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Sources of Productivity Growth in the American Coal Industry 1972–95

Denny Ellerman, Thomas M. Stoker,
and Ernst R. Berndt

9.1 Introduction

Aggregate productivity statistics succinctly and conveniently measure the efficiency with which resources are being used in a country or industry, but problems of measurement and aggregation in the inevitable presence of heterogeneity require that these statistics be interpreted carefully to avoid misleading results.

This paper exploits an unusual database to explore the differences between productivity trends as they appear at the aggregate level and as they may be experienced at the firm level. The Mine Safety and Health Administration (MSHA), as part of its mandated regulatory effort, has collected labor input and coal output information for every mine in the United States since 1972, along with data on site locations, operator identity, and mining techniques (U.S. Department of Labor, MSHA, "Part 50 Coal Mining Address/Employment and Accident/Injury Files"; henceforth USDOL, MSHA, Part 50). Thus, labor productivity can be observed for this industry at the lowest practicable level; and, based on this microdata, a national aggregate, as well as any number of subaggregates, can be formed from the bottom up. Working from microdata all the way up to the aggregate industry level not only supplements industry aggregate statistics but also permits an examination of the root causes of aggregate productivity change with greater clarity than is usually the case.

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9.2 The American Coal Industry

9.2.1 Postwar Output, Price, and Productivity Trends

Although the database for this paper limits analysis to 1972–95, a longer view helps to place these years, and particularly the extraordinary decade of the 1970s, in perspective. Figure 9.1 provides the essential aggregate statistics for the U.S. coal industry: the price and quantity of output and an index of total factor productivity (TFP) from the late 1940s until 1991 (Jorgenson, 1990, plus update). The year our microdata begins, 1972, is close to the year 1969, which according to anecdote as well as statistics, marked a turning point for the industry.

The Mine Safety and Health Act was passed in 1969, signaling the beginning of what was to be a decade of increasing regulation to address issues associated with the health, safety, and environmental aspects of coal mining. Perhaps not coincidentally, 1969 also marked the end of a long period of declining real price and moderately increasing productivity. The 1970s were to be characterized by sharply rising nominal and real prices for output and significant declines in coal mining productivity. Then, in

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Massachusetts Institute of Technology, and director of the Program on Technological Progress and Productivity Measurement at the National Bureau of Economic Research.

This work has been made possible by the dedicated efforts of a succession of research assistants who have worked on the massive database underlying the research. We are particularly indebted to Susanne Schennach and Chiaming Liu, the most recent of these assistants and formerly graduate students in MIT's Department of Economics and Sloan School of Management, respectively, who performed much of the final regression and simulation analyses. Their work and this paper would not have been possible, however, without the earlier contributions of Frank Felder, Babu Bangaru, Kevin Wellinius, and Narasimha Rao, all former MIT graduate students who assembled the database that made this analysis possible.

Personnel at the Mine Safety and Health Administration in Denver, Colorado, the source of our data, have been extremely helpful in clarifying definitional and procedural issues concerning the data collection. Special thanks are due Alice Brown, chief of statistics, and Rhys Llewellyn, head of the data division.

This research has been funded chiefly by the Center for Energy and Environmental Policy Research through grants from a number of corporate sponsors supporting MIT research in energy and environmental economics. Early funding for this project was also provided by the Office of Coal, Uranium, and Renewable Fuels Analysis at the Energy Information Administration in the U.S. Department of Energy. To all, we are grateful.

This paper has benefited from comments and insights provided by a number of persons in the U.S. coal industry and participants in the NBER/CRIW conference at which this paper was first presented. Among coal industry personnel, particular gratitude is due William Bruno of Consolidation Coal Company, William Dix of the Pittsburg and Midway Coal Mining Company, and the senior management of both Cyprus Amax Coal Company and the Pittsburg and Midway Coal Mining Company. Among NBER/CRIW participants, we are especially indebted to our respondent, Larry Rosenblum, and to Dale Jorgenson and the late Zvi Griliches for insightful and encouraging comments. Responsibility for any errors is, however, solely ours.

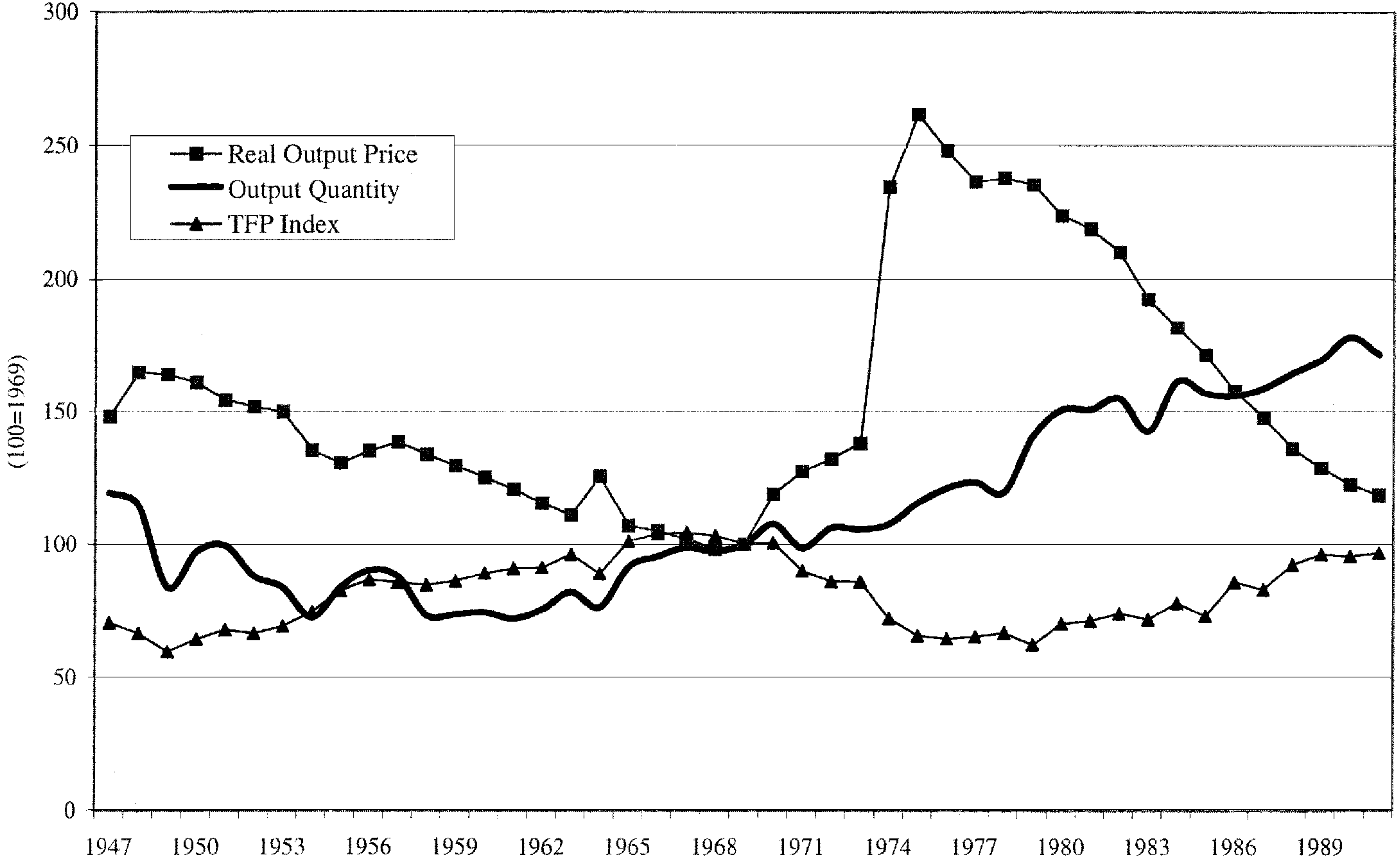

Fig. 9.1 Price, quantity, and TFP, U.S. coal industry

the 1980s and continuing to the present, the former trend of declining real price and rising productivity resumed, albeit at an accelerated pace.

9.2.2 Elements of Heterogeneity in the Industry

There are a number of reasons for approaching aggregate coal productivity statistics with caution. Coal is produced in many locations in the United States, from the Great Western Basin to the Appalachian Mountains, and labor productivity differs among coal-producing regions, whose shares of output have changed significantly over the past twenty-five years. In particular, coal from the Powder River Basin (PRB, in the northeastern corner of Wyoming and adjacent parts of Montana) increased from less than 1 percent of national production in 1970 to 25 percent in the mid-1990s. Although the PRB is located far from most coal markets, unusually favorable geology enables operations there easily to produce twenty to thirty tons of coal per hour of labor input. In contrast, eight to ten tons per hour is as much as the best mines in the Midwest or Appalachia can reasonably hope to achieve. Thus, even if there were no change in productivity within any region, the increasing PRB share would cause the national aggregate for labor productivity to increase.

Although quantity of output is conventionally measured in tons of production, the ultimate service sought by nearly all coal purchasers is heat content (measured in British thermal units, or Btu), which also varies considerably across regions. Again, the PRB requires special consideration: The Btu content of each ton of coal produced there is a third to a quarter less than the heat content of Midwestern or Appalachian coals. Thus, although the increase in PRB coal production has been great, however production is measured, statistics based on tons overstate the importance of the PRB and growth in aggregate national labor productivity. The same arguments apply for lignite (an even lower rank of coal than that produced in the PRB),[1] whose share of national output has also increased, though not as spectacularly as that for PRB coal.

Traditionally, coal mining has been an underground operation in which a shaft is sunk or tunnels are extended into the seam, from which coal is removed and transported to the surface. Underground mining techniques are further divided into two basic types: continuous and longwall mining. Continuous mines employ machines with giant bits mounted in front that advance into a seam to remove coal from the face and pass it back to a

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[1] Coal is conventionally classified by rank (from highest to lowest quality) as anthracite, bituminous, sub-bituminous, and lignite. Rank is determined by a number of characteristics, among which is Btu content. Most coal produced in the United States is of bituminous rank, which ranges from 21 to 28 million Btu (mmBtu) per short ton. Sub-bituminous coals, including that produced in the PRB, range from 16 to 23 mmBtu per ton, and Lignites have a heat content from 12 to 17 mmBtu/ton. Production of anthracite coal is insignificant and can be ignored for all practical purposes after the Second World War. For a more complete discussion of coal classifications, see U.S. DOE/EIA-0584(94), *Coal Industry Annual 1994,* table C1.

shuttle car or conveyer belt system to transport to the surface. Such systems require tunnels, and a portion of the coal must be left in place as pillars to support the roof. Longwall mining, on the other hand, involves an elaborate shearing device that operates along an extended face (hence the term *longwall*), an attached shield that supports the roof, and a conveyor belt to take the coal to the surface. The distinctive feature of longwall mining is that the whole device—shearer, roof shield, and conveyor system—advances into the face as coal is removed. The strata above the coal seam are then allowed to subside into the cavity created by the advancing longwall.[2] As a result, a higher percentage of the reserve can be removed by longwall mining than by continuous mining. The longwall shearer also separates a greater volume of coal from the seam per unit of time than does the continuous miner.

Coal lying close to the surface is mined by techniques in which the overburden is stripped away to expose the coal seam, after which the overburden is put back in place and the original surface condition is restored. Bulldozers, steam shovels, draglines, and trucks are employed in a giant earth-moving operation more akin to modern road building than to the underground mining that conjures traditional images of black-faced miners tunneling through the bowels of the earth. All three production techniques compete in most coal-producing regions, although some areas, such as the Powder River Basin and the lignite-producing areas of Texas and North Dakota, are mined exclusively by surface methods.

9.2.3 Eleven Relatively Homogeneous Subaggregates

In order to account for such geographical, geological, and technological heterogeneity, we assign each coal mine in the United States to one of eleven subaggregates, or groups. Table 9.1 lists these groups and the average heat content assumed for coal produced by each. In general, the western foothills of the Appalachian Mountains divide the Appalachian and Interior regions, and the Great Plains separate the Western and Interior regions. Coal quality generally diminishes westward from Appalachia. We separate Western surface mining into three groups: the PRB; lignite, produced only in North Dakota, Texas, and Louisiana and the only coal that is surface mined in these states; and all other Western surface mining (subsequently called Western Surface Ex or WSX). This latter group is extremely heterogeneous but not very important.

Labor productivity varies widely among the eleven subaggregates. As if to offset the tendency of coal quality to decline from east to west, the absolute level of labor productivity improves from east to west. In particular, the PRB enjoys levels that are from two to eight times greater than other regions. The two other Western surface regions also have labor pro-

[2] The roof is supported in the conventional manner for a passage to provide entry and egress at one end of the advancing longwall face. See USDOE/EIA (1995) for more details.

Table 9.1 Characteristics of the Eleven Subaggregates

Geographic Region	Production Technology	Heat Content (mmBtu/short ton)
Appalachia	Underground/continuous	23
	Underground/longwall	23
	Surface	23
Interior	Underground/continuous	21
	Underground/longwall	21
	Surface	21
Western	Underground/continuous	22
	Underground/longwall	22
	Powder River Basin	17
	Lignite	13
	Other surface	20

ductivity higher than all groups excepting the PRB, although by the end of the period, Western longwall productivity had drawn equal to their level. Labor productivity has also varied over time. Labor productivity declined for all the subaggregates through the late 1970s or early 1980s, and improved thereafter. From 1972 to 1978, the national aggregate coal productivity declined from 45 to 37 mmBtu/h of labor input (2.0 to 1.6 standard tons),[3] and thereafter increased steadily to a value of 112 mmBtu/h (4.9 standard tons) in 1995.

The relative shares of Btu output by these eleven regions in terms of Btu output are given in figure 9.2. The three Appalachian regions are the bottom three bands, representing continuous, longwall, and surface production, respectively, followed by the three Interior regions, with the five Western regions at the top of the graph. Two points are notable. First, the contribution of Western coal has increased tremendously, from slightly less than 8 percent of coal Btu output in 1972 to 40 percent in 1995. In particular, the PRB has risen from 1.5 percent to 24 percent of the U.S. coal industry's Btu output. Second, despite a decline in share from 66 percent to 48 percent between 1972 and 1995, Appalachia remains the largest producer of Btu's from coal.

9.3 Aggregate Measures of Productivity Change

9.3.1 Labor and Total Factor Productivity

Though our purpose in this paper is not to address the difference between aggregate TFP and labor productivity growth, the two are closely

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[3] The unit of quality-adjusted output for these productivity figures is millions of Btu per hour (mmBtu). As noted in table 9.1, a standard (eastern) short ton of coal is equivalent to about 23 mmBtu.

Fig. 9.2 Btu output shares by component, 1972–95

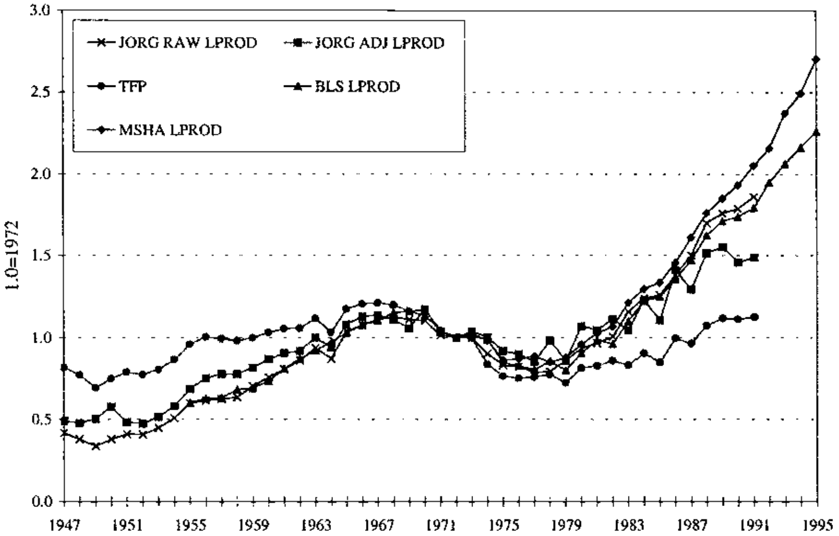

Fig. 9.3 Comparison of labor productivity with TFP

related. Figure 9.3 displays the total factor productivity (TFP) index, first introduced in figure 9.1, with various labor productivity indexes. Five indexes are shown, all normalized to the 1972 value. Three indexes, spanning the years 1947–1991, draw upon aggregate coal industry statistics developed by Jorgenson and associates:[4] output quantity divided by raw labor hours (Jorg Raw Lprod), labor productivity when labor hours are adjusted for quality differences (Jorg Adj Lprod),[5] and total factor productivity. The fourth index (BLS Lprod), extending from 1955 through 1995, is the Bureau of Labor Statistics' measure of labor productivity, which for all practical purposes coincides with Jorgenson's non–quality adjusted labor productivity index (USDOL, BLS, 1996). The last index (MSHA Lprod) is formed from the 1972–95 MSHA data by summing each year's production across all mines and dividing by the comparable sum for labor hours.

The close correspondence among the MSHA, BLS, and Jorgenson non–quality adjusted labor productivity indexes indicates that the same underlying phenomena—coal output and undifferentiated labor input hours—are being measured. Moreover, labor productivity and TFP move together, albeit at different rates. During the progressive periods, labor productiv-

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[4] The development of these aggregate statistics is described in Jorgenson, Gollop, and Fraumeni (1987) and Jorgenson (1990). Updated series through 1991 were kindly provided by Dale Jorgenson and Kevin Stiroh.

[5] Output is treated as homogeneous, notwithstanding some notable differences in the quality of coal produced by different mines and regions. We address this issue in what follows.

ity improves at a rate greater than that for TFP; during the one period of regress, labor productivity does not fall as sharply as TFP. Earlier econometric work using Jorgenson's industry-level statistics suggests the coal industry has a strong labor-saving bias to technical change (Berndt and Ellerman 1996). This bias explains most of the difference between the rates of TFP and aggregate labor productivity improvement that can be observed in figure 9.3. That research also suggests that a more or less constant relation exists between rates of change in labor productivity and TFP.

Finally, labor constitutes the largest input value share in output for the coal industry. Approximate aggregate shares are labor, 40 percent; materials, 30 percent; and capital and energy, about 15 percent each, although in recent years there has been a slight tendency for the labor share to decline and for the materials share to increase. This suggests that observed changes in labor productivity can, with appropriate adjustment, be used as an indicator of change that is highly correlated with TFP.

Further support for viewing labor productivity as a proxy for TFP can be found in the relationship between output prices and labor productivity in different coal-producing regions. If factor proportions are more or less constant across regions, output prices would reflect, inversely, differences in absolute labor productivity. In fact, such an inverse relationship is observed. Coal produced in the extraordinarily productive PRB currently sells for \$4–5 per ton at the mine, whereas lower-productivity coal produced in the Midwest sells at the higher price of \$18–23 per ton, and still lower-productivity Appalachian coal sells for even more, \$22–28 per ton (*Coal Markets,* various issues). These price relationships are roughly the inverse of average 1995 mmBtu/h productivity levels in these regions.

9.3.2 Decomposition of the National Aggregate

The national aggregate for coal labor productivity is the sum of output across the component mining groups or subaggregates divided by the analogous sum for labor input. As shown in equation (1), this aggregate is equivalent to an input weighted average of labor productivity in each mining group.

$$(1) \qquad \frac{Q}{L} = \frac{\sum_i Q_i}{\sum_i L_i} = \sum_i \frac{L_i}{\sum_i L_i} \frac{Q_i}{L_i}$$

In this equation, Q represents output and L labor hours, and subscripts denote components of the aggregate. The absence of a subscript indicates the aggregate for the respective variable. The aggregate rate of change can be decomposed into the sum of changes (denoted by d) in input shares and in productivity (Q/L) for each component, weighted by output:

$$\frac{d\left(\frac{Q}{L}\right)}{\frac{Q}{L}} = \sum_i \frac{Q_i}{Q} \frac{d\left(\frac{Q_i}{L_i}\right)}{\frac{Q_i}{L_i}} + \sum_i \frac{Q_i}{Q} \frac{d\left(\frac{L_i}{L}\right)}{\frac{L_i}{L}} \tag{2}$$

The first term on the right-hand side of equation (2) can be used to form an index that would indicate average *output*-weighted productivity improvement. The second right-hand side term is a similarly weighted index of the change in *input* shares. It indicates the extent to which aggregate productivity is affected by reallocation of labor input resulting from both shifts in the geographical distribution of the demand for coal and differing rates of labor productivity improvement among the subaggregates. The easiest interpretation of this second term is that it indicates the extent to which a completely aggregated index of labor productivity (i.e., the left-hand side term) differs from the output weighted average of changes in labor productivity for the components of the aggregate (i.e., the first right-hand side term).[6] The first term on the right-hand side would be the appropriate aggregate measure of productivity change if production from the various components did not compete in the market.

Table 9.2 provides several aggregate measures of productivity change in the U.S. coal industry, based on the MSHA data. The top row in table 9.2 represents the conventional measure of aggregate labor productivity, where the numerator, output, is stated in tons of coal. The second row is the Btu corrected ("quality adjusted") expression of the same index, using the heat content assumptions listed in table 9.1. Treating all tons as if they were equal leads to a slight overstatement of productivity improvement: about a third of a percentage point in annual growth over the entire period. The bottom two rows represent Btu output-weighted indexes for labor productivity improvement, using two different decompositions.[7] The bottom line treats each of the eleven subaggregates as independent, noncompeting entities—obviously, a lower bound. A more nearly correct estimate is provided by the three-region index, in which the implicit assumptions are that coals produced by continuous, longwall, and surface techniques compete within the Appalachian, Interior, and Western regions, but not between these regions.

Table 9.2 also displays values at the key turning points for these indexes and the intervening annual rates of change. In both the 1970s and 1980s,

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[6] The second right-hand side term in equation (2) would sum to zero only if (a) labor productivity change were uniform across components and output shares were unchanged, or (b) output is increasing at the same rate as labor productivity for each component. Although not impossible, it is unlikely that either condition would occur.

[7] In constructing these indexes, we use the Törnqvist approximation of the Divisia index, in which the share weights are the arithmetic average of the beginning and ending shares for each discrete, annual change.

Table 9.2 **Alternate Measures of Productivity Change**

Index	1972	1978	1995	1972–78 (%)	1978–95 (%)	1972–95 (%)
Tons	1.00	.850	2.704	−2.71	+6.81	+4.32
Btu	1.00	.819	2.458	−3.33	+6.47	+3.90
Three regions	1.00	.756	1.963	−4.55	+5.77	+2.98
Eleven mining groups	1.00	.657	1.634	−7.00	+5.36	+2.14

the national aggregates, whether in tons or Btu's, provide a misleading picture of productivity change in the coal industry. Productivity declined during the 1970s, but the severity of the decline in the subaggregates is masked in these national aggregates by the increasing share of the higher-productivity Western regions. The Btu index suggests that labor productivity declined at a rate of about 3.3 percent per annum from 1972 through 1978, while the disaggregated index indicates that labor productivity was falling on average by more than twice that rate, or 7.0 percent per annum. During the subsequent period of rising productivity, the misstatement of the national aggregate (i.e., not taking into account compositional changes) is not as severe, but is still present. The national Btu aggregate indicates a rate of improvement from 1978 to 1995 of 6.5 percent per annum, whereas the production weighted average improvement in labor productivity in the constituent groups for these years is 5.4 percent per annum. Over the whole period from 1972 to 1995, labor productivity is not 2.7 times its 1972 level, but from 1.65 to 1.95 times that level, and the annual rate of improvement is about half of what it otherwise would appear to be.

9.3.3 Differing Trends among the Subaggregates

So far we have noted only the differences in absolute levels of labor productivity among the eleven subaggregates, and the changes of share among them. An equally, and perhaps more interesting, aspect is the very different rates of productivity improvement observed among these mining groups. Of particular note is that labor productivity of Western longwall mining was more than five times its 1972 level in 1995; its improvement is twice that of the mining group experiencing the next greatest improvement in labor productivity (Appalachian longwall mining). Moreover, four of the five surface mining subaggregates have labor productivity levels in 1995 very little different than in 1972, although better than in the late 1970s. The fifth surface mining region, the PRB, experienced more labor productivity improvement, but only as much as the least progressive underground mining subaggregates. By contrast, Western longwall mining is only the most outstanding of what is generally impressive productivity improvement for all underground mining. Another regularity is that for each of the three main regions, longwall mining is experiencing greater rates of productivity improvement than are continuous mines. Finally, there is a clear regional ordering in rates of productivity improvement by coal mining technology. Given the mining technique, labor productivity is highest in the West, followed by Appalachia, with the Interior region in last place.

9.4 Data and Methodology

9.4.1 Database Description

The Mine Safety and Health Act of 1969 requires each coal mine in the United States to report quarterly to the MSHA on accidents and incidents, as well as tons produced, employees, and hours worked (USDOL, MSHA, Part 50). Each mine is issued a unique mine identification number that is retained as long as the mine is active. In addition to accident data, the quarterly reports contain the following information:

current name of the mine and reporting address
location of the mine, by county and state
tons of coal produced for the quarter being reported
number of employees and employee hours associated with the mine
whether the coal is mined by underground or surface techniques[8]

Our study has summed the quarterly data to obtain annual observations, of which there are some 86,000 on 19,098 individual mines that reported production during at least one quarter from 1972 through the end of 1995.

Production is measured in "clean" tons produced. A clean ton is a ton that has been screened and washed to remove rock and dirt and is ready for shipment to the customer. Although the raw ton that comes from the mine is not clean, the factor to convert raw, run-of-mine coal to clean coal is well known and applied prospectively by operators for MSHA reporting purposes. This factor tends to be mine specific, reflecting the geology of the mine, but is not necessarily constant over time.

In order to identify longwall production, we had to add data to the MSHA database. The industry magazine *Coal Age* (now *Coal*) has conducted an annual longwall survey since the late 1970s (*Coal Age,* various issues). This survey lists every longwall mine for the given year and indicates, among other things, when the longwall panel was first installed. We use the name, location, and other information from the longwall survey and another industry publication (*Keystone Coal Industry Manual* 1996) to match each reported longwall mine with an underground MSHA mine

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[8] We defined surface techniques to include the small amounts of coal produced by augers and dredging and from culm banks.

identification number. Unless the industry survey indicates that a longwall has been removed, we consider all production at a mine since the installation of a longwall to be longwall production.[9]

Because output prices vary considerably by location, separate price indexes were created to correspond to the Appalachian, Interior, Western, Lignite, and PRB subaggregates. The Energy Information Administration of the U.S. Department of Energy collects and publishes nominal mine-mouth coal prices by state on an annual basis.[10] For the Appalachian, Interior, and Western regions, the prices reported for each coal-producing state within these regions are weighted by that state's quantity share of coal production for the region, as reported in the MSHA database, and summed to form a regional index of nominal coal prices.

Unlike coal output prices, labor markets are reasonably well integrated not only across coal-producing regions, but also with competing employment in construction and other related industries. Accordingly, we use a single national index for the wage rate in all regions: average hourly earnings for production workers in Standard Industrial Classification (SIC) number 12 (Coal Mining), as reported in the *Employment, Hours, and Earnings* series published by the Bureau of Labor Statistics. Finally, nominal prices for output and labor are deflated to real prices using the consumer price index. Further data details are spelled out in Ellerman, Stoker, and Berndt (1998, a more detailed version of the present chapter with tables appended).

9.4.2 Specification of the Model for Estimating Labor Productivity

The principal aim of our empirical analysis is to describe succinctly how labor productivity varies over individual mines in order to gain a better understanding of changes in aggregate coal productivity. In our panel data set, we incorporate fixed mine effects and time effects.

For coal mines, numerous geological features are essentially unique to each mine location and remain more or less constant over time. For instance, for underground mines, these features include seam height; roof conditions; width, length, and slope of the seam; and surface structures relevant to accessibility of various parts of the seam.

Other important features tend to change over time but affect all mines more or less equally in a given year. New advances in coal-mining technology tend to diffuse quickly across mines and raise labor productivity, but the precise impact on a given mine still varies with the mine's ability to

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[9] In fact, continuous miners used to prepare the longwall panels and ancillary passageways account for some of the production.

[10] See USDOE/EIA, *Coal Production Annual* (now *Coal Industry Annual*) for various years since the 1970s. Prior to the formation of the U.S. Department of Energy and the Energy Information Administration in the 1970s, this data was collected by the Bureau of Mines and published in the *Minerals Yearbook.*

benefit from a particular advance in technology. Other time-varying factors are specific to particular years, such as strikes, which featured prominently in coal mining during the 1970s. Several prominent regulatory programs were also enacted and implemented during this decade, and these measures could be expected to affect coal-mining productivity in one year or over several years. Finally, although mine-mouth prices vary according to netback considerations involving location and coal transportation systems, those prices tend to move together from year to year within a given coal-producing region, moderated at some mines by long-term contract terms.

Annual output Q_{it} and labor (man-hours) input L_{it} is observed for each mine i for each year t that the mine produces, $i = 1, \ldots, N_{group}$ and $t = T_{1i}, \ldots, T_{Ti}$, where "producing" is defined as having positive observed output. Mines were classified into the eleven groups indicated in table 9.1: three broad geographic regions (Appalachia, Interior, and Western); three distinct mining technologies (surface, continuous, and longwall) for each of these regions; and two unique surface mining regions (Lignite and the PRB) located in the Western United States.

A standard modeling approach for productivity analysis assumes price-taking behavior for output and input prices at each mine, with optimal output levels chosen either when marginal profits became zero or when output reached the physical maximum capacity of existing production facilities. That is, labor productivity is implied by the optimal choices concerning output and inputs, given the price of coal (net of transportation costs) and prices of all associated inputs. The existing facilities and types of technology are chosen via a medium- to long-term planning process, based on geological features of the mine site and expectations of future prices.

We have not adopted this standard approach mostly because appropriate price information is not available and mine-specific capital cannot be observed. Moreover, output at most mines is produced under coal supply contracts of more than a year's duration that specify many features of the contracted supply, including the quantity to be produced. The duration and incidence of these contracts is less in the 1990s than in the 1970s, and the contracts have always been more prevalent in the West than in the East, but these contracts still largely define the conditions under which coal is produced for market (Joskow, 1987). Thus, in modeling labor productivity, we assume that output quantity is determined exogenously by contract, and that operators strive toward efficiency and higher labor productivity, conditional on output scale.[11]

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[11] In a related paper (Berndt, Ellerman, Schennech, and Stoker 1999), we carry out numerous statistical tests of the exogeneity of output and find no evidence that the estimates presented here would change substantially by relaxing this assumption.

For mines within each of the eleven group classifications, the basic model takes the form

$$(3) \qquad \ln\left(\frac{Q_{it}}{L_{it}}\right) = \tau_t + \alpha_i + F(\ln Q_{it}) + \varepsilon_{it}.$$

The parameters τ_t, $F(\cdot)$ and α_i vary by group classification in our analysis, although for simplicity the group distinction is omitted from the notation.

The mine-specific fixed effect α_i captures all time-invariant, mine-specific geological and technical attributes by establishing a base level of (log) labor productivity for each mine. The time effect τ_t represents the common impact of all year-specific changes, such as common technological advances, input price effects, and regulations for each classified group of mines. The disturbance ε_{it} is assumed to capture all other idiosyncratic features of productivity for each mine, to be normally distributed with mean zero and constant variance, and to be uncorrelated across mines and time periods.[12]

Estimation of the model, as well as numerous diagnostic tests, are covered in a related paper by Berndt and colleagues (1999). In the present paper, a brief description of the basic approach to estimation is given, and issues relating to interpretation of the model are discussed. The resulting estimates are presented in the following section.

Of particular interest is the way labor productivity varies with scale of operation; this is represented by the unknown function $F(\cdot)$ of (log) output Q_{it}. A nonparametric approach to the specification of $F(\cdot)$ is adopted on the assumption that it is well approximated by a polynomial in log output. Within the context of the panel model in equation (3), the order of the log output polynomial for each region is chosen by least squares cross validation.[13] The result is that all regions are adequately described by a cubic polynomial in log output:

$$(4) \qquad F(\ln Q_{it}) = \beta_1 \ln Q_{it} + \beta_2(\ln Q_{it})^2 + \beta^3(\ln Q_{it})^3.$$

Specifically, for six of the groups, a cubic polynomial is indicated; for three groups, a quadratic polynomial is indicated ($\beta_3 = 0$); and for two groups, a log linear function is indicated ($\beta_2 = 0$, $\beta_3 = 0$).

In the panel data format, time effects τ_t capture the impacts of all variables that are time varying but equal across mines during any given time period. In order to examine the relationship between coal productivity and

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[12] Little detailed information is available on mine features that vary across mines and time other than output and labor input. Seam height is reported; however, close inspection of this data showed that the values given were almost always constant over time, and thus part of the fixed effect for each mine.

[13] We considered up to fifth-degree polynomials. For a general discussion of cross validation, see, among many others, Green and Silverman (1994).

prices, these time effects are related to real prices and wages, in a separate equation, as follows:

$$\tau_t = \kappa + \gamma_p \ln p_t + \gamma_w \ln w_t + \delta D_t + \eta_t \tag{5}$$

where ln p_t is the log of real coal price and ln w_t is the real wage rate. Here γ_p is the labor productivity elasticity with respect to real coal prices on common productivity levels and γ_w is the elasticity with respect to real wage changes. We include a test of the hypothesis that $\gamma_p = -\gamma_w$ for each region, which tests whether the time effects depend only on the coal price-wage ratio. The variable D_t is a dummy variable for 1972 and 1973, found to be empirically necessary to account for the change of regime in the outlook for coal that followed the four-fold increase in the price of oil associated with the Arab Oil Embargo in late 1973. On the basis of testing, we apply $\gamma_p = -\gamma_w$, to define a restricted form of equation (5) and set $\delta = 0$ for groups where those restrictions are not rejected. The remainder, η_t, gives the common log productivity level net of price and wage effects.

There are several important features to note from this structuring of the time effects. First, without additional assumptions on the structure of η_t, the price and wage effects are not identified, and equation (5) places no restriction on the panel equation (3). Consequently, we adopt a two-stage approach to estimation. The first stage is to estimate equation (3) by ordinary least squares (OLS), with fixed time and mine effects, giving a series of estimated time effects $\hat{\tau}_t$, $t = 1, \ldots, T$. The second stage is to estimate equation (5) using OLS with the estimated time effects $\hat{\tau}_t$ as dependent variables. This gives estimates of the price and wage elasticities, as well as the coefficient on the 1972–73 dummy variable. The estimated residuals from equation (5), $\hat{\eta}_t$, represent the remaining time effects after taking price effects into account (what we later term *residual time effects*). This is consistent with an assumption that the residual time effects are stochastic with zero mean, and

$$\operatorname{cov}(\ln p_t, \eta_t) = 0; \quad \operatorname{cov}(\ln w_t, \eta_t) = 0 \tag{6}$$

where covariance is taken over time periods. However, the structure of equations (5) and (6) is not imposed on equation (3) for the initial estimation, because of our interest in the overall level of time effects.

One way to view this procedure is that we are assuming equations (3)–(6) but using an inefficient two-stage estimation procedure. Another way is that we are not assuming equation (6), but are using OLS to define the split between price and wage effects, and residual time effects in equation (6) (imposing the empirical analogue of equation [6]).

The panel data approach gives a flexible empirical model for accounting for mine heterogeneity. Because of this flexibility, some interesting issues are difficult to study. Suppose one were interested in measuring linear depletion (or mine-specific learning) effects by including the age of the mine as a regressor. Age, however, is perfectly collinear with a linear combination of the mine and time effects. A model with the linear age effect has the same fitted values as a model without such an effect, with the estimated age effect not necessarily representative of the aging process (separate from the mine and time effects). If a specific nonlinear aging profile were available for representing depletion, then a depletion effect could be measured; however, we have no a priori reason for choosing a particular depletion profile.

Before proceeding with the discussion of empirical results, we comment briefly on the interpretation of our methodology. Although this approach for studying labor productivity is very flexible, it serves primarily as a method for describing mine-level changes in productivity over the past two decades. The approach is clearly reduced form in nature, in that the process under which particular innovations give rise to improvements in productivity with scale is not specified, nor is the way those innovations differentially impact mine types and regions. Our work is therefore best viewed as a cohesive description of general patterns of change in coal-mining productivity. Improving upon this would require a more detailed accounting of other factors involved in coal production and in the choice of mining technique.

Earlier we noted the importance of the assumed exogeneity of scale in our approach. A number of other potential sources of bias are avoided by our panel data format, in particular by the estimation of mine-level fixed effects. For instance, selection bias may arise from excluding nonoperating mines, so the estimates could commingle efficient production decisions with the decision whether to keep a mine in operation. In fact, the rate of coal mine turnover is quite pronounced. However, the impact of selection on our model would be to introduce a familiar (Mills ratio) bias term that would reflect the probability of a mine's continuing in operation. To the extent that this term does not vary substantially over time, it is included as a component of the fixed effect estimated for the mine. We view the decision to keep a mine in operation as strongly influenced by mine-specific factors, so the fixed effects adequately account for selection bias. If additional information that suggests a strong correlation between scale changes and exit (given mine-specific factors) were to arise, our scale structure could be subject to some bias in estimation. In that case, our scale estimates are interpretable as including those correlations relevant to the decision to continue mine operation.

9.4.3 Regression Results

Full sets of estimates of the panel equation (3) are attached as an appendix to Ellerman, Stoker, and Berndt (1998). As discussed earlier, the scale-labor productivity relationship in equation (3) is modeled as a polynomial in log output, of orders 1, 2, or 3, chosen on the basis of cross validation (cf. equation [4]). Estimates of these scale effects are presented in table 9.3 for underground mines and in table 9.4 for surface mines. Actual magnitudes of the coefficients are generally difficult to assess (because they are polynomial coefficients embedded in the model with firm and time effects); nonetheless, some common patterns can be discerned.

Underground continuous mines are characterized by clear estimated nonlinear patterns of log labor productivity increasing with scale. For underground longwall mines, two groups (Appalachia and Interior) are log linear with strong positive scale effects. Western longwall mines have an estimated structure with the same shape as that for underground continuous mines.

These estimates are all consistent with substantial economies of scale. For example, it is easy to verify that if the log linear models, Appalachia

Table 9.3 **Cubic Scale Coefficients: Underground Mines**

	Continuous			Longwall		
	Appalachia	Interior	Western	Appalachia	Interior	Western
ln Q	1.784	5.223	2.192	0.471	0.333	9.212
	(35.9)	(11.3)	(6.86)	(33.57)	(7.66)	(2.97)
$(\ln Q)^2$	−0.158	−0.411	−0.165			−0.731
	(−28.7)	(−10.0)	(−4.81)			(−2.863)
$(\ln Q)^3$	0.00519	0.0113	0.00467			0.0199
	(26.0)	(9.40)	(3.95)			(2.863)
Number of mines	8,339	173	128	111	14	29
N	38,100	1,295	902	1,216	106	224
R^2 within mines	0.335	0.634	0.556	0.774	0.923	0.573
R^2 overall	0.265	0.439	0.609	0.745	0.865	0.797

Notes: Polynomial order chosen by cross validation, and t-statistics in parentheses.

Table 9.4 **Cubic Scale Coefficients: Surface Mines**

	Appalachia	Interior	Western	Lignite	PRB
ln Q	1.686	1.502	1.207	1.178	1.801
	(24.6)	(7.93)	(15.93)	(13.70)	(14.204)
$(\ln Q)^2$	−0.128	−0.114	−0.0314	−0.0222	−0.0447
	(−17.2)	(−6.12)	(−9.24)	(−6.32)	(−9.366)
$(\ln Q)^3$	0.0037	0.00348			
	(14.0)	(5.802)			
Number of mines	9,019	1,260	87	40	30
N	37,161	5,219	789	506	450
R^2 within mines	0.302	0.391	0.673	0.767	0.828
R^2 overall	0.177	0.179	0.619	0.529	0.609

Notes: Polynomial order chosen by cross validation, and t-statistics in parentheses.

Table 9.5 **Relative Price Effects**

				Test of General Equation (5)	
	Log Relative Price Effect	Log Relative Wage Effect	Dummy 1972–73	R^2	$\gamma_P = -\gamma_W$ (p-value)
Underground continuous mines					
Appalachia	−0.399	−0.011	−0.130	0.923	0.0075
	(−13.5)	(−0.1)	(−4.8)		
Interior	−0.759	0.321	−0.287	0.802	0.2098
	(−6.8)	(0.8)	(−4.0)		
Western	−1.071	0.870	−0.079	0.554	0.7477
	(−4.2)	(1.1)	(−0.6)		
Underground longwall mines					
Appalachia	−0.858	0.202	−0.407	0.968	0.0021
	(−21.6)	(1.0)	(−11.2)		
Interior	−1.449	1.140	—	0.877	0.5341
	(−8.9)	(1.9)			
Western	−1.432	1.474	−0.735	0.380	0.9691
	(−3.2)	(1.1)	(−3.3)		
Surface mines					
Appalachia	0.174	−0.500	0.389	0.742	0.2006
	(3.3)	(1.8)	(8.0)		
Interior	−0.252	0.105	0.259	0.538	0.7561
	(−1.6)	(0.2)	(2.6)		
Western	−0.110	−0.379	0.517	0.530	0.4330
	(−0.4)	(−0.5)	(4.1)		
Lignite	−0.617	−0.360	−0.031	0.877	0.0001
	(−9.0)	(−1.6)	(−0.6)		
Powder River Basin	−0.399	0.002	0.263	0.688	0.4468
	(−3.9)	(0.0)	(3.1)		

Notes: Each category: twenty-four time periods, and t-statistics in parentheses. Dash indicates no production prior to 1976.

and Interior longwall, arose from Cobb-Douglas technologies, the overall output elasticities implied by the estimates are 1.471 and 1.333, respectively, which are substantially greater than 1, the value associated with constant returns to scale.[14] The patterns of coefficient signs are uniform across regions and technologies with cubic scale effects, quadratic scale effects, and log linear scale effects.

Table 9.5 summarizes the results of regressing the time effects estimated

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[14] Berndt and colleagues (1999) examine returns to scale estimates under several alternative stochastic assumptions. While their estimates differ, they find virtually no evidence against the overall hypothesis of increasing returns to scale for each group.

with equation (3) on the log of real coal price and log real wage rate. The elasticity of coal price is expected to be negative, as higher coal prices call forth the employment of less productive labor. The estimates are in fact negative and significantly different from zero at ($p < 0.05$) for eight mining groups. The elasticity of labor productivity with respect to real wages is expected to be positive, but it is statistically insignificant for all mining groups in this estimation presumably because of the very slight variation in the real wage rate over the period of this study. The 1972–73 dummy is statistically discernible for eight of the ten mining groups for which it is applicable. The p-values for the test of the restricted form of equation (5) against the general equation (5) are reported for each mine group, and the equality is accepted for eight of the eleven subaggregates. On the whole, the degree of correlation between estimated time effects and log coal prices is quite high.

9.4.4 Indexes of Productivity Change by Source

We now decompose the aggregate change in labor productivity in U.S. coal mining into basic sources of productivity change in order to understand the roles of price, scale, time, and the features embodied in each mine. The data and model permit productivity indexes to be created for each mine group, as follows.

The measurement of sources of productivity growth follows the decomposition inherent to the basic equations (3) and (5). For each group, aggregate productivity at time t is given as

$$(7)\quad \frac{\sum_i Q_{it}}{\sum_i L_{it}} = \frac{\sum_i L_{it} \exp\left(\ln \frac{Q_{it}}{L_{it}}\right)}{\sum_i L_{it}} = \frac{\sum_i L_{it} \exp(\hat{\tau}_i) \exp(\hat{\alpha}_i + \hat{F}(\ln Q_{it}) + \hat{\varepsilon}_{it})}{\sum_i L_{it}}$$

using equation (3), where "hats" denote the use of the estimated parameter values. Using equation (5), this simplifies to

$$(8)\quad \frac{\sum_i Q_{it}}{\sum_i L_{it}} = \exp(\hat{\kappa} + \hat{\gamma}_p \ln p_t + \hat{\gamma}_w \ln w_t + \hat{\delta} \mathrm{D}_t)$$

$$\exp(\hat{\eta}_t) \frac{\sum_i L_{it} \exp[\hat{\alpha}_i + \hat{F}(\ln Q_{it}) + \hat{\varepsilon}_{it}]}{\sum_i L_{it}}.$$

Equation (8) suggests the following definitions of productivity indexes. First, price impacts on productivity are indicated by the price effect index based on equation (5):

$$P_t = \exp(\hat{\kappa} + \hat{\gamma}_p \ln p_t + \hat{\gamma}_w \ln w_t + \delta D_t). \tag{9}$$

The remaining common time effects, namely those net of prices, are indicated by the residual time effect index, based on the estimated residual in equation (5):

$$R_t = \exp(\hat{\eta}_t). \tag{10}$$

The overall common time pattern is completed as the product, $P_t \cdot R_t$.

The remaining term in equation (8) captures elements that vary across mines within each time period. In general, this term does not cleanly decompose. The following approximate decomposition can be defined, consistent with the notion that fixed effects, scale effects, and residual (microheterogeneity) terms are independently distributed (in the labor weighted distribution of firms).

Scale effects are indicated by the scale effect index:

$$SC_t = \frac{\sum_i L_{it} \exp[\hat{F}(\ln Q_{it})]}{\sum_i L_{it}}. \tag{11}$$

The mine-specific (initial) productivity levels for each mine are indicated by the fixed effect index:

$$FE_t = \frac{\sum_i L_{it} \exp(\hat{\alpha}_i)}{\sum_i L_{it}}. \tag{12}$$

Finally, the remaining heterogeneity in labor productivity across mines is indicated by the residual microheterogeneity index:

$$MR_t = \frac{\sum_i L_{it} \exp(\hat{\varepsilon}_{it})}{\sum_i L_{it}}. \tag{13}$$

The final term in equation (8) is not generally equal to the product of these three indexes because of correlation between estimated fixed effects and scale, or because of higher order moments between fixed effects, scale effects, and the residuals from the estimated equation (3). As a result, changes in observed aggregate labor productivity for each of the eleven mining groups will not be exactly replicated. Consequently, the predicted productivity index, defined as

$$PR_t = SC_t \cdot FE_t \cdot MR_t \cdot P_t \cdot R_t, \tag{14}$$

will err to the extent that the scale effects, fixed effects, and residual microheterogeneity are not independent. The predicted index in equation (14) permits a ready decomposition of the change in aggregate labor productivity into five sources: price, time, scale, fixed mine-specific features, and residual microheterogeneity.

9.5 Sources of Productivity Change

We now report results obtained when the conceptual framework just described is implemented empirically.

9.5.1 Scale Effects

The panel data regression yields estimates of the effects of changing output on labor productivity; these effects are significant and positive for all eleven mining groups, as indicated by the results reported in tables 9.3 and 9.4. We refer to these effects as scale effects, but the term *scale* is being used in a very limited sense. It refers to the changing levels of output over time. Inputs into the production process other than labor are not observed, so we do not know whether the conventional definition of scale as a proportionate increase of all inputs would apply. Also, the relation between productivity and output is estimated only over time, and not across mines during the same time period. To the extent that there is a persistent cross-sectional relation between output and productivity, it would appear in equation (3) as a fixed effect.

The estimated value for the productivity-output elasticity varies according to the output level for those mining groups requiring a higher-order polynomial. The values of these productivity-output elasticities are remarkably uniform. All take positive values lower than unity, and most values fall in a range between 0.30 and 0.50. Even though the cubic specification permits great flexibility, a tendency toward uniformity by mining technique was found. The three typically large mine-size Western surface mining groups show declining elasticity with output, whereas the Eastern surface mining and continuous mining subaggregates show increasing elasticity with output. The longwall mining subaggregates form the exception to the general uniformity by mining technique. For two longwall regions, Appalachia and Interior, the quadratic and cubic terms drop out of the estimating equation so that the indicated scale elasticity is constant over the range of observed output. For Western longwalls, the full cubic specification is required and scale elasticity rises steadily and dramatically over the observed range. In fact, the value approaching unity, indicated for the largest output observed for this mining group, must be questioned because such values imply that labor has ceased to be an essential input.

The extent to which the productivity-output elasticity affects aggregate productivity depends in part upon the change in output level at mines that continue in production from one year to the next. Because entering and exiting mines would affect average size but not scale effects as defined here, average mine size is not a perfect indicator of the extent to which this elasticity matters. Nevertheless, it is an acceptable one for this data set because average mine size changes mostly as a result of changing output levels at continuing mines, not because entering or exiting mines are on average significantly larger or smaller than continuing mines.

National average mine size increased by about 2.5 times between 1972 and 1995, but the components exhibit tremendous diversity. Western mining groups increased steadily in average mine output over the period, whereas Interior and Appalachian subaggregates experienced a decline in average mine size during the 1970s and an increase thereafter. As of 1995, average mine size was larger than it was in 1972 for all subaggregates except Interior surface mining. The three largest increases were registered by three Western subaggregates—PRB, Lignite, and Western longwall mining—where average mine size rose 4.5–6 times over the 1972 levels.

The effect of changing output levels on labor productivity is represented by the scale effect indexes, computed as a scale elasticity weighted change in observed output at any given mine. Among the eleven mining groups, four subaggregates stand out: Appalachian longwall (App LW) mining and the three Western mining groups (the PRB, Lignite, and Western longwall mining). Our model indicates that if nothing else had changed, increases in output levels at continuing mines would have increased labor productivity from 1.7 (App LW) to 2.2 (Lignite) times the 1972 level. For the other seven subaggregates, the contributions of changing output levels to labor productivity were not particularly important. The 1995 indexes for these mining groups range from 0.85 (Interior surface) to 1.22 (Appalachian surface).[15]

9.5.2 Fixed Effects

As seen in equation (12), the fixed effect index is the labor-share weighted sum of the fixed effect coefficients for producing mines in each successive year. The average of fixed effect coefficients for all producing mines over all time periods is zero; however, the mean of fixed effect coefficients for any single year within the sample can differ from zero, and typically varies as individual mines with differing coefficients enter and exit. As such, it reflects the extent to which time-invariant, mine-specific features of producing mines are causing productivity to increase or decline.

One obvious and plausible interpretation of the fixed effect index is that it reflects the productivity-enhancing effects of the technology embodied

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[15] The scale effect index for Appalachian continuous mining is less than 1.0 in 1995, whereas average mine size is 30 percent larger than in 1972. This mining group is characterized by a short average mine life (four years) and a high degree of entry and exit. In this case, new mines tend to be bigger, but the output level at mines does not increase during their short average lives.

in each new vintage of mines. If capital equipment and other features of mine layout and design improve labor productivity with each successive vintage, then the mean of fixed effects coefficients would increase over time. As earlier noted, the index could be expected to increase if cross-sectional scale effects exist.

There are other interpretations for changes observed in the fixed effect index. Geological features are an important consideration in a minerals extraction industry such as coal mining. The successive development and depletion of the best prospects over time would contribute to a declining fixed effect index, although for coal, the ordering of mines for development does not necessarily follow geological criteria, since transportation cost can be as important as mining cost in determining economic viability.[16] It has also been suggested to us that, at least in Appalachia, the sale of coal reserves previously owned by integrated steel companies has led to the exploitation of better reserves during much of the period of this study. Finally, if unionized mines are characterized by lower labor productivity, as is asserted, then the increasing share of nonunion mines would increase the mean of the fixed effects coefficients. Considerably more analysis is required to distinguish among these various interpretations. For the present, we take the index to represent potentially all these influences on mine-level productivity.

We find that the fixed effect indexes for the eleven subaggregates have regional patterns that are almost the exact complement of what we found for the scale effect indexes. Five of the seven regions that were not particularly distinguished by scale effects now reveal steadily rising labor productivity due to the changing composition of mines. These five regions include all three continuous mining subaggregates and Appalachian and Interior surface mining. In contrast, the four regions experiencing a significant increase in the scale effect index show very little impact from fixed effects; one region, lignite, shows a marked decline. For two of these regions, the PRB and Western longwall mining, the fixed effect means are approximately the same in 1995 as they were in 1972, although the means declined markedly during the 1970s and rose at 2–3 percent per annum during the 1980s and 1990s. Rising fixed effect indexes are consistent with improving technology with each new mine vintage, but it is curious that this effect would occur consistently only with continuous mining in all regions and Appalachian and Interior surface mines.

These indexes' differences in behavior by mining group emphasize one important qualification to be remembered when interpreting the indexes: When the number of mines is small, as is the case in some mining groups during some years, a single mine's entry or exit can unduly influence the

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[16] The PRB illustrates the development of good geological prospects far from market on a national scale; the same effect could occur within any subaggregate.

Table 9.6 **Maximum (minimum) Number of Mines by Subaggregate**

	Longwall Mines	Continuous Mines	Surface Mines
Appalachia	64 (32)	2,137 (870)	2,438 (864)
Interior	9 (1)	65 (36)	382 (93)
Western	15 (2)	58 (16)	47 (20)
Lignite	n.a.	n.a.	26 (13)
Powder River Basin	n.a.	n.a.	26 (5)

Note: n.a. = not applicable.

index. Table 9.6 shows the maximum and minimum number of mines observed in any year for each subaggregate.

Only three of the subaggregates have a number of mines in all years sufficiently large that the yearly means would not be greatly affected by the entry or exit of a few mines, or even a single one. For the others, particularly for those with very small numbers, the changing composition of mines can have a large influence.

9.5.3 Residual Microheterogeneity

The residual microheterogeneity index also reflects the effects of changes in mine composition within a subaggregate. Microheterogeneity can be usefully compared to macroheterogeneity, which is captured in our analysis by decomposing the very heterogeneous national aggregate into eleven more homogeneous subaggregates. Although the mines within each of these groups are more alike than they are similar to mines in other groups, heterogeneity does not stop at the subaggregates. There is every reason to believe there are differences among mines within these groups that are not captured in the primary panel regression. The effect of these differences on labor productivity will manifest itself, along with measurement error and stochastic variance, in the error term for each mine-year observation. The labor input weighted error terms for each year are then formed into an index to indicate the extent to which such unexplained microdifferences affect labor productivity.

For many of the subaggregates, the residual microheterogeneity indexes remain close to the 1972 level throughout the twenty-four-year period; however, a few subaggregates remain consistently above or below the rest, indicating greater error between observed and predicted productivities at individual mines. The indexes for longwall, continuous, and surface mining in the West are always above their 1972 levels and comparable index levels for all the other subaggregates. At the other extreme, indexes for Lignite

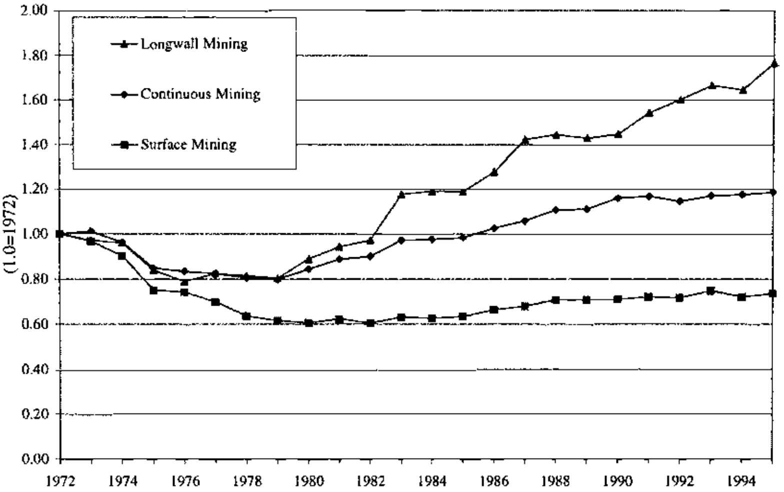

Fig. 9.4 Undifferentiated time effect indexes by mining technique

are consistently well below comparable indexes for all other subaggregates. These four mining groups—all in the West—are in fact the most heterogeneous of the eleven. Although there are differences within the Interior and Appalachian subaggregates, none are as great as those that occur in the West—for instance, between lignite mining in Texas and North Dakota, or between surface mines in New Mexico and Utah.

9.5.4 Time and Price Effects

The time coefficients from the primary panel regression create a very distinctive pattern of time effects in which two features stand out. First, the pattern is one of decline in the 1970s, regardless of technique or location, followed by a steady rise at varying rates of growth beginning in the late 1970s or early 1980s. Second, there is a definite clustering of these time effects by technology, as shown in figure 9.4.[17] In the middle and late 1970s, surface mining experienced a much greater time-related drop in labor productivity than did either of the underground mining techniques. Moreover, once the bottom was reached, the improvement in time-related effects was greatest for longwall mines (4.9 percent per annum), followed by continuous mining (2.5 percent), with surface mining showing the least improvement (1.4 percent). As a consequence of its deeper trough and slower recovery, surface mining's index of time-related productivity effects was only

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[17] The aggregate national indexes by mining technique are output-weighted products of the indexes for the constituent mining groups. Thus, the longwall index includes the Appalachian, Interior, and Western longwall mining groups. The Lignite and PRB mining groups are included in the surface mining index.

74 percent of the 1972 level in 1995, whereas the longwall and continuous mining indexes in the same year were 1.77 and 1.19 times the 1972 level, respectively. The explanation for these differing rates of change by technique lies in untangling several time related influences.

One of the most significant features of the American coal industry since 1970 is the dramatic change in the evolution of real output prices. As is shown in figure 9.1, the real price index for coal output more than doubled during the early 1970s and peaked in 1975. Real output prices in some regions peaked later; however, by the early 1980s, real output prices were falling in all regions, and they did so persistently thereafter, reaching the pre-1970 level by the early 1990s.

The fourfold increase in the price of oil during 1973 and 1974 transformed the outlook for coal, and this transformation affected both the price of coal and the relationship between coal prices and labor productivity. The effect upon coal prices was the most obvious and immediate, especially in Appalachia, where 65 percent of national Btu output from coal was then produced. The extraordinary increase in Appalachian coal prices in 1974 resulted from the combined effects of rapidly increasing oil prices following the late 1973 Arab Oil Embargo, increasing curtailments of natural gas deliveries, and the impending and actual strike by the United Mine Workers of America (UMWA) in late 1974 (U.S. Executive Office of the President 1976). The effects on output price showed up first and most strongly in Appalachia because it was the most well-developed coal-producing region, and spot and short-term contracts were far more prevalent there than elsewhere in the country (Joskow 1987). The UMWA strike passed quickly enough, but the high oil prices and continuing natural gas curtailments remained and were joined by official federal government policy to encourage domestic production of energy, epitomized by Project Independence (U.S. Federal Energy Administration 1974).

The transformed outlook created a surge of investment in coal and a very noticeable increase in the proportions of other factors of production to labor. Labor input rose sharply during the 1970s. Peak employment occurred in 1979 with 405 million employee hours, 58 percent above the 1972 level, corresponding with a 33 percent increase in output. Thereafter, output continued to increase, by another 33 percent by 1995, but labor input fell by 55 percent from the 1979 peak to 28 percent below its 1972 level. Part of this reduction is explained by the shift of production to higher labor productivity regions, notably the PRB, but trade journals and industry lore leave little doubt that a major response of operators, when faced with disappointing output prices in the 1980s, was to reduce labor input.[18]

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[18] For most of the eleven mining groups, labor input peaked in 1978–80. Labor input continued to rise only for the Interior and Western longwall groups, which enjoyed phenomenal rates of increase in output (11 percent and 15 percent per annum, respectively, to 1995) from very small 1979 levels.

The investment surge in the 1970s was not limited to labor, and the increases in other factors of production affected labor productivity. Detailed data on other factors of production are not available at the mine level, but aggregate input statistics are available at the industry level, and their testimony is eloquent. The comparison of the near panic year of 1974 with the preceding year is indicative of what characterized the mid and late 1970s. Quantities of input increased by 23 percent for labor, 85 percent for materials, 117 percent for energy, and 216 percent for capital services, whereas output increased in this strike-constrained year by only 1.9 percent.[19] Observed labor productivity declined by 17 percent, but the more important effect, from the standpoint of the relation between prices and labor productivity, was the increase in the ratios of capital to labor, energy to labor, and materials to labor. For the same output-labor price ratio, labor productivity shifted upward as a result of the even greater increases of other input quantities, all fueled by the stunning transformation in the outlook for coal after 1973.

The dramatic changes in output price and in factor proportions associated with the events of the mid-1970s and the transformation of the outlook for coal are the justification for the dummy variable that is introduced in equation (5) as a means of differentiating various time related influences on labor productivity. A curious result obtains, however. Although the coefficients for this variable are significant for nearly all the relevant mining groups, the sign is consistently different for the underground and surface mined coal groups. The negative coefficient for underground mining is what would have been expected: When output and labor input prices are held constant, the post-1973 world brought enhanced labor productivity reflecting the changes in the ratios of capital (and other inputs) to labor. In contrast, the positive coefficient for surface mining indicates lower labor productivity in the post-1973 world despite the increased proportions of other inputs to labor.

The explanation for this seeming paradox lies in the sequencing of regulatory requirements imposed upon the coal industry during the 1970s. The first major piece of regulatory legislation was the Mine Safety and Health Act, passed by Congress in 1969. The productivity-depressing effects of this legislation fell primarily on underground mining, and those requirements had been largely internalized by the mid-1970s (Baker, 1981). Surface mining regulations were imposed later. The defining legislation was the federal Surface Mining Control and Reclamation Act (SMCRA), which was enacted in 1977. Some states had imposed comparable requirements earlier, but widespread implementation of SMCRA requirements did not occur until the late 1970s. Because the MSHA data begin in 1972,

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[19] This comparison is based on aggregate industry data updated through 1991 that was provided by Dale Jorgenson and Kevin Stiroh, as reported in the appendices to Ellerman and Berndt (1996). See also note 4.

much of the productivity-depressing effect of the regulation of underground mining is already incorporated in the base year, whereas the full productivity-depressing effect of SMCRA on surface mining in later years is reflected in the indexes.

After 1973, the outlook was bright for coal, however mined, but surface mined coal had to contend with regulatory costs that underground mining had already internalized by 1973. The effect was to increase inputs and thereby to reduce surface mining productivity offsetting what otherwise would have been an increase in labor productivity due to the changed factor proportions, as observed in underground mining. The statistical result is that the sign of the 1972–73 dummy is reversed for surface mining, indicating higher labor productivity in these early years than in later ones, when labor input and output prices are held constant.

The later and staggered implementation of SMCRA implies that a dummy for the years 1972 and 1973 would not be a particularly good indicator for this effect. In fact, extending the 1972–73 dummy to include some later years for the surface mining regions greatly improves the fit of equation (5) as well as the precision of the estimated coefficients. For instance, expanding the 1972–73 dummy for the PRB to include 1974 and 1975 improves the fit from 0.69 to 0.95, as seen from the PRB entry in table 9.7. Every surface mining region exhibits a similar partition of data points, although the year that determines the shift differs from one group to another. Table 9.7 provides the reestimated coefficients for the auxiliary regression, corresponding to table 9.5 above, for the surface mining groups when the dummy is varied so that it corresponds to the year in which the shift of regime is observed.

For all surface mining groups, the fit is improved—significantly so for the Interior, PRB, and other Western surface mining groups. The effect of implementing this dummy for presumed SMCRA effects is to make the output price elasticities negative and statistically significant for four of the five regions instead of only two, and to change the Appalachian Surface mining coefficient from being significant and positive to being insignificant. The SMCRA dummy is highly significant and positive for all groups except Lignite. We have no explanation for the unexpected sign for the Lignite group, other than the usual note that the number of mines is small (see table 9.6) and the coal very different.

For some of the mining groups, prices and the dummy variable so completely account for time effects in the primary panel data regression that the price effect indexes (equation [9]) predict the values for the yearly time dummies. The resulting price effect indexes are plotted in figure 9.5. The index for Western longwall mining is erratic, but all the indexes display the same pattern that can be observed in the time dummies from the primary panel data regression, namely, decline and recovery, with differing rates of decline and recovery by mining technique.

Residual time effects are what remain of the undifferentiated time effects

Table 9.7 **Auxiliary Regression with Alternative Surface Mining Regulation Dummies**

Mining Group	Time Period of Dummy	Log Price Effect	Log Wage Effect	Dummy Effect	Adjusted R^2	p-value of Test of $\varepsilon_P = \varepsilon_W$
Appalachia surface	1972–74	0.051	0.035	0.351	0.886	0.6172
		(1.5)	(0.2)	(13.1)		
Interior surface	1972–77	−0.310	0.153	0.250	0.919	0.4227
		(−5.7)	(0.7)	(11.5)		
Western surface	1972–76	−0.605	0.732	0.425	0.906	0.6464
		(−6.1)	(2.2)	(12.8)		
Lignite	1972–77	−0.879	0.084	−0.159	0.918	0.0002
		(−8.8)	(0.4)	(−3.2)		
Powder River Basin	1972–75	−0.454	0.379	0.320	0.947	0.7249
		(−11.0)	(1.6)	(12.4)		

Note: t-statistics in parentheses.

[a] Except Powder River Basin and Lignite.

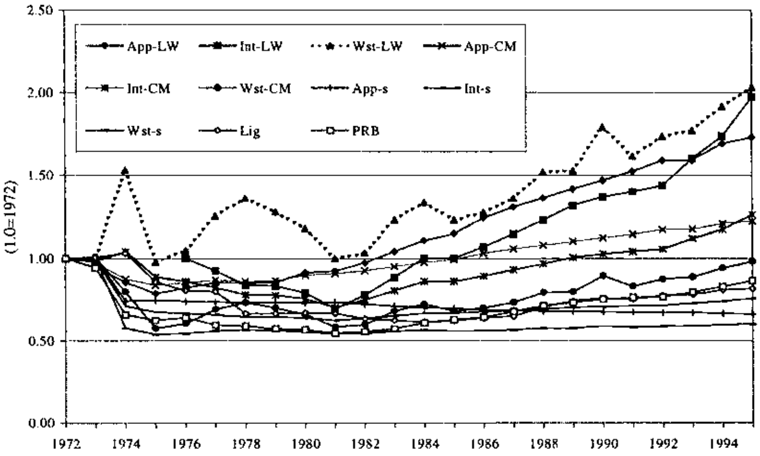

Fig. 9.5 Price effect indexes

after accounting for the influence of changing output price and the anomalous early years (equation [10]). The most remarkable feature of the residual time indexes is the absence of a strong trend for any subaggregate. There are some large variations, particularly by Western longwall-mining and four surface-mining groups in the 1970s, but for the most part the residual time effects appear to be true, trendless residuals. As a result, the auxiliary regression in tables 9.5 and 9.7 indicate that the distinctive pattern of declining productivity in the 1970s and rapid recovery thereafter is largely explained by the effects of the extraordinary changes in output price that were experienced from 1972 through 1995.

There is also a clear difference in the time trend by technique. The auxiliary regressions in tables 9.5 and 9.7 suggest that the difference is attributable to differing abilities to respond to changes in output price. Whether it is Appalachia, the Interior, or the West, the ordering of elasticities is always largest for longwall mining, next for continuous mining, and least for surface mining. Such a difference is possible, but it must also be recognized that differences in the underlying rates of technical improvement over time would tend to be attributed to price in the auxiliary regressions. The crude categorical variable we use to separate the pre-1974 and pre-SMCRA years is correlated with the years when output prices were rising, so that what might otherwise remain as a residual time effect is confounded with the price effect. It would not be surprising to observe such effects, since longwall mining is a newer technology than continuous mining, and has been increasing its share of production in all parts of the country. In contrast, continuous and surface mining are more conventional, "mature" technologies for which there may not be as much potential for improvement.

Still, even allowing for a greater degree of learning with the newer technology, surface mining remains a distinct laggard. Moreover, the Appalachian surface mining group remains a prominent exception to the generally significant negative relation between labor productivity and output price. One explanation, which has found confirmation in discussions with industry participants, is depletion. Surface mining reserves are inherently limited from below by underground reserves. The depth at which it is more economical to burrow into the earth to extract the coal than to remove the overburden determines the split between surface and underground reserves and the extent of surface mining reserves. Although underground mining reserves are also limited from below because costs increase with depth, they are at least expansible below, as advances in mining technology reduce costs and make greater depths more economically accessible. Such a depletion effect would be most likely to occur in Appalachia, and it could account for the failure of Appalachian surface mining to exhibit any price elasticity. For this mining group, for which prices peaked early, the productivity-depressing effects of depletion at individual mines may be offsetting the productivity-enhancing responses to lower output prices that operators would otherwise be making.

In the end, two features of the productivity time trends are clear. The sharp increase and subsequent decline in coal price over the years 1972–95 has significantly influenced coal-mining labor productivity. This factor appears to explain most of the reduction in observed productivity during the 1970s, along with the effects of surface-mining regulations during the latter half of the decade. There is secondly a marked tendency for underground mines, especially longwall mines, to experience more improvement in labor productivity over time than surface mines.

9.5.5 Aggregating the Sources of Productivity Change into a National Aggregate

The five separate productivity effects—scale, fixed, price, residual time, and microheterogeneity—can be aggregated in two ways. For any subaggregate, the five indexes can be multiplied, as in equation (14), to provide a predicted productivity index for that mining group. For most of the mining groups, the predicted productivity index is effectively indistinguishable from the observed aggregate indexes, as indicated in table 9.8, which gives the R^2 from a regression of the observed aggregate labor productivity on the reconstructed aggregate indices for the eleven subaggregates.

Three surface mining groups—Interior, Lignite, and PRB—have R^2's less than 0.95. These discrepancies, which are still not large (except for Lignite), reflect the error in the approximation used to split the last term of equation (8) into three separate indexes.

A second aggregation of the indexes can be made across mining groups to create national indexes for each source of productivity change. Here,

Table 9.8 **For for Predicted Aggregate Productivity with Observed Aggregate Productivity**

	Longwall	Continuous	Surface
Appalachian	0.998	0.995	0.981
Interior	0.999	0.991	0.872
Western	0.990	0.952	0.958
Lignite	n.a.	n.a.	0.758
Powder River Basin	n.a.	n.a.	0.908

Note: n.a. = not applicable.

Table 9.9 **Sources of Coal Mining Labor Productivity Growth (percent annual rates of change)**

	1972–78	1978–95	1972–95
Observed	−7.00	+5.24	+2.05
Predicted	−7.10	+5.44	+2.17
Scale effect	−2.06	+1.62	+0.66
Fixed effect	+1.68	+1.74	+1.73
Price effect	−4.72	+1.70	+0.03
Residual time effect	−1.00	+0.08	−0.20
Microheterogeneity	−0.99	+0.30	−0.04

the index for each subaggregate is weighted by its share of national output, and the resulting national indexes for each source of productivity change are then multiplied to form a national aggregate index of coal-mining labor productivity.

The observed change in national aggregate labor productivity for coal mining can be decomposed almost exactly into the sources of productivity change identified by this analysis. Table 9.9 shows annual rates of growth for the indexes for the periods of falling and rising productivity and for the entire period 1972–95.

During the 1970s, nearly everything seemed to conspire to reduce labor productivity, but the largest effect was attributable to the rising price of coal. The higher marginal revenue product of labor justified applying more labor to the task, and both statistics and anecdotes suggest that the first response of coal-mine operators was almost literally to throw labor (and other inputs) at the coal face. The inevitable result was lower productivity. The only phenomenon countering these productivity-depressing trends was the persistent improvement embodied in each successive vintage of new mines, as indicated by the fixed effect index. By the end of the 1970s, this source of productivity improvement was 15 percent above the 1972 level, but even this was more than overwhelmed by the combined effect of the other negative factors.

As seen in table 9.9 the period of rising labor productivity during the

1980s and 1990s is largely explained by three phenomena that contribute about equally. New mines (fixed effect) continued to have higher productivity, as they did during the 1970s; but the contributions from scale and price effects are what explain the more rapid observed increase in labor productivity since 1980. In the case of the price effects, the explanation is opposite in sign to what occurred during the 1970s. Also, during the 1980s and 1990s, continuing mines in all mining groups, particularly those in the West and those using longwalls, were able to increase output steadily with concomitant improvements in labor productivity.

9.5.6 What Is the Rate of Advance of the Technological Frontier?

Not far beneath the surface of most productivity research lies a desire to identify and quantify the rate of technological change, and this inquiry is no exception. For the U.S. coal industry, the question is especially intriguing because aggregate statistics suggest a period of significant technical regress in the 1970s. Properly defined as the technical know-how of producing coal, such regress seems implausible. Our analysis suggests that the observed reduction in labor productivity is largely explained by the unprecedented increase in the real price of coal during the mid-1970s and, to a lesser extent, by the internalization of regulatory requirements. Even though these factors were reducing observed labor productivity, the technical capability to produce coal was improving.

The national fixed effect index in table 9.9 would appear to be a likely candidate as a measure of the rate of underlying technical change, because of its very steady 1.7 percent rate of increase from 1972 to 1995. Yet, this index has its own problems. It is just the aggregation over the eleven subaggregates, and the component subindexes are not increasing for all of the mining groups, including some that exhibit the greatest improvement in labor productivity. Interestingly, mining groups that exhibit little or no growth in the fixed effects index invariably have a steadily increasing scale effects index. One index or the other contributes most of the increase in productivity over the whole period, and whichever one it is, the other contributes little. Moreover, the index that is more or less steadily rising appears to be related to average mine life and mining technique. Table 9.10 shows the annual rates of change for these two indexes from 1972 through 1995, and for the two combined, as well as the average mine life for each mining subaggregate.

The eleven subaggregates are listed in descending order of average mine life, and there is a definite tendency for one effect or the other to dominate, as indicated by the bold-faced numbers, depending on average mine life and mining technique. The scale effect tends to be the main driver of productivity improvement for subaggregates with longer mine lives, whereas the fixed effect is the main driver for subaggregates with shorter mine lives. Also, scale effects are more important for large western surface mines and

Table 9.10 **Relation of Average Mine Life to Scale and Fixed Effects Indexes**

		Average Annual Growth Rate, 1972–1995		
	Average Mine Life	Scale Effects	Fixed Effects	Combined
Powder River Basin	15.00	+**2.77**	+0.46	+3.23
Lignite	12.65	+**3.43**	−2.37	+1.06
Appalachian longwall	10.96	+**2.21**	−0.09	+2.12
Western surface	8.99	+**0.77**	+0.09	+0.86
Western longwall	7.72	+**2.97**	+0.60	+3.57
Interior longwall	7.57	+**1.00**	−0.55	+0.45
Interior continuous	7.49	+0.46	+**1.61**	+2.07
Western continuous	7.00	+0.46	+**3.15**	+3.61
Appalachian continuous	4.57	−0.30	+**3.17**	+2.87
Interior surface	4.14	−0.72	+**2.39**	+1.67
Appalachian surface	4.12	+0.87	+**2.16**	+3.02
National total	n.a.	+0.66	+1.73	+2.38

Note: n.a. = not applicable.

for longwall mining regardless of geographic region, whereas fixed effects are more important for continuous mining in all regions and for surface mining in the East.

The appearance of an underlying rate of technical change in one or the other index can be explained. Subaggregates with average mine lives of four years experience a great deal of entry and exit over a twenty-three-year period, and such rapid turnover creates ample opportunity to embody new technology in the many new mines. Moreover, with a short expected life, the emphasis must be on achieving the design output level early and maintaining it. The opposite circumstance holds for subaggregates with very long mine lives, such as the PRB, where little entry or exit occurs and there is concomitantly less opportunity to introduce technical improvements by this route. Nevertheless, operators would not likely forego incorporating technical advances into current operations. These advances could be expected to reduce cost, improve the competitive position of mines making the improvement, and lead to an expansion of output. Such a pattern of incorporating technical change would tend both to show up as a scale effect and to weaken any fixed effect. In this regard, it is worth noting that although most mining groups exhibit positive productivity-output elasticities, the only groups with significantly rising scale effect indexes are those with longer-lived mines.

Mining technique also seems to correlate with the predominance of the scale or fixed effect index, as seen most clearly for the mining groups with average mine lives of about seven years. Scale effects are more important for longwall mining, and fixed effects are more important for continuous mining. This distinction picks up a recurrent story in the industry and reflects the greater lumpiness of longwall mining equipment. It is often reported that longwall cutting machines's ability to separate coal from the face often exceeds the ability of the conveyor systems to deliver the coal to the surface. Consequently, installation of a new longwall machine is often followed by a process of de-bottlenecking, which increases production and improves productivity. In a sense, the full technological potential is embodied in the new mine, but the manner by which that potential is ultimately exploited causes it to show up in our regressions as a scale effect rather than as a fixed effect. In contrast, continuous miners are more divisible with respect to cutting capability at the coal face, and less prone to oversizing with respect to the mine's delivery capabilities.

The tendency for the appearance of a continuing rate of technological advance to show up in either the scale or fixed effect index suggests that the combination of these two indexes at the regional and national level would provide an appropriate statistic for the rate of technological change. Mines do not have uniform lives within the mining groups. Mining groups with short average mine lives have long-lived mines in which technological improvements would appear as scale effects, just as groups with long average mine lives have some mines with short lives, for which technological advances would appear in the fixed effect coefficient. Because these exceptions carry less weight within the group, the effect would be weak, as is manifest in the mining group index. From this point of view, combining the two to make a single index of technological change would capture the full effect within a particular mining group. At the same time, neither the scale nor the fixed effect index reflects only the advance of the technological frontier. As we have had occasion to note, other effects are also reflected, such as those of overcapacity, geology, and the increasing number of nonunion mines.

We have computed these "technological change" indexes for the eleven subaggregates and then aggregated them to form a national index of technological advance. As seen in figure 9.6 the combined technical change index is not entirely satisfactory in conforming to our prior expectation of steady technological advance. The national index is close to being monotonically rising, but from 1972 through 1978 it plateaus. The cause of this plateau can be determined from the highly detailed data from which this index is built. Table 9.11 provides the contributions of the mining groups to the scale, fixed effect, and combined technical change indexes, as well as some explanatory statistics.

From a purely mathematical standpoint, the plateau in the national technological change index between 1972 and 1978 is caused by the boldfaced scale contributions, which sum to −0.1465. If these effects are removed, the combined national index would be +0.1237, which would yield an average annual rate of advance of about 2 percent. The underlying

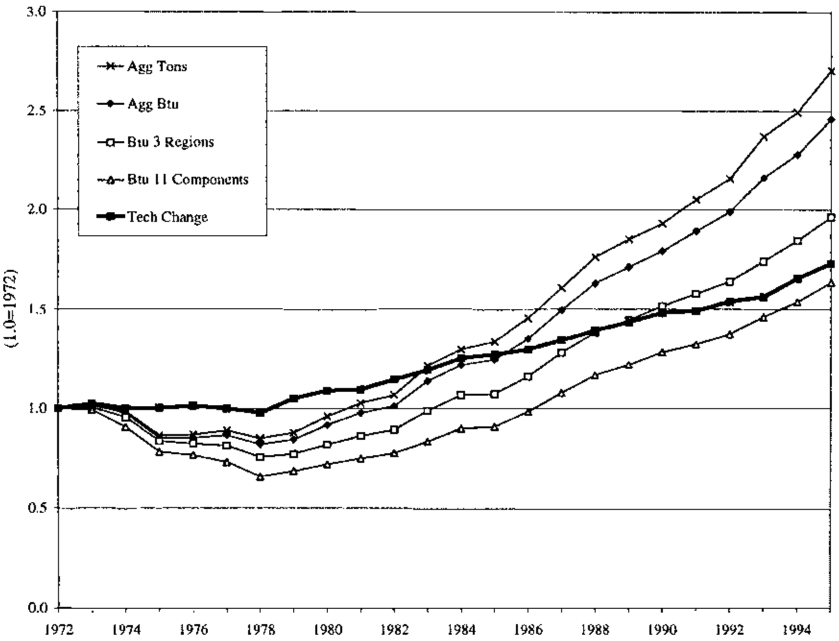

Fig. 9.6 Index of technological advance compared to aggregate measures of U.S. coal labor productivity

cause of these negative scale contributions is the large increase in number of mines between 1972 and 1978 without a commensurate increase in production. In 1978 the number of mines peaked at 5,209, compared with 2,883 in 1972. Not only did aggregate demand increase less than would have been required to match this investment, but for many subaggregates, production declined substantially. As a result, output per mine and labor productivity declined for all subaggregates except the large western surface mines. When aggregated to the national level, these transitory effects of overinvestment in coal-mining capacity mask the underlying rate of technological change.

This surge of investment in new mines is the long-run response to sharply higher coal prices in the mid-1970s, in a manner analogous to the short-run response discussed under section 5.4. New mines could be expected to embody new technology and to cause the fixed effect index to rise, and for all the major mining groups in the 1970s, the fixed effect contributions are positive.[20] Yet, if investment exceeds the actual growth in demand, output per mine will be less and, with positive productivity-

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[20] The numbers of mines in 1978 for the Interior Longwall, Western Longwall, Lignite, and PRB mining groups in 1978 were two, five, eighteen, and thirteen, respectively.

Table 9.11 **Contributions from Scale and Fixed Effects, 1972–78**

	Scale Contribution	Fixed Contribution	Combined Contribution	Ratio of Number of Mines (1978/1972)	Ratio of Total Output (1978/1972)
Appalachian longwall	−**.0110**	+.0012	−.0098	1.63	1.01
Interior longwall	−**.0005**	−.0002	−.0007	2.00	1.21
Western longwall	−**.0007**	−.0009	−.0016	2.50	1.60
Appalachian continuous	−**.0673**	+.0420	−.0253	1.55	0.71
Interior continuous	−**.0126**	+.0040	−.0086	1.12	0.81
Western continuous	−**.0004**	+.0046	+.0042	1.23	1.71
Appalachian surface	−**.0153**	+.0275	−.0122	2.07	1.59
Interior surface	−**.0387**	+.0269	−.0118	2.62	0.81
Western surface extraction	+.0033	+.0050	+.0083	2.15	2.72
Lignite	+.0101	−.0092	+.0009	1.29	3.29
Powder River Basin	+.0098	−.0003	+.0095	2.60	5.89
National total	−.1234	+.1006	−.0228	1.81	1.13

[a] Except Powder River Basin and Lignite.

output elasticities, productivity will decline and be reflected in the scale effects indexes.

An illustrative comparison can be made between Appalachian and Interior surface mining in table 9.10. Both experienced a doubling in their number of mines, and the fixed effect contributions to productivity were positive and of approximately equal magnitude. For both, the investment in new mines exceeded actual demand, which led to negative scale effect contributions. However, the disproportion between new mines and the actual increase of demand was much less for Appalachian surface mining than for Interior surface mining, because demand increased by 60 percent for the former, whereas it declined by 20 percent for the latter. As a result, the net balance between scale and fixed effects was positive for Appalachian surface mines, but negative for Interior surface mines.

Like the fixed effects index, the scale effects index reflects influences other than the underlying advance of the technological frontier. In the late 1970s, for instance, it appears to have been depressed by the effects of overinvestment and resulting overcapacity in the coal fields. Nevertheless, this index comes closer to reflecting the underlying rate of technical change than any other that arises out of our analysis. Neither the 1972–78 period nor the 1978–95 epoch is appropriate for gauging this underlying rate because of the interaction between overcapacity and scale effects, namely, to depress the technical change index in the former period and accelerate it in the latter. The entire 1972–95 period offers a better measure because it spans this period of significant distortion in production relationships.

As is shown in table 9.10, the rates for the subaggregates vary from a high of 3.6 percent for Western longwall mining to a low of 0.5 percent for Interior longwall mining. This is a wide range, particularly for the same mining technique, but the small numbers for these two mining groups make the potential contribution of a single or a few idiosyncratic mines especially problematic. Greater confidence may be placed in mining groups for which larger numbers obtain—Appalachian and Interior surface mining, and Appalachian continuous mining—which indicate an underlying rate between 1.7 percent and 3.0 percent per annum.

9.6 Concluding Remarks

Within the last several decades, significant theoretical and empirical developments have occurred in modeling, measuring, and interpreting relationships among productivity growth, embodied and disembodied technological progress, scale economies, and capacity utilization. Our paper builds on this growing literature and begins to exploit a very rich, large microdatabase containing thousands of individual coal mines' annual observations, and a quarter-century–long time series domain, as well.

The MSHA data set is as rich as any database on production at the microlevel for any industry of which we are aware. Still, information on mine-specific capital investments; labor force characteristics (e.g., age, experience, and union status); utilization of energy inputs, materials, and auxiliary services; and geological and regulatory environments, is lacking. This limitation necessitated our focus in this research on variations among mines over time in labor productivity, defined as Btu-adjusted coal output per hour of labor input.

Our initial analysis of this extraordinary data set has yielded numerous insights that would not have been possible with highly aggregated data. For example, scale effects tend to be the principal force increasing productivity in areas where mines with longer lives predominate, while fixed effects appear to be more important for subaggregates with shorter lives. For long-lived mines, such as longwalls in all regions and western surface mines (including Lignite and the PRB), increased output levels and rising productivity may be associated with unobserved later investment and the removal of logistical bottlenecks. The observed increase in labor productivity would appear to be the result of learning and disembodied improvements, but may in fact reflect unobserved embodiment or the delayed realization of initially embodied technical advances. By contrast, for those subaggregates dominated by short-lived mines, such as continuous mining in all regions and eastern surface mines, the rapid turnover due to entry and exit necessitates rapid exploitation from new technologies—achieving optimal capacity quickly and maintaining it. For short-lived mines, the embodiment of new vintage technologies apparently manifests itself as growth over time in the fixed effects index.

These two distinct microeconomic forces—scale and fixed effects—can be combined, yielding an aggregate time series with persistent positive labor productivity growth for all years except for a no-growth epoch from 1972–78. The micronature of the data set allows us to explain this pattern, as well. As coal output prices increased more rapidly than wages between 1972 and 1978, companies opened mines that were not only smaller, but also apparently geologically inferior, for labor productivity at these marginal mines was clearly much lower than for continuing mines. Not surprisingly, these mines closed within several years, as real coal output prices fell, thereby bringing about a price-induced increase in industry-level labor productivity. Although this price effect explanation is intuitively plausible based on economic theory, the microlevel data uniquely permit us to assess empirically and confirm this prediction. More generally, the productivity effects of significant changes in the relation between output and labor input prices over this time period explain most of what appeared to be a period of technical regress in the 1970s and subsequent high rates of productivity improvement.

After identifying and accounting for these scale, fixed, and price effects, we are left with residuals that exhibit considerable variation, but which revert to zero. In brief, these microdata have enabled us to decompose the productivity residual into distinct and more specific components. In this way, not only does our micro analysis complement aggregate industry studies, but it provides considerable unique insight into the root causes of aggregate growth.

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Comment Larry Rosenblum

The authors should be commended for digging below the surface of aggregate industry data to examine trends in coal mining. Using mine-level data, they discern four trends: Labor productivity is positively influenced by scale, and mine size more than doubled (U.S. Department of Energy 1993 shows that average mine size triples over this period); newer vintages of mines are more productive than older vintages, ceteris paribus; the Powder River Basin is much more productive than other regions, and coal production there increased enormously; and the rapid rise in coal prices allowed less productive, smaller mines to enter or remain in the 1970s, and the coal price collapse of the early 1980s forced many of these mines to exit the industry. The result of these trends was that labor productivity declined sharply in the 1970s and rose after 1979.

These conclusions are quite plausible, and reaching them with a data set that has coal production and hours data is quite remarkable. One of the surprising results of the paper is the large scale effects, on the order of 40 percent. The authors acknowledge that the scale effects should not be interpreted as a measure of returns to scale because other inputs, most notably capital, are omitted. This poses the question of how to interpret the scale effect. Because the model is a reduced form, it can be instructive to compare this model to a structural model so that we can interpret the parameters. For simplicity, we assume production for mine i in period t follows a Cobb-Douglas form in which output Q is produced by capital K and labor L, and b and c are output elasticities. (The other symbols in the following equation follow the authors' notation.) Labor productivity can be written as

$$\begin{aligned}\ln(Q_{it}/L_{it}) = {} & (2 - b - c)\alpha_i && \text{(Fixed Effect)}\\ & + (2 - b - c)\tau_t && \text{(Time Effect)}\\ & + (b + c - 1)\ln Q_{it} && \text{(Scale Effect)}\\ & + b(2 - b - c)\ln K_{it} - (1 - c(2 - b - c))\ln L_{it}. &&\end{aligned}$$

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It is clear that the production function yields a model that is empirically identical to the reduced form except for the last term. This last term is simply some variation on the capital intensity of the mine. As long as capital intensity can be completely characterized by a mean and a common trend, the last term can be subsumed into the fixed and time effects. Without loss of generality, the last term can be written as some function $g^{it}(K_{it}, L_{it})$. There is a mine specific mean $g^{i}(K_{i}, L_{i})$ and a common time trend over all mines $g^{t}(K_{t}, L_{t})$. Adding the mean to the fixed effects and the common trend to the time effects, and subtracting these terms from the function g^{it}, the equation becomes

$$\begin{aligned}\ln(Q_{it}/L_{it}) = {} & (2 - b - c)\alpha_i + g^{i}(K_i, L_i) && \text{(Fixed Effect)}\\ & + (2 - b - c)\tau_i + g^{t}(K_t, L_t) && \text{(Time Effect)}\\ & + (b + c - 1)\ln Q_{it} && \text{(Scale Effect)}\\ & + g^{it}(K_{it}, L_{it}) - g^{i}(K_i, L_i) - g^{t}(K_t, L_t) && \end{aligned}$$

The final term will be zero as long as the time and fixed effects completely describe g^{it}. However, if capital intensity cannot be completely characterized by a mean and a trend, the final term is not zero and may be correlated with other terms, leading to potential biases in the estimates. Of principle concern is the likelihood that output and capital intensity may be positively correlated. This is equivalent to wondering if larger mines are more capital intensive. By any measure, returns to scale of 40 percent are quite large and impart a large cost advantage to large producers, so the possibility that the scale effects are overestimated must be considered, and the authors should investigate this more thoroughly in their paper. However, coal mines are not like other producers because the scope of production is circumscribed by the size of the coal field. As a result, mining is an industry where economies of scale might exist without the usual industry dynamics. Instead, large mines should enjoy high rents instead of increasing market share, and this can be empirically tested.

Although there is no definitive test for the correlation of output and capital intensity with this data set because capital data are unavailable, examining the scale effects in more detail might provide reassurance that such scale effects exist. If scale effects exist, we should expect that small mines are more likely to exit than are large mines of the same vintage, ceteris paribus. We might also expect that across regions, but within a type of mine, scale economies should be approximately equal. Similarly, economies of scale are not likely to vary significantly across time unless new technologies alter the optimal scale of operation. Splitting the sample in half across time should produce similar estimates in each time period, and both should be similar to the original estimates. Finally, the model could be estimated imposing constant returns to scale to see if many of the plausible inferences about entry and exit and time effects are obtained. If not, this further strengthens the likelihood of increasing returns to scale.

Regardless of this potential omitted variable bias, we need to take care in interpreting scale effects. Because scale effects include both returns to scale and the effect of omitted inputs such as capital services, the data do not allow the authors to compare the importance of pure scale effects to other determinants of labor productivity. If larger mines are much more capital intensive, the scale effects do not suggest a course of action for improving productivity in coal mining. That is, the presence of returns to scale suggests that (labor or multifactor) productivity will increase as long as new mines are larger than the average existing mine. If the scale effect largely reflects differing capital intensities, then multifactor productivity will not be improved by altering average mine size.

The authors estimate labor productivity effects in two stages. In the first, labor productivity depends on scale effects, aggregate time effects, and fixed effects. In the second stage, time effects are divided into price effects, residual time effects, and microheterogeneity effects. The authors use this two-stage technique so that each effect can be identified and so that no bias arises from entering price and wage data into the first equation.

This is a wise strategy because wage and especially coal price data cannot be observed for each mine. Instead, a state average price is used for coal and a national price for labor. As a result, price effects and microheterogeneity may overlap in their effect. That is, price trends reflect the effect of changing prices on the time effect of mine labor productivity, whereas microheterogeneity reflects unobserved changes in the composition of mines over time, including differences in the prices received for their coal and paid to their workers. It is certainly plausible that relative coal prices are nearly constant across mines within a region, but as table 9C.1 illustrates, this is unlikely because coal prices are often determined by long-term contracts. Unless these contracts expire at the same time, relative coal prices are bound to vary across mines within a region. Again, the aggregate price trend effect is not mismeasured, but the disaggregation is not as clear cut as the analysis implies.

Table 9C.1 shows both the open market and contract price for coal for selected states. In some states the prices differ dramatically. Furthermore, contracts are often for as much as twenty years, and in 1993 almost half of all coal was sold under contract. This means that the contract price may bear little relationship to the marginal cost of producing coal and that these prices may well include rents to the mine or the contract holder, depending on the price of coal. When aggregating coal production to create regional or national statistics, the authors use superlative indexes that employ value share weights. These weights are appropriate as long as price reflects the marginal cost of production, but if coal prices have been fixed years before production takes place, value share weights may not accu-

Table 9C.1 Average Mine Coal Price by Area, 1994

Area	Open Market	Captive Market
Illinois	22.28	22.44
Kentucky	24.90	23.55
Ohio	23.68	52.54
Pennsylvania	26.38	19.86
West Virginia	26.43	32.35
Wyoming	6.37	12.77
Appalachia	26.98	35.11
Interior	22.05	11.88
Western	10.23	14.16

Source: U.S. Department of Energy (1994a).

rately reflect marginal costs. As the authors show in table 9.1, the stylized facts of a productivity slowdown followed by a rebound can be seen in four very different productivity measures. However, the preferred measure (eleven-region weighted labor productivity) shows the greatest productivity slowdown followed by the weakest rebound. Although the contract prices do not affect the parameter estimates derived from microdata in the first stage of the model, the growth accounting exercise depends on the choice of the aggregate measure of labor productivity, which in turn depends on the index formula used to aggregate individual mines.

Next, the authors might want to consider a couple of tests to strengthen their findings. First, mine output is included in the sample provided there is any output in a given year. However, labor strife has been common in coal mining, especially in 1981. Furthermore, a strike makes a mine appear to be smaller than its true size. If strikes curtail labor productivity, scale effects will appear greater than if dummy variables are used to control for strike periods or the production is adjusted to reflect a full year of production. Similarly, the authors use a dummy variable for 1972 and 1973 to control for the sharp price rise of coal, but no similar dummy when prices collapse. The authors might demonstrate that the scale, time, and fixed effects remain when either corresponding dummy variables are added or the sample is limited to 1974–95.

Finally, I have one small quibble. The authors divide the analysis into two regimes, 1972–78 and 1979–95, presumably because a variety of labor productivity measures in figure 9.5 begin their rebound in 1979. However, the regime of high energy prices lasted until 1986, and coal prices peaked in 1984 (U.S. Department of Energy 1994a, table 9.12). Price effects are the largest source of declining labor productivity prior to 1979. If price effects are dominant and strongly influence mine size, then a later date might be more insightful for the analysis.

Despite these qualifications, the basic conclusions of the paper provide a coherent explanation of labor productivity trends in coal mining. A jump in the price of coal after 1973 not only allowed small mines to remain in the industry but also encouraged small mines to enter. Because small mines have lower labor productivity than do bigger mines, labor productivity declined throughout the 1970s even though entering mines had larger fixed effects (presumably reflecting greater efficiency) than did existing mines. The price collapse of the 1980s unwound the entry of relatively inefficient mines as mines became larger and entering mines continued to have greater labor productivity than did existing mines, ceteris paribus. The result was a productivity rebound.

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