ln I_t^{M}$			0.13 (0.31)	0.17 (0.16)	
$\Delta \ln\left(\frac{I_t}{S_t}\right)^{TRA}$	-0.28*** (0.00)	-0.28*** (0.00)			
$\Delta \ln\left(\frac{I_t}{S_t}\right)^{M}$			-0.21 (0.52)	-0.28 (0.39)	
$\Delta \ln\left(\frac{I_t}{K_t}\right)^{A}$		-0.00 (0.93)		-0.07 (0.11)	-0.04 (0.26)

Note: see notes to table 4A.1.

Table 4A. 4: 10-year annual estimates of UK agricultural labour productivity growth

	(1)	(2)	(3)	(4)	(5)
$\Delta \ln L_t^A$	-1.19***	-1.19***	-1.03***	-1.02***	-1.26***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
$\Delta \ln I_t^{TRA}$	-0.01	-0.01			
	(0.56)	(0.56)			
$\Delta \ln I_t^M$			0.26***	0.29***	
			(0.00)	(0.00)	
$\Delta \ln \left(\frac{I_t}{S_t}\right)^{TRA}$	-0.13***	-0.13***			
	(0.00)	(0.00)			
$\Delta \ln \left(\frac{I_t}{S_t}\right)^{M}$			-0.76***	-0.82***	
			(0.01)	(0.01)	
$\Delta \ln \left(\frac{I_t}{K_t}\right)^{A}$		0.00		-0.05**	-0.02
		(0.88)		(0.04)	(0.49)

Table 4A. 5: 10-year annual estimates of US Service sector productivity growth

	$\Delta \ln I_t^{TRK}$	$\Delta \ln \left(\frac{I_t^{TRK}}{S_t^{TRK}}\right)$	$\Delta \ln I_t^{HW}$	$\Delta \ln \left(\frac{I_t^{HW}}{S_t^{HW}}\right)$	$\Delta \ln I_t^{RW}$	$\Delta \ln \left(\frac{I_t^{RW}}{S_t^{RW}}\right)$	$\Delta \ln I_t^{WW}$	$\Delta \ln \left(\frac{I_t^{WW}}{S_t^{WW}}\right)$
Dependent variable: $\Delta \ln A_t^S$ (TFP growth)								
(1)	-0.32***	0.43***						
	(0.01)	(0.00)						
(2)			-0.09**	0.13*				
			(0.04)	(0.09)				
(3)					0.76**	-0.97***		
					(0.02)	(0.00)		
(4)							-0.31	0.43
							(0.25)	(0.15)
(5)	-0.06***	0.11*			0.75***	-0.93***	-0.07	0.21
	(0.00)	(0.09)			(0.00)	(0.00)	(0.60)	(0.16)
(6)			-0.09***	0.18***	0.89***	-1.09***	-0.08	0.18
			(0.00)	(0.01)	(0.00)	(0.00)	(0.55)	(0.24)
Dependent variable: $\Delta \ln y_t^S$ (LP growth)								
(1)	-0.37	0.41***						
	(0.00)	(0.01)						
(2)			-0.17	0.16				
			(0.18)	(0.35)				
(3)					0.72**	-0.85***		
					(0.03)	(0.01)		
(4)							-0.35	0.50*
							(0.17)	(0.08)
(5)	-0.14**	0.19*			0.71**	-0.76**	-0.21	0.29
	(0.04)	(0.10)			(0.02)	(0.02)	(0.29)	(0.22)
(6)			-0.09***	0.15*	1.03***	-0.52	-0.04	0.02
			(0.00)	(0.08)	(0.00)	(0.12)	(0.79)	(0.92)

Note: see notes to Table 4.6.

4A.2. Data Appendix

Real GDP: *US:* real GDP is measured as gross value added (billions of chained 2000$). The sources for economy-wide real GDP are: 1840-1869: '*Historical Statistics of the United States, Millennial Edition*' (Vol. 3), page 3-23, edited by Carter *et al.* (2006); 1869-1953 is from Kendrick (1961); and 1953-2008: '*US Bureau of Economic Analysis (BEA)*' online database – http://www.bea.gov/. The sources for sectors are as follows. Agriculture: 1840-1869: Towne and Rasmussen (1960); 1870-1971: '*Historical Statistics of the United States, Millennial Edition*' (Vol. 4), page 4-204, edited by Carter *et al.* (2006); and 1971-2008 is from World Development Indicators (WDI) online database – http://web.worldbank.org/. Manufacturing: 1840-1869 Davis (2004); and for 1871-2008 the sources are same as of economy-wide real GDP. Services: 1840-1869 is from Rhode (2002); and for 1871-2008 the sources are same as of economy-wide real GDP.
UK: real GDP is measured as gross value added (billions of constant 2000$). The sources for economy-wide and sectoral real GDP are: 1840-1970 from Mitchell (1988); and 1970-2008 from WDI online database – http://www.worldbank.org/. In the UK agricultural sector, for period 1840-1855, real GDP data is taken from Clark (2002).
In each case, the later series is spliced with earlier series to get a complete database on annual basis for the period 1840-2008.

Employment: *US:* employment is measured as total labour force or persons engaged in each sector (in thousands). The sources are same for overall economy, agriculture and manufacturing sectors: 1840-1869 is from '*Historical Statistics of the United States, Millennial Edition*' (Vol. 2 and 4), 2-63, 2-110, 4-77, edited by Carter *et al.* (2006); 1869-1957 is from Kendrick (1961); and 1957-2008 is from OECD online database – http://stats.oecd.org/Index.aspx. Service sector: 1840-1956: source is same as economy-wide employment; 1957-2008: *'US Bureau of Labour Statistics (BLA)'* – http://www.bls.gov/.
UK: The sources are same for economy-wide employment and employment in each sector: 1840-1860 is from Mitchell (1988); 1860-1965 is from Feinstein (1972); and 1965-2008 is from OECD online database: http://stats.oecd.org/Index.aspx. Employment in the service sector for the period 1965-2008 is taken from National Statistics Online (NSO): http://www.statistics.gov.uk/default.asp.
In each case, the later series is spliced with earlier series to get a complete database on annual basis for the period 1840-2008.

Labour Hours: *US:* 1840-1950: '*Historical Statistics of the United States, Millennial Edition*' (Vol. 2), 2-301, edited by Carter *et al.* (2006); and 1950-2008: OECD online database – http://stats.oecd.org/Index.aspx.
UK: 1840-1870: Mitchell (1988), page 147; 1870-1913: Huberman (2004); 1913-1969: Mitchell (1988); and 1970-2008: OECD online database – http://stats.oecd.org/Index.aspx.

Land: *US:* 1840-1961 is from '*Historical Statistics of the United States, Millennial Edition*' (Vol. 4), edited by Carter *et al.* (2006); and 1961-2008 is from the online database of 'Food and Agricultural Organization (FAO)': http://faostat.fao.org/default.aspx.
UK: 1840-1961 is from Mitchell (1988); and 1961-2008 is from the online database of 'Food and Agricultural Organization (FAO)': http://faostat.fao.org/default.aspx.
The later series is spliced with earlier series to get a complete database on annual basis for the period 1840-2008 for each economy.

Capital: To calculate capital stock from investment series perpetual inventory method is used, where 3% and 8% depreciation rates are taken for non-residential structures and equipments and machinery respectively.
US: While capital formation data for the overall economy is available in the period 1840-2008, the data for each sector is for the period 1869-2008. Overall economy: Capital formation data for 1840-1869 is from Rhode (2002); real capital stock in non-residential structures and equipments and machineries for 1869-1947 is from Kendrick (1961); and investment in non-residential structures and equipments and machineries for 1947-2008 is from NIPA series of 'US Bureau of Economic Analysis (BEA)' online database – http://www.bea.gov/. Agricultural sector: real capital stock in non-residential structures and equipments and machinery for 1869-1947 is from Kendrick (1961); and for 1957-2008 agricultural capital index data is collected from 'US Department of Agriculture' (USDA): http://www.ers.usda.gov/Data/AgProductivity/. Manufacturing sector: manufacturing capital input index data for 1869-1947 is from Kendrick (1961); for 1947-2000: private fixed investment in structures and machinery and equipments is from '*Historical Statistics of the United States, Millennial Edition*' (Vol. 4), edited by Carter *et al.* (2006); and for 2000-2008: private fixed investment in structures and machineries and equipments is from NIPA series of 'US Bureau of Economic Analysis (BEA)' online database – http://www.bea.gov/. Service sector: A depreciation rate of 8% is chosen to calculate capital stock series from total investment series for services using perpetual inventory method. Real capital indices for trade, transport and communication and public utilities are used to construct total service sector capital index for 1869-1947. The source is Kendrick (1961); and for 1947-2008 the source is OECD online database: http://stats.oecd.org/Index.aspx.
UK: the sources are same for economy wide and for each sector. Capital stock is measured as net capital stock at constant prices. For the period 1882-1948: Feinstein (1972); and for 1948-2008: National Statistics Online (NSO): http://www.statistics.gov.uk/default.asp.

Farm machineries and equipments: *US:* Farm machineries include tractors, motor trucks, automobiles, grain combinations, corn pickers, pick-up balers, field-forage harvesters, cotton pickers and milking machines. The data is available for the period 1910-2008. The period 1890-1910 is extrapolated using data from 1910 to 1930. The source is '*Historical Statistics of the United States, Millennial Edition*' (Vol. 4), edited by Carter *et al.* (2006) for the period 1890-1986. For the period 1986-2008, the data is from Food and Agricultural Organization (FAO)': http://faostat.fao.org/default.aspx and annual reports of 'US Department of Agriculture' (USDA):

http://www.ers.usda.gov/Data/AgProductivity/. The later series is spliced with earlier series to get a complete database on annual basis for the period 1910-2008.
UK: The source is Brassley (2000) for the period 1909-1961. Missing years are interpolated to get the series in annual basis. In the period 1961-2008, the data is from Food and Agricultural Organization (FAO)': http://faostat.fao.org/default.aspx.

Real R&D expenditure in US agriculture: Appropriations to agricultural R&D by federal and state for the period 1890-1970 is collected from '*Historical Statistics of the United States, Millennial Edition*' (Vol. 4), edited by Carter *et al.* (2006). The data is then deflated by agricultural R&D deflator collected from Pardey *et al.* (1989). The series is spliced with 'real agricultural research funding by public sector' for the period 1970-2008, collected from 'US Department of Agriculture' (USDA): http://www.ers.usda.gov/Data/AgProductivity/. Real R&D expenditure before 1890 was spliced with 'agricultural patents applied in the US collected from Schmookler (1966), table A2, page 223.

US Transport Vehicles: This data include trucks, highway vehicles, mileage of trucks, distance travelled by trucks, mileage of total highway vehicles, mileage of railroads and water vessels. Most of **t**he data for US transport vehicles are available for the period 1920-2008, except railroads which is available for the whole sample period. The missing data are extrapolated backward for the period 1890-1920 using data from 1920-1950. The source for 1920-1990 is from '*Historical Statistics of the United States, Millennial Edition*' (Vol. 4), edited by Carter *et al.* (2006); and in the period 1990-2008 data is collected from 'US Bureau of Transport Statistics' (BTS): http://www.bts.gov/publications/national_transportation_statistics/.

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Chapter 5

CONCLUDING REMARKS

This thesis has investigated endogenous technological progress and its contributions to long run economic growth. Over the past four hundred years we have seen dynamic patterns of growth that varied across countries and over time. In the eighteenth and nineteenth centuries, Britain was the technological leader, with Germany and France catching up, and then in the twentieth century the world saw a new leader where the United States forged ahead of Europe. Although it is too early to forecast the next economic leader, lessons from historical events like these can offer valuable insights for current developed and developing states to frame new policies and upgrade their positions in the economic ranking of nations.

The first and foremost issue that arises in this context is to find an accurate theoretical explanation for such experiences in history. To study any episode concerning economic growth, a theory is needed that organizes the facts, clarifies causal relationships and draws hidden implications from them (Aghion and Howitt, 2009). Although this thesis does not take the theoretical literature in a new direction, it marks a clear distinction among existing models that can be termed a theory of long run growth. Supporting the claims of Greasley and Oxley (1997a, 1997b), who provide evidence in favour of endogenous growth modelling, this study finds the new innovation-based growth theories, particularly the Schumpeterian growth model, to be more appealing in explaining the technological epochs over time. The next section will discuss briefly the findings of this thesis. Section 5.2 will state the contributions made by this thesis and finally section 5.3 will suggest some future directions of research in this area.

5.1. Summary of Thesis Findings

This thesis is a collection of three self-contained empirical studies, where in each chapter, one important technological epoch back in time is examined. Moreover, to understand the different forces of economic growth and to characterise each stage of development, a time series perspective is undertaken, using dynamic time series techniques and estimation methods.

Chapter 2 takes into account the *'First and Second Industrial Revolutions in Britain'* that marked this country as the first industrialized nation in the world. The chapter also extends the time period to the modern growth regime for the UK. By introducing land as a factor of production in the endogenous growth models, this study has shown that innovations and population growth have been the principal factors explaining per capita growth rates in Britain since 1620. Population growth was a significant drag up to the mid 19th century because land was, until then, a significant factor of production. Despite a surge in innovative activity during the First Industrial Revolution, per capita growth rates were rendered negative by a marked increase in population size. Significant positive per capita growth rates were first experienced after the start of the Second Industrial Revolution due to an increase in research intensity and a decline in population growth along with a reduction in the importance of land as a factor of production. Furthermore, the chapter tests the ability of two competing second-generation endogenous growth models to account for the British growth experience. The results suggest that innovative activity was an important force in shaping the Industrial Revolution and that the British growth experience is consistent with Schumpeterian growth theory in the period 1620-2006.

Chapter 3 empirically investigates another episode called the '*British Agricultural Revolution'* and finds that technological progress was a determining factor in improving the labour productivity growth in British agriculture during the period 1620-1850. In doing so, the study again discriminates between the modern endogenous growth models, namely, the Schumpeterian and semi-endogenous models of economic growth, where more support is gained in favour of Schumpeterian growth models. The results are robust to different control variables and also to two different sources of data available for that time. Finally, the study shows that 'number of technical farming books published' can be used as an alternative measure of innovative activity and is perhaps a superior indicator to agricultural patent counts.

Chapter 4 of this thesis focuses on a new episode at the start of the twentieth century, where the United States grew at a faster rate than Europe and became the world technological leader. In this chapter the sectoral productivity growth is compared between the US and the UK in the period 1840-2008. From the first half of the twentieth century, R&D expenditure through increased levels of R&D and research intensity, favouring both versions of the Schumpeterian growth models, and technology augmented investment such as in tractors and other farm machineries created increasing returns to scale when applied to huge land resources in the agricultural sector of the US. Furthermore, in the presence of land as a factor of production, American agricultural productivity growth in the first half of the twentieth century was augmented due to low labour growth in the agricultural sector, where productivity growth becomes a race between technological progress and population growth drag. While the agricultural miracle is short-lived, increased productivity growth in the US service sector was sustained until 1970. Revolutionary changes in the transport sector, with heavy investment in trucking and roadways, comprise a large part of the service sector growth in this period.

All findings are important and fill a number of gaps in the literature of economic growth and economic history. The next section summarizes the contributions made by this thesis.

5.2. Contribution made by this Thesis

The foremost contribution of this thesis is that this study has shown modern endogenous growth models can successfully explain events back in history such as the 'British Industrial Revolutions' and the 'British Agricultural Revolution'. To my knowledge, this study is the first of its kind to empirically test the modern endogenous growth models with long historical data spanning almost four centuries. Although Ha and Howitt (2007), Madsen (2008b) and Madsen *et al.* (2010) have found that the Schumpeterian growth theory is most consistent with the growth experience of modern growth regimes, there was no assurance before this study that the theory would apply during the Malthusian and the post-Malthusian growth regimes. [1] However, results from chapter 2 have shown that the functional relationship between growth and innovation in Britain since 1620 follows that of the Schumpeterian growth model and R&D has permanent growth effects in the long run.

The results from chapter 2 have important implications for growth modelling and the history of the British Industrial Revolution. Taking land as a factor of production, which creates population growth drag in the long run, this study shows, for the first time, that innovations and population growth have been the principal factors explaining per capita growth rates in Britain since 1620. The simulation results from chapter 2 confirm that population growth drag was important until the mid nineteenth century because until then land was a significant factor of production. Higher positive per capita growth was first experienced after the start of the Second Industrial Revolution due to increases in research intensity.

Another essential contribution to the literature of economic growth and British history is that it seeks to explain the 'British Agricultural Revolution' through the lens of endogenous technological progress. Despite the importance of agriculture for industrial revolutions, economic development and take-off, very

[1] Endogenous growth models were assumed to apply only to modern economic growth where land is not a factor of production, because innovative activity is often assumed to be of an informal nature before World War II.

little work, if any, has been undertaken to explain agricultural productivity advances based on innovative activity. Complementing the findings from chapter 2 and supporting the views of Rostow (1959), results from chapter 3 confirm that innovative activity and labour growth are the principal forces of British agricultural labour productivity growth in the period 1620-1850, where the latter produces a growth drag due to land as a factor of production.

In chapter 3, in addition to ‘agricultural patent counts’, ‘number of technical books published on farming’ is considered as an additional measure of R&D activity. Not many alternative measures of innovative activity can be found for economies before the mid-twentieth century. This empirical study is unique in its use of this alternative indicator following Sullivan (1984, 1985). While the number of patents is a direct measure of innovative activity, the number of published technical farming books measures the discovery and the dissemination of new and existing knowledge of agricultural methods and, as such, captures innovative activity and the dissemination of the knowledge stock in the agricultural sector. For both indicators, the study has found that increased levels of research intensity in the agricultural sector shaped the ‘British Agricultural Revolution’ that rendered the Industrial Revolution possible.

Finally, findings from chapter 4 provide some new insights for the current developing and developed world in terms of the taking-off and catching-up hypothesis. This study highlights the considerable economic significance of technology acquisition in agriculture and service sectors of the US that helped this economy to leapfrog other advanced economies at the start of the twentieth century. Four important characteristics of the American take-off process have been demonstrated.

First, while the manufacturing sector had an early but constant lead from the mid nineteenth century, the agriculture and service sectors boosted the US productivity growth at the beginning of the twentieth century. Second, in the US agricultural sector, endogenous R&D augmented investment created increasing returns to land by which agricultural productivity was further enhanced in the period. The technology diffusion process supports both versions of the Schumpeterian model of economic growth, where increased levels of R&D and research intensity augmented the productivity growth in the US agricultural sector. The UK, unlike the US, could not take advantage of this mainly due to the absence of natural resources and its failure to generate R&D augmented investments in agriculture. Third, due to lower labour growth in the first half of the twentieth century, US agricultural productivity growth was further enhanced. Finally, in the US service sector, the transport sector had major transformations in the twentieth century from railways to roadways system. Thus, in contrast to studies that only give importance to the manufacturing sector as the driving force behind productivity growth, this study shows that agriculture and services play important roles in the catching-up phenomenon in the advanced countries. Moreover, technological diffusion has significant impacts on augmenting productivity growth in sectoral levels.

Overall, contributions from all three chapters fill a number of important gaps in the literature and have significant policy implications for both advanced and currently growing economies.

5.3. Scope for Future Research

One important topic for future research, which goes together with this study, is to examine the roles of innovative activity and population growth in advancing the productivity growth of Australia from as far back as possible. Australia holds special interest in this respect because of three important characteristics. First, currently the Australian government is facing huge challenges to open up or to close down its border in terms of migration to boost the productivity growth. Results of such a study would confirm whether population growth drag is present in Australia in the current period or not. This will have direct policy implications for the current Australian government. Second, the Australian economy is more like a hybrid of the US and the UK, where, like the US, Australia has huge natural resources which can generate increasing returns to land in the agricultural sector, and due to its British colonial origin, it has many institutional characteristics similar to the UK. Third, before the American take-off in 1890, Australia’s GDP per capita was well above the US and the UK and was twice as much as Canada (Greasley and Oxley, 1998). However, Australia could not maintain the lead in the twentieth century. Research in this direction could confirm the causes of its failure in generating higher productivity growth and will have direct policy implications for the future.

A second area of interest covers the importance of human capital diffused with technological progress in accelerating the productivity growth in the European economies. However, lack of available data retards a detailed analysis on this pertinent issue in the present study. Results from chapter 2 show some evidence of higher demand for skilled workers and a reduced demand for number of children, where there was less population growth drag at the time of the Second Industrial revolution in the UK. Discussion from chapter 3 also highlights higher literacy rates among British farmers at the time of the Agricultural Revolution in the UK, where an increased 'number of books published' indicates a higher diffusion of knowledge among farmers at the local level. Some recent studies e.g., Galor and Weil (2000) and Galor (2005) stress the origin of human capital formation and the determinants of parental choice regarding the quantity and quality of offspring for transformation of an economy from a Malthusian age to a modern growth regime. Empirical studies with suitable theoretical backgrounds in this direction will provide further insights in the take-off phenomenon of the advanced economies. Policy implications in this respect will also apply to Australia, where currently the education industry comprises a major part of the export sector[2].

A third opportunity for future research is to investigate how financial constraints in an economy, particularly for growing economies, affect productivity growth through the channel of R&D in the economy. The common argument in this respect is higher financial constraints will restrict organizations' ability to get sufficient external funding for R&D, which in turn affects the research intensity in the economy and thus lowers productivity growth (Aghion and Howitt, 2009, Ch 9). Ang (2008) recently examine the phenomenon in the context of South Korea in the period 1967-2005 and finds that financial liberalization has the potential to

[2] The Australian Bureau of Statistics valued Australian international education services as an AUD 10 billion export industry in 2008. This shows the economic importance of this industry to Australia.

improve economic growth via increasing knowledge production. Ang and Madsen (2008) test the phenomenon for India in the period 1950-2005 and found that financial liberalization discourages corporate investment, but increases knowledge production. A thorough study in this respect for economies such as the US and the UK using long historical data can provide further insights into the take-off phenomenon of a country, provided data constraint do not create serious problems.

Finally, I will like to end this chapter and the thesis, with the hope that the findings from this study encourage new emerging economies and less developed economies to frame their policies in the direction of higher technological progress and to generate higher research intensity in the economy. Technology, knowledge spillovers and entrepreneurship have played salient roles in many emerging economies such as India (Madsen *et al.*, 2010). This study shows that technological progress and population play the key roles, where technology is endogenous and has permanent growth effects in the long run following the Schumpeterian model of economic growth. If models with endogenous technological progress and population growth can explain mysteries in human evolution like ‘the British Industrial Revolution’ or the ‘Great Divergence’, policy implications from such models indeed have the potential to solve bigger problems in the future.

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ADDENDUM

P.1, Para 1, line1: add 'real' before 'gross domestic product'.
P.4, last Para, after first line, add sentence: 'In the simplest neoclassical production function of equation (1.1), if α is assumed to be one, then the equation reduces to Y=A.K with A= constant>0. This is why these models are termed as AK models in the literature.'
P.7, Para 2, line 11: after 'any variable' add '(not spurious)'.
P.8, Para 2, line 9: after 'attempts to test' add 'the predictions of'.
P.8, last line: replace 'back in history' by 'in the past'.
P.9, last Para, line 3: add reference: (Rostow, 1959).
P.11, fn. 6: add reference after Clark (2007): Mokyr (2009) and Allen (2001). Add after 'different growth models' 'different views'.
P.12, last line: replace 'inadequate land resources' by 'lower amount of agricultural land'.
P.14, insert after reference 4: Allan, R. C. (2001), The Great Divergence in European Wages and Prices from the Middle Ages to the First World War, *Explorations in Economic History,* Elsevier, vol. 38(4), pages 411-447.
P.15, insert after reference 15: Mokyr, J. (2009), *The Enlightened Economy: An Economic History of Britain 1700-1850.* Yale.
P.18, Para 1, line 5: add at the start of sentence: 'The theoretical prediction is that'
P.19, Para 2, line 6: read 'Greasley and Oxley (1997)' as Greasley and Oxley (1997, 2007)".
P.20, Para 1, line 3: replace 'given' by 'assumed'.
P.23, Para 3, line 5: add 'predictions of' after 'found that'
P.24, Para 1, line 2, add 'in the process of unified growth' after 'Based on historical evidence'
P.25, Para 2, line 3: read 'independently and identically' as 'identically and normally'.
P.25, Para 2, line 4: replace 'it follows that variables in the square brackets are cointegrated' by 'it follows that variables are individually stationary and then trivially cointegrated as any liner combination would be I(0).'
P.26, Para 1, add at the end of last line: ', which is allowed to vary between zero and one.'
P.26, Para 3, line 3: add 'predictions of' after 'between'
P.28, Para 2, line 3: add at the end of point 2) 'In other words, whether the coefficients follow the correct signs of the second generation growth models'
P.28, Para 2, line 15: add at the end of sentence: 'with higher income and higher living standards'
P.30, Para 2, line 10: read '(see Boehm and Silberston, 1967)' as '(see Boehm Silberston, 1967; Moser, 2004, 2005).
P.35, Para 1, replace sentence 'Regarding the tests....' by 'Regarding the tests of semi-endogenous growth theory, the results show that for the periods 1760-1850 and 1760-2006, the null of no cointegration is not rejected; in all other cases the null of r=0 is rejected in favour of at least r=1."
P.36, Para 1, line 6: replace sentence 'Overall the results...' by 'Overall the results in Table 2.2 does not provide much support in favour of semi-endogenous theory, where either no cointegration among the variables or no long run relationship was found.'
P.35, 36, 48 notes to Table 2.3, 2.4 and 2A.2: replace 'pinned down' by 'selected'
P.37, Para 1, line 3: replace 'fairly constant' by 'not very fluctuating, ranging between -2.17 to -3.25,'
P.37, fn. 2, add before first line 'Considering the historiography of Britain,'
P.39, replace line 1 by: 'The estimated coefficients of research intensity do not refute the predictions of Schumpeterian growth theory, while the estimated coefficients of the growth in patents refute the predictions of semi-endogenous growth theory.'

P.40, Para 1, line 1: read ‘The empirical estimates do not refute the hypothesis....’
P.41, Para 1, line 10: delete phrase ‘rather well’
P.41, Para 2, after last line, add fn.: ‘Increasing population growth rates was also matching with increased life expectancy rates and vice versa in each point of transition.’
P.43, Para 1, add fn. at the end: ‘Our argument does not refute that there are other theories of British Industrial Revolution, such as theory of enlightenment forwarded by Mokyr (2009) and standard of living through real wages forwarded by Allen (2001).
P.55, insert after reference 16: Moser, P. (2004), “Determinants of Innovation Evidence from 19th Century World Fairs", *The Journal of Economic History,* 64(02), 548-52.
Moser, P. (2005), "How Do Patent Laws Influence Innovation? Evidence from Nineteenth-Century World's Fairs", *The American Economic Review*, 95(4), 1214-36.
P.58, Para 1, add reference after first line 1: (Deane, 1969)
P.59, Para 1, line 6, replace ‘sufficiently’ by ‘empirically’.
P.59, Para 1, line 14, add ‘, such as agriculture,’ after ‘at the sectoral level’
P.61, fn.3, add reference: Greasley and Oxley (1996)
P.67, delete first sentence and replace by ‘This is due to the fact that in absence of land as factor of production, following a labour shock, capital stock endogenously adjusts and (K/L) ratio gets back to its original position in the long run.’
P.68, and elsewhere in the chapter: α should be read as α_t.
P.69, Para 1, line 2: add ‘necessarily’ after ‘eq. (3.7) and eq. (3.9) will’
P.69, Para 2, line 1: add ‘nested’ between ‘the following’ and ‘growth model’
P.70, Para 1, add after sentence in line 6: ‘The estimation results may add wrong inferences.’
P.70, Para 3, line 6: add sentences: ‘CPI series is consistent over the whole period. The data source is in data appendix at the end of the chapter.’
P.72, Para 1, line 2: replace ‘There were no comprehensive statistics for Great Britain before 1851.’ by ‘Before 1851, the statistics for Great Britain is highly debatable among many authors.’
P.74, Para 2, line 6: add ‘over earlier versions of technology’ after ‘overall improvement’. Add reference after sentence: ‘(Greasley and Oxley, 2000)’.
P.77-78: replace first sentence by ‘For both types of measures of technological progress, the series are volatile in the period 1815-1830. This was due to the fact that many wars were fought at that time, including French Revolutionary Wars (1803-1814) and the Anglo-Burmese War (1823-1826).’
P.78, Para 2, line 1: add ‘gross’ between ‘Overall the’ and ‘agricultural technological indicators’
P.78, Para 3, line 1: replace ‘graphically tests’ by ‘shows graphically’
P.80, Para 1, replace last sentence by ‘This shows no support for semi-endogenous growth model, which predicts productivity growth should be explained by R&D growth in the economy.’
P.82, Para 2, add sentence after first sentence: ‘Hence graphically if the trends of research intensity and productivity growth over time does not show in similarity in trends and fluctuations, there is little chance that the data would be supported by the theory.’
P.84, Para 2, add sentence after first sentence: ‘In Table 3.2, the last column shows the result in three different unit root tests. I(1) indicates the variable is non-stationary in levels but stationary in first differences in all three different unit root tests. Similarly, I(0) indicates the variable is stationary in levels in all three different tests. And I(0)/I(1) means that the variable turned out to be stationary in levels in at least one test and non-stationary under others.’
P.84, Para 2, line 2: replace ‘Zibot-Andrews’ by ‘Zivot-Andrews’
P.84, last Para, line 3: replace ‘cannot be rejected’ by ‘is rejected’

P.87, replace last line by: ‘The trace statistic and maximum eigenvalue statistic show that the null of no co-integration among variables ln (*Y*1/*L*), different measures of ln *X* and ln *L* cannot be rejected in most cases.’
P.88, Para 1, last line: delete ‘and hence the results are satisfactory.’
P.88, Para 2, line 13: replace ‘not much support is obtained for semi-endogenous theory’ by ‘the predictions of semi-endogenous theory do not hold’
P.90, notes to Table 3.6, line 3: replace ‘robust estimates’ by robust standard errors.’
P.98, Para 1, after last line: add reference: (Crafts and Mills, 2009)
P.98, Para 2, replace last line by ‘The bigger coefficients perhaps show that effect of technical farming books as a measure of innovative activity a superior indicator to patent counts.’
P.98, last Para, line 7: replace ‘difficult to match with any other time periods in history’ by ‘as the start of the industrial period for Britain.’
P.102, insert after reference 20: Crafts, N. and T. C. Mills. (2009), "From Malthus to Solow: How Did the Malthusian Economy Really Evolve?" *Journal of Macroeconomics*, 31(1), 68-93.
P.103, insert after reference 8: Greasley, D. and L. Oxley. (2000), "British Industrialization, 1815-1860: A Disaggregate Time-Series Perspective", *Explorations in economic history*, 37(1), 98-119.
P.107, Para 2, line 5: add reference: (Allen, 2000)
P.112, line 2: add footnote after World War I: ‘World War One was seen as the end of the first phase of globalisation and the end of a golden era.’
P.112, add sentence after Para 1: ‘The two wars manifest themselves are ‘blips’ in the upward, stationary trend growth of the US economy that never suffered occupation or significant destruction of domestic infrastructure or domestic fixed capital.’
P.118, add sentence after first sentence: Negative TFP growth at any point of time would imply that technological change is not happening.’
P.127, Para 3, line 2: delete ‘correctly’ and add ‘better’ before ‘measureable and contribute’
P.131, last line, add footnote after sentence: ‘Overall economy denotes all sectors of the economy. The annual hours worked for manufacturing and service sector is assumed to be same as overall economy because as an economy becomes more developed, higher proportion of labour join these two sectors and the productivity of labour in the economy are driven mostly by these sectors.’
P.131, last line: add before sentence ‘Although there is no empirical evidence’,
P.132, first line, replace ‘there was no restriction on working hours of farmers unlike manufacturing and services’ by ‘farmers were more free to choose their working hours compared to manufacturing and service sectors.’
P.132, Para 3, line 6: delete word ‘finally’
P.132, Para 3, line 1: add after ‘R&D expenditure’ ‘, which is shown in the first panel of figure 4.5,’
P.133, Para 2, line 9: add footnote after sentence: ‘It is empirically tested that the results are not sensitive to constraining tractors to zero before 1910.’
P.138, adds sentence before last sentence: ‘Greasley and Oxley (1998) argue in favour of the role of high skilled graduates in enhancing US productivity especially when compared to the type of tertiary graduates being produced in the UK.’
P.143, notes to table 4.6, delete the line ‘The AR(1) term is included as an additional regressor in a few estimations to correct for serial correlation.’
P.152, line 6: add reference after sentence: (Habakkuk, 1962).
P.161, Para 2, line 2: add before the start of sentence: ‘Within the constraints of the models tested,’
P. 64: replace Table 3.1 by the new table below.

Table 3.1: Output and labour productivity growth in English agriculture (% per annum)

Period	Output		Labour Productivity	
	Clark	Deane & Cole	Clark	Deane & Cole
1620-1700	0.12	----	0.07	----
1620-1750	0.27	----	0.18	----
1750-1800	-0.09	0.51	-0.12	0.39
1800-1850	0.86	2.65	0.51	2.13
1760-1850	0.40	1.72	0.21	1.41
1700-1850	0.43	1.14	0.26	0.88
1620-1850	0.32	----	0.19	----

Note: Average annual growth rates over the period are considered for each variable. Data for Deane and Cole is only available in the period 1700 onwards.

P. 64: replace the first two paragraphs following Table 3.1 by the paragraphs below.

"The trends of output and labour productivity growth rates of British agriculture presented in Table 3.1 shows that according to Clark's data the average annual growth rates were lower in c. 1620-1700 (0.12% and 0.07%) compared to c. 1620-1750 (0.27% and 0.18%). The growth rates were further negative in c. 1750-1800 (-0.09% and -0.12%). Although this is not reflected in Deane and Cole's data, which shows positive growth rates in that period, estimates from Clark's data indeed supports Allen's scepticism about contribution of agriculture in the post 1750 period until c. 1800. However, considering the break point at 1700 and comparing the growth rates between pre 1700 to post 1700 periods, both output and labour productivity grew at a higher rate in the period 1700-1850, ranging from 0.43% to 1.14% for output and 0.26% to 0.88% for labour productivity, respectively. The most productive period is identified in the second half of the revolution period from 1800-1850, when output grew at a rate of 0.86% to 2.65% and labour productivity grew at 0.51% to 2.13%, respectively. Thus, Table 3.1 confirms the existence of an agricultural revolution in the first half of nineteenth century (Allen, 1999; 2004). Overall, compared to c. 1620-1700, the average annual growth rates of output and labour productivity in the period 1700-1850 are more than triple, and the growth rates are even higher in the period 1800-1850. In addition, above evidence provides support in favour of Allen (1999, 2004) of higher agricultural contribution before 1750 and after 1800, but not in between c. 1750-1800.

The average annual growth rate is always higher for Deane and Cole as compared to Clark. This is due to limitations and differences of these data sources, which are discussed in more details in section 3.4 under measurement issues. Nonetheless, evidence presented in Table 3.1 shows that input productivity figures were almost doubled in 1850 as compared to 1700. This indeed suggests that the output growth was accompanied by increased labour productivity growth in the period 1700-1850, except in the period 1750-1800, when the growth rates were either negative according to Clark's data or low according to Deane and Cole's data. Keeping in mind that addition of land input was sluggish and proportion of labour in agriculture was falling, input productivity of land and labour were increasing, particularly after 1800. With diminishing returns to factor inputs, this increase in labour productivity can only be sustained by successful technological progress. The next section models the agriculture sector with land as a fixed factor of production and shows that in the absence of capital, labour productivity growth in the agricultural sector is a race between growth in technological progress and growth in the agricultural labour force."

P. 99 (conclusion section): replace second paragraph by the paragraph below.

"Although results from this chapter confirm that throughout the period 1620-1850 there was a positive role played by higher research intensity in the British agricultural sector in augmenting the labour productivity growth, this study does not provide any clear-cut support in favour of when the Agricultural Revolution happened in England. Section 3.2 shows that output and productivity growths were higher in post 1800 as compared to c. 1750-1800, where the growth rates in the later period were found to be negative in case of Clark's data. Combining this evidence with the empirical results, it is probably the case that higher spill over effects ran from industry to agriculture in the post 1800 period with the introduction of new farm machineries and techniques (Allen, 2004). The growth in agricultural sector continued till 1750/60 and then slowed down at the beginning of the Industrial Revolution in c. 1760. However, the growth in agriculture was again restored after c. 1800, when higher technological progress facilitated higher input productivity growth in Britain. Allen (2004) describes this increase in farm output in 1850 as compared to 1700 as twofold: due to increase in use of land, labour and capital by agriculture and due to improvements in farm methods and organisation. These improvements resulted sharp rise in productivity after c. 1800. Thus even though this study does not specify any date of occurrence of Agricultural Revolution, empirical results confirm that by c. 1850 the role of technological progress remained eminent in augmenting agricultural growth in England. Innovations in both small and large farms helped in advancing the integrity in farming and also gave new initiatives for a commercialized agriculture in England."

P. 102: insert after reference 3: Allen, R. C. (2004), "Agriculture during the industrial revolution, 1700–1850." The Cambridge Economic History of Modern Britain (Vol. 1), R. Floud and P. Johnson (eds.), Cambridge, Cambridge University Press.

P. 113-117: replace paragraph 2 in p.113 to paragraph 1 in p. 117 by the paragraphs below and in P. 114, P. 116: replace Figure 4.1 and Figure 4.2 by the new figures below.

"Figure 4.1 below shows the comparative total factor productivity (TFP) and labour productivity (LP) of the US and the UK in the period 1840 to 2008. Comparative TFP is defined following Broadberry (1993). However in contrast to Broadberry (1993), land is here incorporated as an additional factor of production, where comparative TFP is the geometric weighted average of comparative capital productivity, comparative land productivity and comparative labour productivity. This can be expressed as equation (4.0A) below. In case of manufacturing and service sectors, land is not included as additional factor of production and thus equation (4.0A) can be translated as equation (4.0B).

$$\frac{TFP^{US}}{TFP^{UK}} = \left(\frac{(Y/K)^{US}}{(Y/K)^{UK}}\right)^{\alpha} \left(\frac{(Y/T)^{US}}{(Y/T)^{UK}}\right)^{\beta} \left(\frac{(Y/L)^{US}}{(Y/L)^{UK}}\right)^{1-\alpha-\beta} \quad (4.0A)$$

$$\frac{TFP^{US}}{TFP^{UK}} = \left(\frac{(Y/K)^{US}}{(Y/K)^{UK}}\right)^{\alpha} \left(\frac{(Y/L)^{US}}{(Y/L)^{UK}}\right)^{1-\alpha} \quad (4.0B)$$

where Y is real output, T is land, L is employment and K is the real capital stock. Broadberry (1993) did not include land separately as factor of production and his equation looked like the equation (4.0B). Broadberry measured (1-α) in equation (4.0B) to be 0.77, which is the geometric mean of the US and the UK wage shares in net output in year 1975 following van Ark (1990). The share of comparative land productivity (β) is measured here as share of agricultural income to total income. The value of β is set to 0.1, which is the geometric mean of the shares of agricultural income in total income in the US and the UK in the year 1975. Thus comparative labour productivity in equation (4.0A) is weighted by (1-α-β), the value of which is 0.67, after subtracting β from 1-α. The corresponding year of calculation of the share of comparative land productivity is chosen 1975 to keep the point of times same among all comparative input productivities.

Equations (4.0A) and (4.0B) can be further expressed as equations (4.0C) and (4.0D) in terms of the ratio between comparative output levels and comparative total factor input (TFI):

$$\frac{TFP^{US}}{TFP^{UK}} = \frac{Y^{US}/Y^{UK}}{(K^{US}/K^{UK})^{\alpha}(T^{US}/T^{UK})^{\beta}(L^{US}/L^{UK})^{1-\alpha-\beta}} = \frac{Y^{US}/Y^{UK}}{TFI^{US}/TFI^{UK}} \quad (4.0C)$$

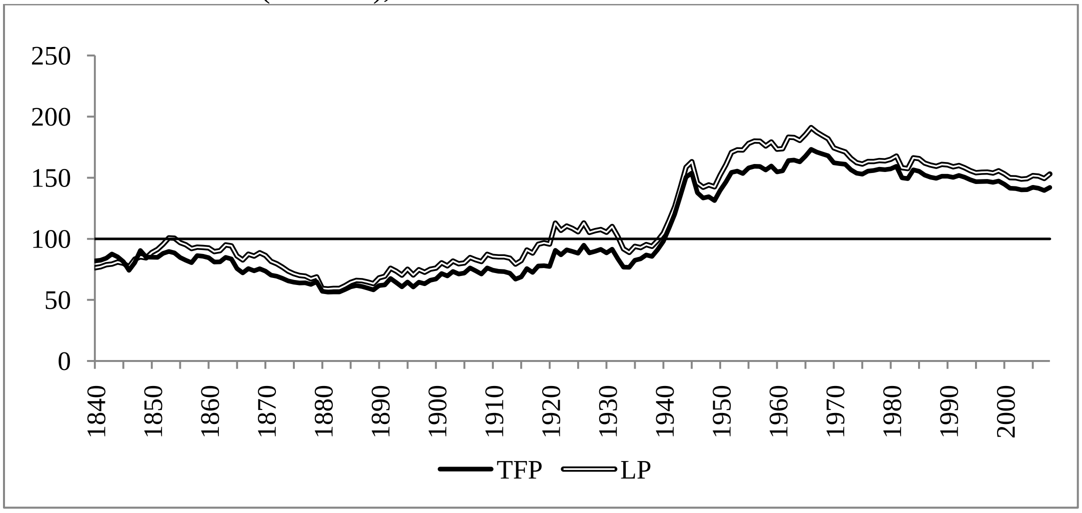
$$\frac{TFP^{US}}{TFP^{UK}} = \frac{Y^{US}/Y^{UK}}{(K^{US}/K^{UK})^{\alpha}(L^{US}/L^{UK})^{1-\alpha}} = \frac{Y^{US}/Y^{UK}}{TFI^{US}/TFI^{UK}} \quad (4.0D)$$

While, equation (4.0C) represents overall comparative TFP and comparative agricultural sector TFP, equation (4.0D) represents the comparative TFP in manufacturing and service sectors. The data sources are described in the appendix of the chapter. In Figure 4.1 the vertical axis measures the ratios of TFP and LP of the US and the UK, respectively. UK is indexed to 100. In terms of catching up and convergence, when UK is the productivity leader, the series are negative and falling. Furthermore, when the series are still negative but rising, it means that the US has started to catch-up to the UK or the gap between the two economies is reducing. However, if the series are positive and rising, it implies that the US has higher productivity growth than the UK.[1]

From Figure 4.1 it is evident that labour productivity in America almost converged to its counterpart in Britain in the mid-nineteenth century, but could not maintain the lead due to the industrial revolutions that Britain was experiencing at that time. Around 1880 and more prominently in the last decade of the nineteenth century, labour productivity growth and TFP growth in America began to increase at a faster rate than in Britain. This is demonstrated by the consistently increasing trend in the comparative labour productivity and TFP in Figure 4.1 from 1880 to 1920. Labour productivity converged between the two economies in c. 1920; whereas US TFP still remained below until c. 1940. The period 1880-1920 can be termed the early take-off period for the US, as it led the foundation for America's dominance of the world economy in the twentieth century. The slowdown in the US growth process in the middle years between 1920 and 1935 was mainly due to the aftermaths of the World War One and early hit by the Great Depression. Thereafter, the US maintained the lead over Britain until present time. The US productivity growth in the post 1930 period till 1945 showed a sharp increase, which was again interrupted by the consequences of the Second World War in c. 1950.

[1] 100 on the vertical axis imply that the productivities of the two economies have converged at that point in time.

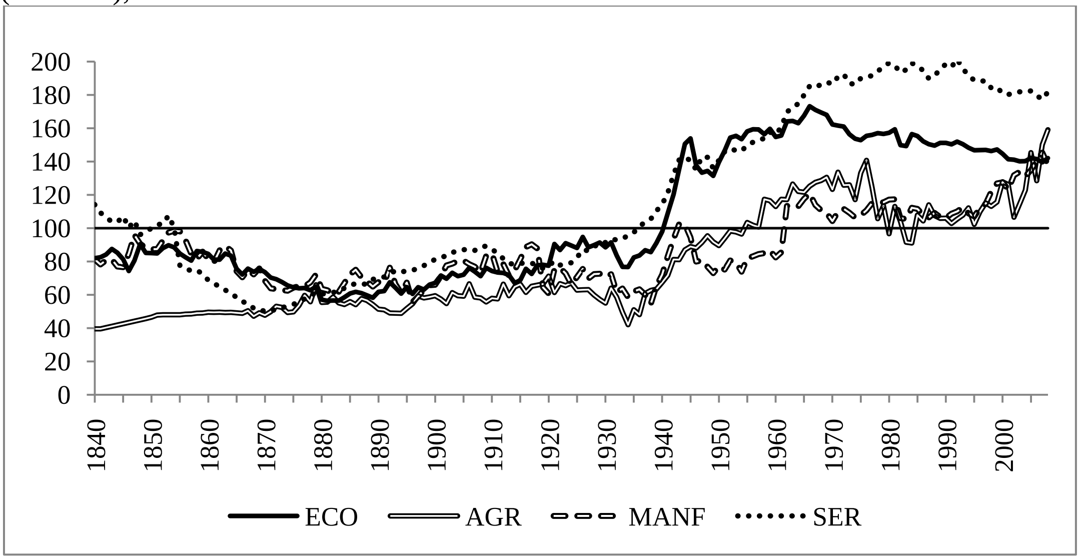
Figure 4.1: Comparative Total Factor Productivity gap and Labour productivity gap in the US and in the UK (UK=100); 1840-2008



Note: The comparative TFP is measured according to equation (4.0A).

Comparative TFP and labour productivity shows a similar trend in Figure 4.1, which almost overlapped in c. 1845, 1885 and in the US growth period of 1935-1945, respectively. Unlike labour productivity, comparative TFP converged for the first time c. 1940 and is always lower than comparative labour productivity. In post-World War II, after 1950s, due to technological catch-up by Europe, the productivity lead of the US slowed down in favour of the UK and finally in the post 1970 period, both LP and TFP gaps show a declining trend, but they are still positive in the current decade.

Figure 4.2: Comparative Sectoral Total Factor Productivity Gap in the US and in the UK (UK=100); 1840-2008



In Figure 4.2 the sectoral comparative TFP gap between the two economies in the period 1840-2008 is examined. The overall economy wide comparative TFP is well represented as the weighted average of the comparative sectoral TFPs throughout the period in Figure 4.2. Sectoral comparative TFPs overlapped with the economy wide comparative TFP in c. 1880, which is the beginning year of strong growth in the US economy. In addition, the slow growth in the US in c. 1920 is identified as the growth drag by agricultural and manufacturing sector in that period due to early hit by the Great Depression. Economy wide TFP gap is still stable because of the US service sector growth, which counterbalanced the decreasing growth of the other two sectors. The sharp productivity growth in the US economy around c. 1935-1945 is contributed by all three sectors with service sector as the highest contributor among the three sectors.

While the service sector had a continuously increasing trend in favour of the US in the periods 1870-1910 and 1920-1970, the US agricultural sector shows a fluctuating but increasing trend in the periods 1840-1920 and 1935-1970. In the 1920s, the sharp decline in America's agricultural TFP lead was due to it being hit early by depression that hit the world in 1930s (Feinstein *et al.*, 2008, page 64). The US was one of the major agricultural exporters before and during World War I, when farmers used to borrow freely to expand their markets. However in the 1920s, debts of the farmers emerged ever larger as the agricultural prices fell and consequently the agricultural sector was caught by early depression. The manufacturing sector TFP gap, on the other hand, had the early lead from the 1840s, which was lost in the subsequent years due to industrial revolutions that Britain was experiencing at that time. Looking at the long run trend in the manufacturing sector gap, it seems that the sector has maintained a stable growth rate until 1930s. The high growth in US economy around c. 1935-1945 has been contributed by all three sectors. However, US manufacturing sector was very badly hit in the post Second World War, which shows the lowest growth among the three sectors in c. 1950-1980.

The first half of twentieth century can be identified from Figure 4.2 as being more productive for both the agricultural and service sectors in the US, when the manufacturing sector gap was roughly constant. Oxley and Greasley (1995) and Greasley and Oxley (1998) compare the industrial production of these two economies on the basis of the catching-up hypothesis, focusing on the industrial gap in terms of per-capita income, real wages and industrial output per worker. They find no convergence in industrial output per worker between these economies. Their results support Figure 4.2, where the manufacturing TFP gap shows no sign of convergence between the economies.
The similarity of the trends between the economy wide and agricultural sector TFP gaps at the start of the twentieth century shows that there was indeed a positive role played by agriculture in the catching up period. The claim of this study is further supported by the fact that the American economy always had the added advantage of vast land resources and technological advancement in farming as compared to Britain. Although these findings support Broadberry and Irwin (2006), who argue that the US manufacturing lead was maintained from the early mid nineteenth century and a more important role was played by the service sector, in addition to their claims, this study identifies that there was a positive role played by agriculture in the period 1840 to 2008. The gap was reduced steadily in the period 1840 to 1920 and also in the period 1935-1970. Since the start of the 1990s, while the service sector shows no high growth in favour of the US, the agricultural and the manufacturing sectors have a lead, showing an upward trend in Figure 4.2."

P. 159: insert after reference 4: van Ark, B. (1990), "Comparative levels of Manufacturing Labour Productivity in Post war Europe", *Oxford Bulletin of Economics and Statistics*, 52, pp. 343-74.