What Drives Mineral Commodity Markets in the Long Run?

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Introduction

What drives mineral commodity markets in the long run? What causes large fluctuations in mineral commodity prices? What determines supply? Why do we observe increasing production, but stable trends in the prices of mineral commodities? This dissertation provides fresh empirical and theoretical perspectives on these issues by exploring a new data set on five widely used mineral commodities, namely aluminum, copper, lead, tin, and zinc, over a far longer period than previous work on mineral commodity markets.

The main messages are: first, major fluctuations in prices are driven mainly by demand shocks; second, demand is determined by industrialization rather than prices; third, on the supply side, economic growth triggers innovation in extraction technology, which makes long-run supply elastic and explains increasing extraction and stable prices in the long term.

Mineral commodities are ultimately produced from mineral resources. They include such fuel minerals as coal, petroleum, and natural gas, metallic minerals, and industrial and construction minerals.[1] According to Black, Hashimzade, and Myles (2009) commodities are homogeneous and interchangeable goods. They can be traded as bulk goods on international markets. These characteristics make their prices volatile in comparison to the sticky nominal prices of many other goods in the economy (Ito and Rose, 2011).

Mineral commodities have been important to human civilization since the Bronze Age. Copper, iron, lead, tin, zinc, and their alloys have been used in a wide variety of applications, such as coinage, construction, tooling, and warfare, which has led to flourishing metallurgy and long-distance trade since early times (Radetzki, 2009; Krebs, 2006; De Callatay, 2005). In today's world economy mineral commodities are

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[1] See the definition employed by the U.S. Federal Government (2009, p. 8).

used as inputs in many production processes. As Table 1 shows, the value of the world production of mineral commodities totalled some US-$ 4.8 trillion in 2010, which is equivalent to about 7.5 percent of world GDP.[2] Mineral commodities and other materials account for up to 47.5 percent (2008) of input costs in German manufacturing (Flechtner, Mohr, and Rockholz, 2012).

Scarcity of supply and price fluctuations are not only recurrent problems for policy-makers and businesses, but also the two main academic issues. Fear of shortages in the wake of the recent price boom have had widespread political implications and has led to competition for resources. The U.S., Japan, Germany, the E.U., and China have established "raw materials" strategies, bundling domestic and external policies to secure access to mineral commodities (Stürmer and von Hagen, 2012a; U.K. Government, 2012). Chinese export taxes and export restrictions in several mineral commodity markets are a prominent case at the World Trade Organization. Price fluctuations affect the macroeconomic conditions of developing and industrialised countries (Bernanke, 2006; World Trade Organization, 2010; IMF, 2012b).

There is a large body of literature on the scarcity of mineral commodities and fluctuations in their prices. The scarcity of non-renewable resources and the implications of a given finite resource stock have been a focus of economic theory since "The Coal Question" by Jevons (1866) and the seminal model constructed by Hotelling (1931). After a wide range of literature developed in the 1970s and 1980s, of which Krautkraemer (1998) provides a good overview, the subject has recently been taken up again. Acemoglu et al. (2012), for example, examine the incentives for resource wars based on the assumption of a finite stock.

The determinants and impact of the boom-and-bust periods in mineral commodity prices have fuelled theoretical and empirical papers, of which Carter, Rausser, and Smith (2011) provide a survey. While many empirical studies focus on the oil market, examples being Hamilton (2009a) and Kilian (2009), theoretical contributions often build on the competitive rational storage model by Williams (1936) and Gustafson (1958a), which were basically developed for agricultural commodities.

The aim of my thesis is to provide a theoretical and empirical long-run perspective on these two subjects with some data reaching back to the 17th century. The core

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[2] Own computation based on world GDP data from the World Bank (2011).

Commodity	World Production in 1000 mt (content)	Value of Production in Mio. US-$
Crude oil[1a]	28,687,070	2,280,622
Natural gas[a]	2,880,877	538,172
Coal[2a]	7,273,298	672,777
Cement[b]	3,310,000	304,520
Steel [b]	1,410,000	270,720
Copper[b]	19,100	146,688
Gold[b]	2.7	101,120
Aluminum[3b]	40,800	93,840
Nitrogen[4b]	131,000	57,247
Nickel[b]	1,590	34,662
Lime[b]	311,000	32,779
Zinc[b]	12,700	28,575
Manganese[b]	14,000	21,000
Chromium[b]	7,290	19,319
Potash[b]	33,700	18,670
Silicon[b]	7,290	16,184
Silver[b]	23	14,853
Phosphate rock[b]	181,000	14,371
Lead[b]	9,290	22,296
Platinum-group metals[b]	0.5	8,640
Molybdenum[b]	242	8,445
Tin[b]	350	7,350
Sum of 70 mineral commodities[b]	44,645,208	4,759,886

Notes: [1]Includes crude oil, shale oil, oil sands, and NGLs. [2]Includes bituminous coal, hard coal, and sub-bituminous coal. [3]Only primary aluminum production. [4]Ammonia produced. The production of metals also includes recycling. Sources: [a]British Petroleum (2011), [b]U.S. Geological Survey (2011a).

Table 1: Quantity and value of the world production of major mineral commodities in 2010.

idea is to look far beyond the two commodity booms of the 1970s and 2000s to put them into historical perspective and better understand the long-run determinants of these markets.

However, most mineral commodities traded on world markets today, such as crude oil and iron ore, were either not widely used in former times or their markets were highly fragmented, owing to trade policies and high transportation costs. I therefore construct and explore a data set on mineral commodities which have long been widely used in industry and traded on the London Metal Exchange and its predecessors as fungible and homogeneous goods in an integrated world market: aluminum, copper, lead, tin, and zinc, all still among the top twenty-five in terms of value of world production. Overall, these five mineral commodity markets have long exhibited characteristics that most other markets of mineral commodities, such as iron ore, crude oil, and coal have only recently acquired.

My thesis consists of three chapters. In the first chapter, my co-author Gregor Schwerhoff and I consider the issue of scarcity. We add an extractive sector to a standard endogenous growth model by Acemoglu (2002, 2009) such that aggregate output is produced from a non-renewable resource and intermediate goods. We replace the assumption of a finite stock, on which the seminal Hotelling (1931) model and subsequent literature rely. In the extractive sector, firms can draw down resource stocks through extraction, but also renew stocks through investment in new extractive technology. Given technological change, the non-renewable resource is inexhaustible and there is no scarcity rent. This assumption is in line with evidence that technological change has offset the depletion of the stock of non-renewable resources in the past (Simpson, 1999, and others) and that non-renewable resources are highly abundant in the Earth's crust given technological change (Nordhaus, 1974, p. 23).

Our model points out the main differences between the two sectors. First, the extractive sector needs to invest in new technologies as the resources is extracted from mineral occurrences of decreasing grades. Second, non-renewable resources are traded as homogeneous goods such that monopolistic competition is not taking place as in the intermediate goods sector, where the variety of intermediate goods increases. As a consequence, the resource sector is fully competitive in the market for extraction technologies. Third, the resource stock increases linearly with R&D in extraction technology as two effects offset each other. Fourth, there are different evolutions of technology due to the necessity of innovation in the extractive sector. The growth rate of technology in the extractive sector needs to increase over time in order to keep the level of production of the non-renewable resource proportionate to aggregate output. This is in contrast to the constant growth rate of technology in the intermediate goods sector.

Our model contributes to resolving a contradiction between theoretical predictions and empirical evidence regarding non-renewable resources. According to theory, economic growth is not limited by non-renewable resources because of three factors: technological change in the use of resources, substitution of non-renewable resources by capital, and returns to scale. Given these factors, growth models with a non-renewable resource typically predict growth in output, decreased non-renewable resource production, and an increase in resource price (see Groth, 2007; Aghion and Howitt, 1998). However, it is a well-established fact that these predictions are not in line with the empirical evidence (see Krautkraemer, 1998; Livernois, 2009; Von Hagen, 1989). We present data for the period from 1792 to 2010 which shows that the extraction of non-renewable resources increase exponentially whereas its prices stay constant over the long-term. Our model is able to replicate these historical trends.

Nordhaus (1974), Simon (1981), and others stress technological change in the extraction of non-renewable resources as an argument against limits to growth. There are several efforts to model this aspect (see Heal, 1976; Slade, 1982; Cynthia-Lin and Wagner, 2007; Fourgeaud, Lenclud, and Michel, 1982; Hart, 2012). However, our model is, to our knowledge, the first to combine technological change in the extractive sector and mineral occurrences of different grades in an endogenous growth model that explicitly models the R&D investment in the extraction technology. It also contributes to the literature by being the first to point out the necessity of innovation in the extractive sector due to its specific characteristics, and their effects on R&D development in comparison to other economic sectors.

Our results suggest that the increasing demand for non-renewable resources in industrializing countries like China is neutralized by R&D investment in extraction technology. This makes extraction from mineral occurrences of lower grades possible. If historical trends continue, resource prices might stay constant in the long term, even if non-renewable resource use and production increase exponentially.

The second chapter considers the determinants of price fluctuations from a long-run perspective. I examine the dynamic effects of supply and demand shocks on mineral commodity prices, using annual data on the copper, lead, tin, and zinc markets from 1840 to 2010. This allows me to capture more than a dozen periods of boom and bust. I am the first to provide long-term evidence on demand and supply shocks in mineral commodity markets. I identify shocks in a vector autoregressive model based on long-run restrictions, which allows me to leave short-run relations unrestricted. I provide a historical account for each mineral commodity market to better understand the dynamics of the markets and to give the identified shocks a proper interpretation. The main conclusion drawn in this chapter is that fluctuations in the prices of the four mineral commodities examined are mainly driven by demand shocks rather than supply shocks.

I provide long-run evidence for a body of literature that is far from conclusive on the driving forces behind these long-run fluctuations. My analysis suggests that extensions of the seminal Hotelling (1931) model such as those by Arrow and Chang (1982), Fourgeaud, Lenclud, and Michel (1982), and Cairns and Lasserre (1986) which explain price fluctuations by supply shocks must be rethought. It also questions the usual interpretation of shocks in competitive storage models (Gustafson, 1958a,b; Wright and Williams, 1982), which views supply shocks as a key to explaining commodity price fluctuations. Supply shocks are only of some importance in explaining fluctuations of tin and copper prices. Such shocks appear to increase with the importance of concentrated industry structures and government intervention in the markets. This evidence is in contrast to industrial organization models which predict that higher product market concentration will reduce price volatility (see Slade and Thille, 2006).

In contrast to the classical competitive storage models, my findings point to inventories as a source of fluctuations rather than a calming agent. My results provide long-term evidence in support of Alquist and Kilian (2010) and others who maintain that storage in the presence of expected supply shortfalls explains price fluctuations. Narrative evidence in this paper, however suggests that shocks due to changes in inventories are rather driven by producer cartels and government stockpiling, and only in recent times by “precautionary” behaviour of consumers or investors in the markets examined here.

My findings have important policy implications for both commodity-exporting and commodity-importing countries. They suggest that the current price boom is temporary, not permanent. This is a key insight for the design of optimal fiscal and macroeconomic policy responses in commodity-exporting developing countries (see IMF, 2012b). Long-term trends are mainly statistically insignificant for the commodities examined in the estimated models. Hence, commodity exporters should take a countercyclical policy stand rather than increase long-term public investment based on the assumption of a permanent price increase. For countries which import mineral commodities, my findings indicate that apprehensions about security of supply are exaggerated in the light of historical evidence concerning widely-used mineral commodities. Various forms of subsidies for overseas mining and the reduction of import dependencies as well as “resource diplomacy” are questionable given that these mineral commodities are traded on world markets, while prices react only moderately to supply restrictions in the short run.

In the third chapter, I provide empirical evidence on the long-run elasticities of demand with respect to manufacturing output and prices for several mineral commodities based on a long panel. To cover the main periods of industrialization, I employ a newly constructed data set for twelve major economies which for some parts spans back to 1840. I focus on the demand for aluminum, copper, lead, tin, and zinc. My study contributes to a rich body of empirical studies of the elasticity of demand for mineral commodities with respect to economic activity and prices (see Hamilton, 2009b; Pei and Tilton, 1999; Kilian and Murphy, 2012, for surveys of the current literature). This literature mainly focusses on energy and only provides empirical evidence for relatively short periods.

My estimation strategy relies on an extension of the partial adjustment model, the standard approach in empirical energy demand analysis, to ensure comparability with the results of previous studies. Derived demand is regressed on some measure of economic activity, the relative price of the respective mineral commodity, and lagged values of derived demand. I introduce a common linear time trend and finally time fixed effects following Pesaran, Smith, and Akiyama (1998). This allows me to take advantage of the panel structure of the data as it makes it possible to control for ommitted common technological trends and spillover effects Pesaran, Smith, and Akiyama (1998).

I find that the estimated long-run manufacturing output elasticities of demand vary significantly between the five examined mineral commodities. An one percent increase in manufacturing output leads to an approximately 1.5 percent increase in the demand for aluminum. This means that its demand increases more than proportional to manufacturing output over time. The estimated manufacturing output elasticity of copper demand is close to one which implies a stable intensity of use over time. The estimates are far below one for lead, tin, and zinc demand. This causes the intensity of use of these mineral commodities to decline over time. The estimated long-run manufacturing output elasticities of the demand for all examined mineral commodities, except tin, are higher or equal to the income elasticity of oil demand (which is 0.55 according to Gately and Huntington (2002) for twenty-five OECD countries over 1971 to 1997). The ones for copper and aluminum are also higher than estimates of the income elasticity of aggregate energy demand (0.8 according to Adeyemi and Hunt (2007) for fifteen OECD countries from 1962 to 2003).

The estimated manufacturing output elasticities of demand suggest that the industrialization in China will cause aluminum to increase relative to manufacturing output, while the demand for copper will grow in proportion to manufacturing output. The demand for lead, tin, and zinc decreases relative to manufacturing output in the long-term. My results are important for developing long-term production strategies and allowing for smooth markets, as mining firms face high upfront costs and long lead times to open up new mines. Moreover, countries dependent on the exports of their mineral commodities may better judge the long-term perspective of the respective markets and adjust their macroeconomic and fiscal policies accordingly. Finally, my results suggest that demand is a larger contributor to the volatility of aluminum and copper prices than to that of lead, tin, zinc, and energy since manufacturing output fluctuations lead to larger fluctuations in the cases of aluminum and copper demand (see Slade, 1991).

The estimated long-run price elasticities of demand are rather low for the examined mineral commodities. Again, there are pronounced differences across the examined mineral commodities. While it is about -0.7 and -0.8 in the case of aluminum demand, it is about -0.4 for copper demand, and below or equal to about -0.2 for lead, tin, and zinc demand. This shows that with the exception of aluminum and copper, the aforementioned mineral commodities are rather essential to manufacturing output as the processing industry changes its use slowly in response to price. The estimates of the price elasticity are in contrast to the literature on oil and energy, where the long-run price elasticity is estimated to be significant (-1.25 for energy demand according to Heal and Chichilnisky (1991) and -0.64 for oil demand in OECD countries according to Gately and Huntington (2002)). These results are important, because according to models of commodity price speculation a low price elasticity of demand makes these markets prone to speculation (see Hamilton, 2009a; Kilian and Murphy, 2012). Moreover, the low price elasticity is a key parameter in shaping the incentives of war over resources as Acemoglu et al. (2012) claim.

My estimation results show that the relationship between per capita manufacturing output, relative prices, and the per capita demand for mineral commodities is rather driven by technological change and consumer preferences that are country specific. Effects that are common to all countries over time play only a role in decreasing aluminum and lead demand over time. The model for tin seems to be misspecified. I find strong evidence for the existence of long-run relationships in all regressions. The estimated speed of demand adjustment is rather slow for all commodities and it takes more than ten years in the cases of lead, tin, and zinc to revert back to equilibrium. This is reasonable, given that adjustments in manufacturing capital are rather slow and that inventories play an important role in these markets. Overall, my empirical results are plausible given narrative evidence on the use of the mineral commodities over time.

Chapter 1

Non-renewable but inexhaustible: Resources in an endogenous growth model[1]

1.1 Introduction

Our model contributes to resolving a contradiction between theoretical predictions and empirical evidence regarding non-renewable resources. According to theory, economic growth is not limited by non-renewable resources because of three factors: technological change in the use of resources, substitution of non-renewable resources by capital, and returns to scale. Given these factors, growth models with a non-renewable resource typically predict growth in output, decreased non-renewable resource production, and an increase in resource price (see Groth, 2007; Aghion and Howitt, 1998).

However, it is a well-established fact that these predictions are not in line with the empirical evidence from the historical evolution of prices and production of non-renewable resources. Over time, real prices have either lacked a trend or remained stationary around deterministic trends with infrequent structural breaks, while the

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[1] This chapter is based on joint work with Gregor Schwerhoff. Special thanks go to him. An earlier version has been published as a Preprint of the Max Planck Institute for Research on Collective Goods (see Stürmer and Schwerhoff, 2012).

extraction of non-renewable resources increased (see Krautkraemer, 1998; Livernois, 2009; Von Hagen, 1989).

We modify the standard endogenous growth model of expanding varieties and directed technological change by Acemoglu (2002, 2009). We add an extractive sector to the model such that aggregate output is produced from a non-renewable resource and intermediate goods. In the extractive sector, firms can draw down resource stocks through extraction, but also renew stocks through investment in new extractive technology. Given technological change, the non-renewable resource is inexhaustible and there is no scarcity rent. This assumption is in line with evidence that technological change has offset the depletion of the stock of non-renewable resources in the past (Simpson, 1999, and others) and that non-renewable resources are so abundant in the Earth's crust that given technological change, "the future will not be limited by sheer availability of important materials"(Nordhaus, 1974, p. 23).

We point out the main differences between the extractive sector and the intermediate goods sector in our model. First, it is necessary to innovate in the extractive sector as resources are extracted from mineral occurrences of decreasing grades. Once the resource stock is depleted, investment in new extraction technology is necessary to make mineral occurrences of lower grades extractable thus continuing production. As a consequence, a specific extraction technology is only applicable for extraction from a mineral occurrence of a specific grade, whereas technologies in the intermediate goods sector have the potential to keep production going.

Second, the resource stock increases linearly with R&D in extraction technology as two effects offset each other. On the one hand, R&D expenditure has to increase exponentially in order to make mineral occurrences of lower grades extractable. On the other hand, the non-renewable mineral resource is distributed in the Earth's crust such that its quantity increases exponentially as the grade of its occurrences decreases.

Third, non-renewable resources are traded as homogeneous goods such that monopolistic competition is not taking place as in the intermediate goods sector, where the variety of intermediate goods increases. As a consequence, the resource sector is fully competitive in the market for extraction technologies.

We illustrate the different evolutions of technology due to the characteristics of the two sectors. In order to keep the level of production of the non-renewable resource proportionate to aggregate output, the growth rate of technology in the extractive sector needs to increase over time. This is in contrast to the intermediate sector, where the growth rate of technology is constant. This difference is due to the necessity of innovation in the extractive sector as extraction from lower grades requires new technology.

Finally, we compare the decentralized solution of our model to the central planner solution. For the social planner R&D investment is endogenous and the aggregate production function exhibits increasing returns to scale instead of constant returns to scale. As a result, aggregate R&D investment increases proportionately with output. Aggregate output increases explosively and there is no balanced growth path.

Our model replicates historical trends in the prices and production of major non-renewable resources as well as world output for which we present data for the period from 1792 to 2010. Exponential aggregate output growth triggers R&D investment in extraction technology. The extraction and use of the non-renewable resource increases exponentially whereas its prices stays constant over the long term.

Our results suggest that the increasing demand for non-renewable resources in industrializing countries like China is neutralized by R&D investment in extraction technology. This makes extraction from mineral occurrences of lower grades possible. If historical trends continue, R&D in extraction technology might offset the depletion of today's resources. Even if non-renewable resource use and production increase exponentially, resource prices might stay constant in the long term.

Nordhaus (1974), Simon (1981), Simon (1998), Tilton (2002), and others stress technological change in the extraction and processing of non-renewable resources as an argument against limits to growth. However, efforts to model this aspect take technological change in the extraction technology as a given and do not include growth of aggregate output. Heal (1976) introduces a non-renewable resource, which is inexhaustible, but extractable at different grades and costs in the seminal Hotelling (1931) optimal depletion model. Extraction costs increase with cumulative extraction, but then remain constant as a "backstop technology" (Heal, 1976, p. 371) is reached. Slade (1982) adds exogenous technological change in extraction technology to the Hotelling (1931) model and predicts a U-shaped relative price curve. Cynthia-

Lin and Wagner (2007) use a similar model with an inexhaustible non-renewable resource and exogenous technological change. They obtain a constant relative price with increasing extraction.

There are three papers, to our knowledge, that are similar to ours in that they include technological change in the extraction of a non-renewable resource in an endogenous growth model. Fourgeaud, Lenclud, and Michel (1982) focuses on explaining sudden fluctuations in the development of non-renewable resource prices by allowing the resource stock to grow in a stepwise manner through technological change. Tahvonen and Salo (2001) model the transition from a non-renewable energy resource to a renewable energy resource. Their model follows a learning-by-doing approach as technical change is linearly related to the level of extraction and the level of productive capital. It explains decreasing prices and increasing use of a non-renewable energy resource over a particular time period before prices increase in the long term. Hart (2012) models resource extraction and demand in a growth model with directed technological change built up from scratch. The key element in his model is the depth of the resource. After a temporary "frontier phase" with a constant resource price and consumption rising at a rate only close to aggregate output, the economy needs to extract resource from greater depths and a long-run balanced growth path with constant resource consumption and prices that rise in line with wages is reached.

Our model is, to our knowledge, the first to combine technological change in the extractive sector and mineral occurrences of different grades in an endogenous growth model that explicitly models the R&D investment in the extraction technology. It also contributes to the literature by pointing out the necessity of innovation in the extractive sector due to its specific characteristics, and their effects on R&D development in comparison to other economic sectors in an endogenous growth model.

To focus on the main argument, we do not take into account externalities, uncertainty, recycling, substitution, short run price fluctuations, population growth, and exploration in our model. In particular recycling will probably become more important for non-fuel non-renewable resources in the future due to an increasing stock of recyclable materials and its comparatively low energy requirements (see Steinbach and Wellmer, 2010; Wellmer and Dalheimer, 2012). As recycling adds to the resource stock, this would further strengthen our argument.

In Section 1.2, we document stylized facts on the long-term development of non-renewable resource prices, production, and world GDP. We provide geological evidence for the major assumptions of our model. Section 1.3 describes how we model technological change in the extractive sector. Section 1.4 presents the setup of the growth model and discusses its theoretical results. Section 1.5 is where we will draw conclusions.

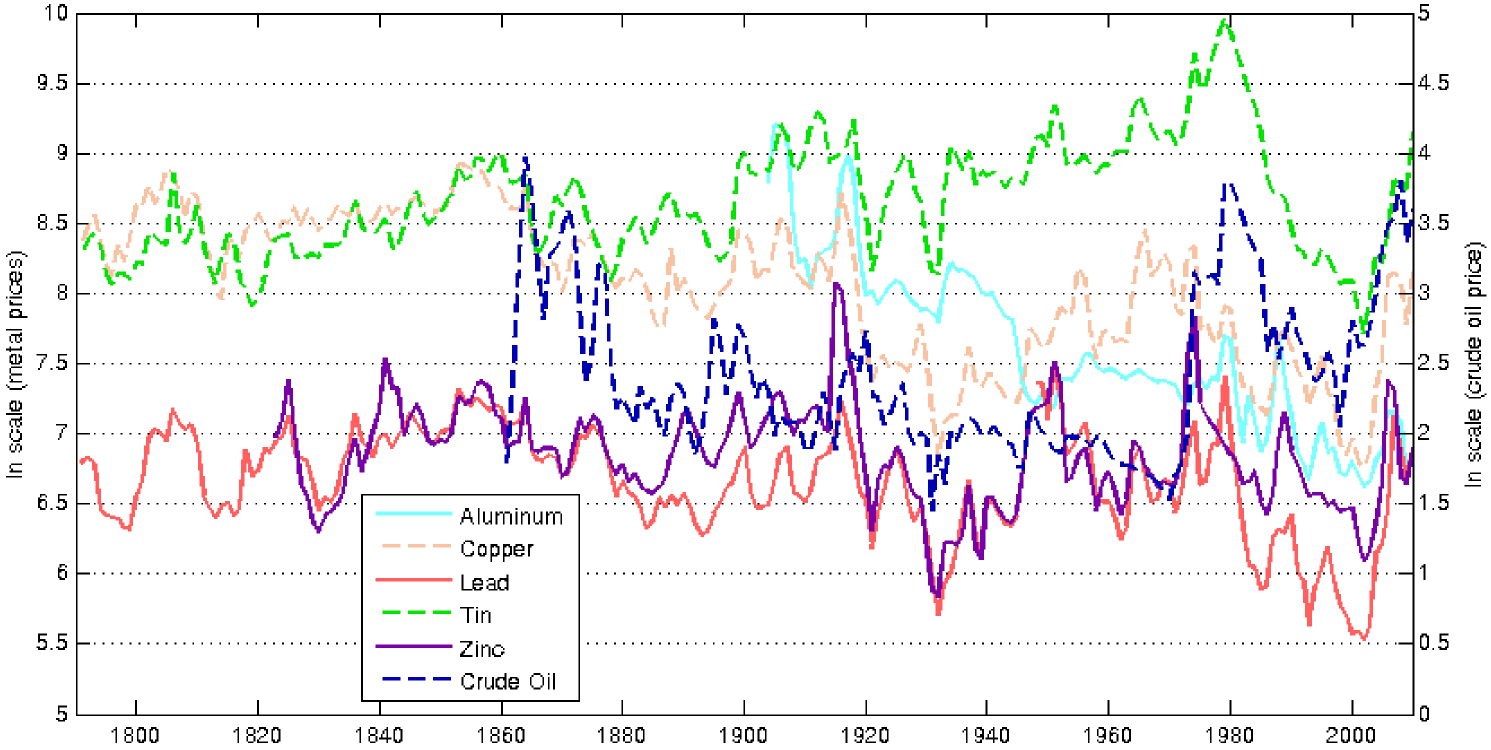
1.2 Stylized facts

1.2.1 Prices, production, and output over the long term

Annual data for major non-renewable resource markets from 1792 to 2010 indicates that real prices are roughly trendless and that worldwide primary production as well as world GDP grow roughly exponentially.

Figure 1.1 presents data on the real prices of five major base metals and crude oil. Real prices exhibit strong short-term fluctuations. At the same time, the growth rates of all prices are not significantly different from zero (see Table 1.2 in the Appendix). The real prices are hence trendless from 1792 to 2010. This is in line with evidence over shorter time periods provided by Krautkraemer (1998), Von Hagen (1989), Cynthia-Lin and Wagner (2007), and references therein. The real price for crude oil exhibits structural breaks, as Dvir and Rogoff (2010) point out. Overall, the literature is certainly not conclusive (see Pindyck, 1999; Lee, List, and Strazicich, 2006; Slade, 1982), but we believe the evidence is sufficient to take trendless long-term prices as a motivation for our model.

Figure 1.2 shows that the world primary production of the examined non-renewable resources and world GDP approximately exhibit exponential growth since 1792. A closer statistical examination reveals that the production of the non-renewable resources exhibits significantly positive growth rates in the long term. The growth rates of the production of copper, lead, tin, and zinc do not exhibit a statistically significant trend over the long term. Hence, the levels of production of these non-renewable resources grow exponentially over time.



Notes: All prices, except for the price of crude oil, are prices of the London Metal Exchange and its predecessors. The oil price time series is the international oil price as assembled by British Petroleum (2011). As price at the London Metal Exchange used to be denominated in Sterling in earlier times, we have converted these prices to US-Dollar by using historical exchange rates. We make use of the US-Consumer Price Index for deflating these prices. The secondary y-axis relates to the price of crude oil. For more details, see the chapter on data sources and description.

Figure 1.1: Real prices of major mineral commodities from 1790 to 2009 in natural logs.

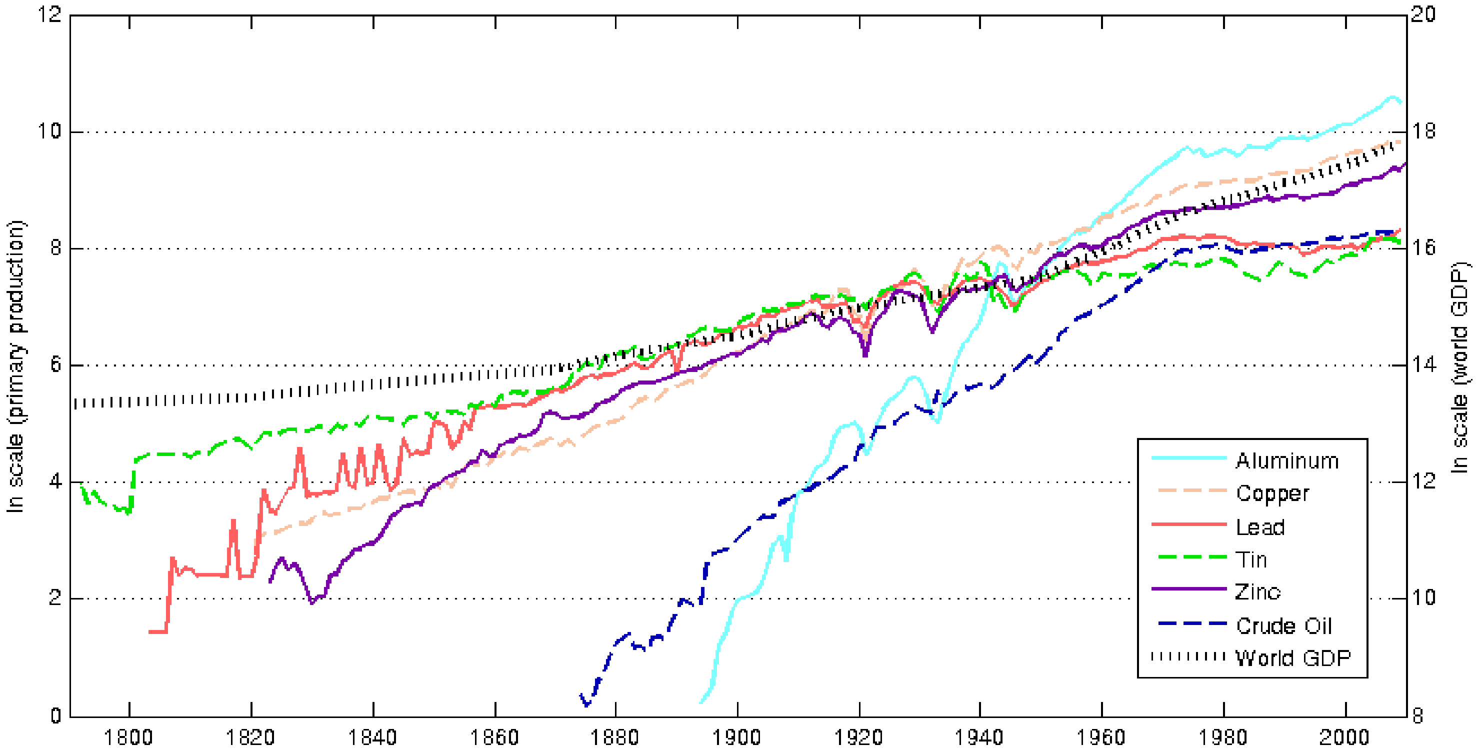


Figure 1.2: World primary production of non-renewable resources and world GDP from 1790 to 2009 in logs.

The level of crude oil production follows this exponential pattern up to 1975. Including the time period from 1975 until 2009 reveals a statistically significant negative trend and therefore declining growth rates over time, due to a structural break in the oil market (Dvir and Rogoff, 2010; Hamilton, 2009b). In the case of primary aluminum production, we also find declining growth rates over time and hence no exponential growth of the production level. This might be due to the fact that recycling has become important in the aluminum production over time (see data by U.S. Geological Survey, 2011a). Recycling is not included in our model nor is it in the data. The growth rates of world GDP exhibit an increasing trend over the long term, hinting at an underlying explosive growth process.

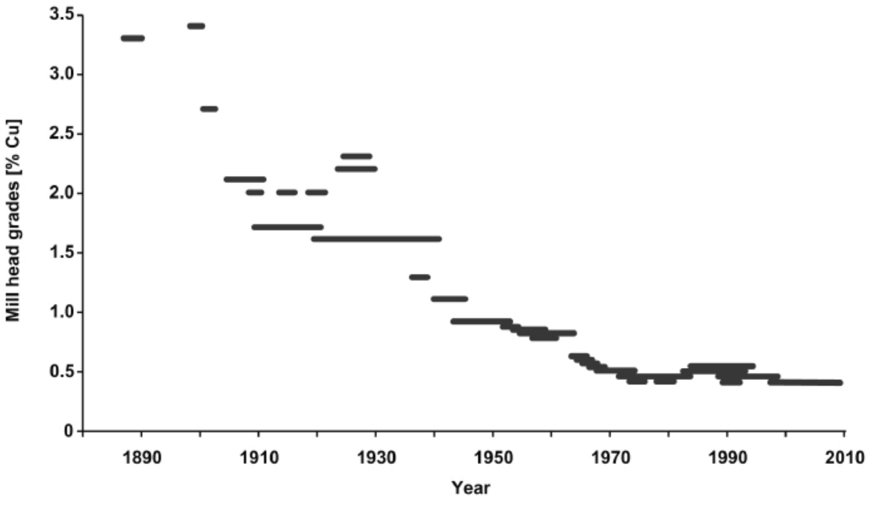
As our model does not include population growth, we run the same tests for the per capita data of the respective time series and find slightly weaker results as Table 1.4 in the Appendix shows. There is strong evidence that the growth rates of the production of copper and zinc are positive and without a trend in the long term. Hence, their levels of production grow exponentially over time. We find the same result for tin but only over the long time period of 1792 to 2009, but not for selected shorter time periods. Growth rates of lead production exhibit a statistically significant negative trend for long time periods and no statistically significant trend for the shorter time periods. The results for per capita aluminum and crude oil production as well as per capita GDP do not change significantly compared to the data in absolute values.

Overall, we take these stylized facts as motivation to build a model that exhibits trendless resource prices and exponentially increasing worldwide production of non-renewable resources as well as exponentially increasing aggregate output.

1.2.2 Technological change in the extractive sector

Technological change offsets the depletion of the stock of a non-renewable resource (Simpson, 1999, and others). Hence, the resource stock is on the one hand drawn down by extraction and use, on the other hand it is renewed by technological change in extraction technology. The reason for this phenomenon is that non-renewable resources such as copper, aluminum, or, hydrocarbons are extractable at different costs from the Earth's crust due to varying grades, thickness, depths, and other characteristics of mineral occurrences. Technological change makes mineral occurrences extractable that due to high costs have not been extractable before (see Simpson, 1999; Nordhaus, 1974, and others).

The definition of resources by the US-Geological Survey reflects this fact. It defines resources as "a concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth‘s crust in such form and amount that economic extraction (...) is currently or potentially feasible." (U.S. Geological Survey, 2011b, p. 193). The term economic "implies that profitable extraction (...) under defined investment assumptions has been established." (U.S. Geological Survey, 2011b, p. 194). The "boundary" between resources and "other occurrences is obviously uncertain, but limits may be specified in terms of grade, quality, thickness, depth, percent extractable, or other economic-feasibility variables." (U.S. Geological Survey, 2011b, p. 194).



Source: Scholz and Wellmer (2012).

Figure 1.3: The historical development of mining of various grades of copper in the U.S.

Over time, R&D in extraction technology, namely in prospection and mining equipment as well as metallurgy and processing, have renewed the stock of the resource by material from occurrences of lower grade or deeper deposits (see Wellmer, 2008; Mudd, 2007). For example, Radetzki (2009) describes how technological change has gradually made possible the extraction of copper from mineral occurrences of decreasing grades. 7000 years ago, human beings used copper in a pure nugget form. Today, humanity extracts copper from mineral occurences of a low 0.2 to 0.3 percent grade.[2] In line with this narrative evidence, Figure 1.3 illustrates that the ore grades of U.S. copper mines have constantly decreased over the long term. Mudd (2007) presents similar evidence for the mining of different base-metals in Australia. Overall, history suggests that the R&D costs in the extractive sector have increased exponentially in pushing the boundary between mineral occurences and resources in terms of grades. Developing technologies to make occurrences of 49 percent instead of 50 percent extractable, has probably required a far smaller investment than developing technologies to make occurrences of 0.2 percent instead of 1.2 percent extractable.

As a consequence, technological change has more than offset the higher cost from obtaining resources from occurrences of lower grade. Figure 1.4 shows that the reserves[3] of copper have increased by more than 600 percent over the last 60 years. One reason is the introduction of the solvent extraction and electrowinning technology. This two stage process has made the extraction of copper from mineral occurences of lower grades economically feasible (Bartos, 2002). There are also the strong effects of innovation on returns-to-scale as larger equipment in mining operations become feasible.[4] Case studies for other minerals also find that technological change has offset cost increasing degradation of resources (see for example Lasserre and Ouellette, 1991; Mudd, 2007; Simpson, 1999).

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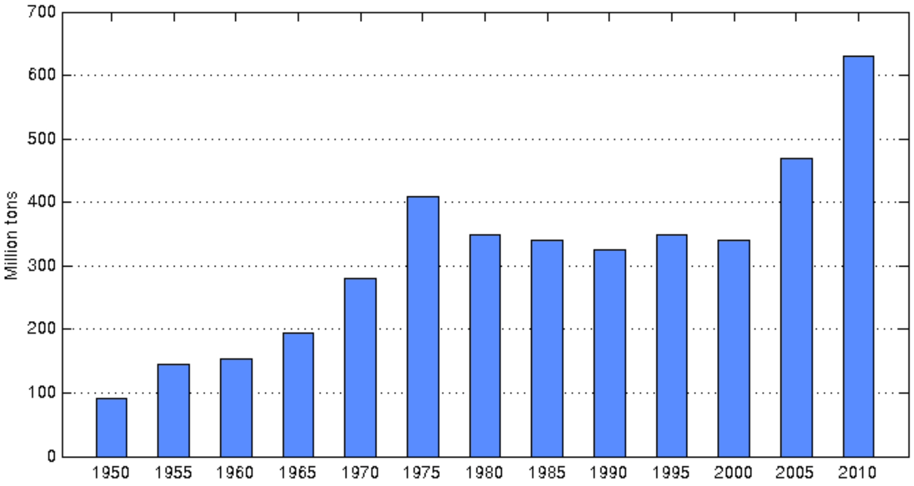
[2] The Aitik copper mine in Sweden is the mine that extracts copper from the lowest deposits of 0.27 percent in the world (personal communication with F.-W. Wellmer).

[3] Reserves are those resources for which extraction is considered economically feasible (U.S. Geological Survey, 2011c).

[4] Personal communication with F.-W. Wellmer.



Sources: Tilton and Lagos C.C. (2007), U.S. Geological Survey (2011b).

Figure 1.4: Historical evolution of world copper reserves from 1950 to 2010.

We observe similar developments in the case of hydrocarbons. Using the example of the offshore oil industry, Managi et al. (2004) show that technological change has offset the cost-increasing degradation of resources. Crude oil has been extracted from ever deeper sources in the Gulf of Mexico as Figure 1.8 in the Appendix shows. Furthermore, technological change and high prices have made it profitable to also extract liquid hydrocarbons from unconventional sources such as light tight oil, oil sands, and liquid natural gas (International Energy Agency, 2012). As a consequence, oil reserves have doubled since the 1980s (see Figure 1.7 in the Appendix).

Overall, empirical evidence suggests that technological change offsets resource depletion by renewing the resource stock from mineral occurrences that had been considered impossible to extract. Furthermore, it is a reasonable assumption that R&D costs in the extractive sector have increased exponentially in terms of making mineral occurences from lower grades extractable and turn them into accessible resources.

1.2.3 Geological distribution in the Earth's crust

Computing the total abundance (or quantity) of each of the elements in the Earth's crust leads to enormous quantities (see Nordhaus, 1974; Perman et al., 2003). Table

1.1 shows the respective ratios of quantities of reserves, resources, and abundance in the Earth's crust with respect to annual mine production for several important non-renewable resources. It provides evidence that even non-renewable resources such as gold, which are commonly thought to be the most scarce, are abundant in the Earth's crust, and that there is evidence "that the future will not be limited by sheer availability of important materials" (Nordhaus, 1974, p. 23). In addition, most metals are recyclable which means that the extractable stock in the technosphere increases (Wellmer and Dalheimer, 2012). The sediments of the Earth's crust are also rich in hydrocarbons. Even though conventional oil resources may be exhausted someday, resources of unconventional oil, natural gas, and coal are abundant. Aguilera et al. (2012) conclude that conventional and unconventional resources "are likely to last far longer than many now expect" (p. 59). Overall, Rogner (1997) states about world hydrocarbon resources that "fossil energy appears almost unlimited" (p. 249) given a continuation of historical technological trends.

	Reserves/ Annual production (Years)	**Resources/ Annual production** (Years)	**Crustal abundance/ Annual production** (Years)
Aluminum	139[1a]	263,000[1a]	48,800,000,000[bc]
Copper	43[a]	189[a]	95,000,000[ab]
Iron	78[a]	223[a]	1,350,000,000[ab]
Lead	21[a]	362[a]	70.000.000[ab]
Tin	17[a]	"Sufficient"[a]	144.000[ab]
Zinc	21[a]	158[a]	187.500.000[ab]
Gold	20[d]	13[d]	27,160,000[ef]
Rare earth elements[2]	827[a]	"Very large"[a]	n.a.
Coal[3]	129[g]	2,900[g]	1,400,000[6i]
Oil[4]	55[g]	76[g]	
Gas[5]	59[g]	410[g]	

Notes: Reserves include all material which can currently be extracted. The definition of resources can be found in section 1.2.2. Sources: [a]U.S. Geological Survey (2012a), [b]Perman et al. (2003), [c]U.S. Geological Survey (2011c),[d]U.S. Geological Survey (2011b),[e]Nordhaus (1974),[f]U.S. Geological Survey (2010a), [g]BGR, 2011b [g]iLittke and Welte (1992). Notes: [1] data for bauxite, [2] rare earth oxide, [3] includes lignite and hard coal, [4] includes conventional and unconventional oil, [5] includes conventional and unconventional gas, [6] all organic carbon in the Earth's crust.

Table 1.1: Availability of selected non-renewable resources in years of production left in the reserve, resource and crustal mass at the current mine production rate.

The elements of the Earth's crust are not uniformly distributed. Geochemical processes have decreased or increased their local abundance throughout history. Unfortunately, geologists do not agree on the distribution of the elements in the Earth's crust. Ahrens (1953, 1954) states in his fundamental law of geochemistry that the elements in the Earth's crust exhibit a lognormal grade-quantity distribution. Skinner (1979) and Gordon, Bertram, and Graedel (2007) propose a discontinuity in this distribution due to the so-called "mineralogical barrier"(Skinner, 1979), the approximate point below which metal atoms are trapped by atomic substitution. Due to a lack of geological data, both parties acknowledge that an empirical proof is still needed. In a recent empirical study, Gerst (2008) concludes that he can neither confirm nor refute these two hypotheses. Based on worldwide data on copper deposits over the past 200 years, he finds evidence for a lognormal relationship between copper production and average ore grades. Mudd (2007) analyses the historical evolution of extraction and grades of mineral occurrences for different base metals in Australia. He comes to the conclusion that production has been continually increasing, partly verging on exponentially, while grades have consistently declined.

The distribution of hydrocarbons in the Earth's crust might also differ from the fundamental laws of geochemistry by Ahrens (1953, 1954) due to the distinct formation processes. For example, oil begins to form in the source rock due to the thermogenic breakdown of organic matter (kerogen) at about 60 to 120 degrees Celsius, which is found at approximately two to four kilometer of depth. However, Farrell and Brandt (2006) and Aguilera et al. (2012) suggest that a log-normal relationship is also true for liquid hydrocarbon production. Aguilera et al. (2012) also point out that there is no huge break between the average total production costs of conventional and unconventional oil resources.

To conclude, with respect to inference about future supply, we acknowledge that there is uncertainty about the distribution of the elements in the Earth's crust. However, we believe that it is reasonable to assume that the elements are distributed according to a lognormal relationship between the grade of its mineral occurrences and its quantity in the Earth's crust.

1.3 Modeling technological change in the extractive sector

The first part of the theoretical analysis determines the return to R&D investment in the extractive sector in terms of the extractable quantity of the resource. Two functions are combined for this. The first function describes the mineral occurences that are extractable for a given state of technology. The second function shows the distribution of the quantity of the resource over grades. Combining these two functions gives the quantity of the resource that becomes extractable from one unit of R&D investment in the extraction technology.

Let N_{Rt} be the accumulated extraction technology at time t. We drop the time index to simplify notation. Let d be the grade of the respective mineral occurrences. We define the extraction cost function as a function mapping grades into extraction costs depending on the state of technology:

$$\phi_{N_R} \colon [0,1] \times \mathbb{R}_+ \to \bar{\mathbb{R}}_+, (d, N_R) \mapsto \phi_{N_R}(d) \ . \tag{1.1}$$

At technology level $N_R \in \mathbb{R}_+$ the cost of extracting the non-renewable resource from occurrences of grade $d \in [0,1]$ is $\phi_{N_R}(d) \in \bar{\mathbb{R}}_+ = \mathbb{R}_+ \cup \infty$. For a given R&D investment in extraction technology the progress in terms of grades decreases. This implies that for a given level of technology N_R, ϕ_{N_R} is non-increasing in d:

$$\forall N_R : \quad d > d' \quad \Rightarrow \quad \phi_{N_R}(d) \leq \phi_{N_R}(d') \ . \tag{1.2}$$

We assume that R&D increases the productivity of the extraction technology for mineral occurrences of all grades. Therefore, an increase in N_R decreases extraction costs for any given grade:

$$\forall d : \quad \frac{\partial \phi_{N_R}(d)}{\partial N_R} \leq 0 \ . \tag{1.3}$$

At time t, the extraction technology increases by $\frac{\partial N_{Rt}}{\partial t}$ and reduces extraction costs. The resource owner determines the R&D expenditure as an optimization between extraction costs and investment in extraction technology. To simplify this optimization problem we assume a simple functional form of the technology function.

Figure 1.5 panel (a) shows the general form of the extraction cost function. The extraction of the resource from mineral occurrences of lower grades generates higher costs, but with increasing R&D the function moves downward.

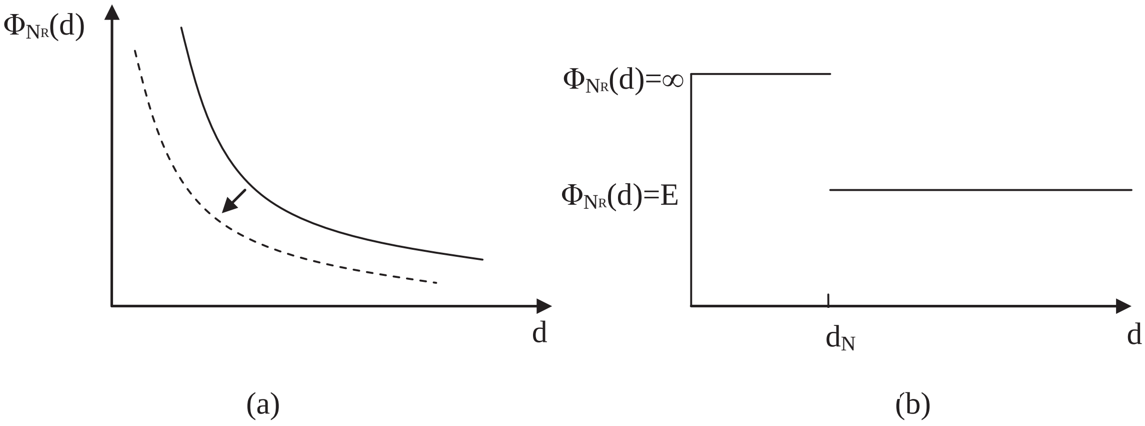


Figure 1.5: Extraction costs ϕ_{N_R} as a function of deposits of different grades d. General and simplified form.

Figure 1.5 panel (b) illustrates a simplified version of the extraction cost function, which we use in the following. A certain grade d_N is associated with a unique level of R&D investment, above which the resource can be extracted at cost $\phi_{N_R} = E$. The function h maps the state of the extraction technology into a value for the grade of the mineral occurrence, which is extractable at cost ϕ_{N_R}:

$$h\colon \mathbb{R}_+ \to [0,1], N_R \mapsto d_{N_R} \; . \tag{1.4}$$

At grades lower than d_N extraction is impossible, because the cost is infinite. The technology function takes the degenerate form of

$$\phi_{N_R}(d) = \begin{cases} E, & \text{if} \quad d \geq d_{N_R}, \\ \infty, & \text{if} \quad d < d_{N_R}. \end{cases} \tag{1.5}$$

This simplifies the optimization. If occurrences with a grade larger than d_{N_R} exist, they are extractable without any additional R&D. Otherwise, R&D is needed to increase the resource stock and to make extraction possible.

In order to determine the cost of R&D we specify a functional form for the extraction technology function h:

$$h(N_R) = e^{-\delta_1 N_{Rt}},\ \delta_1 \in \mathbb{R}_+\ , \tag{1.6}$$

with δ_1 denoting a parameter that determines the shape of the function. Panel (a) in Figure 1.6 illustrates the shape of $h(N_R)$. The marginal effect of the extraction technology on the extractable occurrences declines as the grade decreases. This picks up the suggestion in the stylized facts that R&D costs have increased exponentially in pushing the boundary between mineral occurrences and resources in terms of grades.

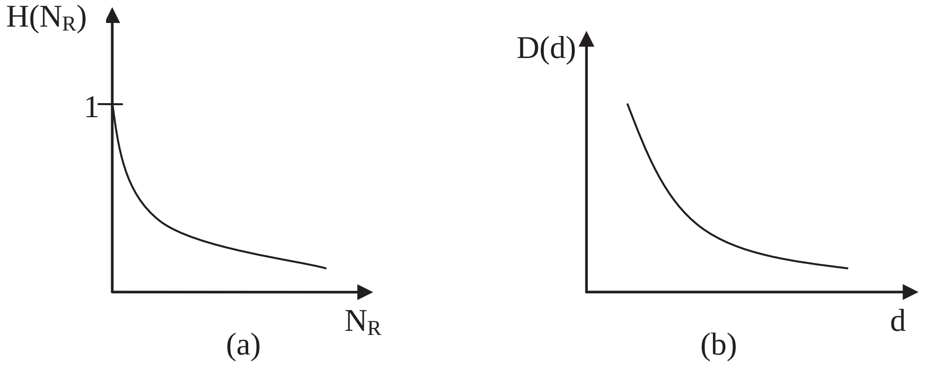


Figure 1.6: (a) Extractable mineral occurrences of grade $h(N_R)$ as a function of the state of technology N_R. (b) The extractable amount of the non-renewable resource in the Earth's crust $D(d)$ at a given grade d of the mineral occurrences.

Panel (b) in Figure 1.6 shows the distribution of the non-renewable resource in the Earth's crust. It maps a certain grade into the total quantity of extractable resources at different grades of the occurrences between d and one, where one corresponds to a 100 percent ore grade or pure metal.

$$D\colon (0,1] \to \mathbb{R}_+, d \mapsto D(d) \tag{1.7}$$

Note that $D(1) = 0$ means that the resource is not found in 100 percent pure form. Figure 1.6 panel (b) illustrates the relationship between the two variables. The total quantity of the non-renewable resource is inversely proportional to the grade: As the grade decreases, the extractable quantity of the non-renewable resource increases.

We formulate the relationship in a general way:

$$D(d) = -\delta_2 \ln(d), \quad \delta_2 \in \mathbb{R}_+ \ , \tag{1.8}$$

where δ_2 determines the steepness of the function.

We combine the two functions and obtain the following proposition. A dot over a variable denotes the time derivative.

Proposition 1. *The total quantity of the resource, which has been made extractable over time due to technological change, is proportional to* N_{Rt}*:*

$$D(h(N_{Rt})) = \delta_1 \delta_2 N_{Rt} \ . \tag{1.9}$$

Consequently, the newly extractable resource from a marginal investment into R&D is

$$X_t = \frac{\partial D(h(N_{Rt}))}{\partial t} = \delta_1 \delta_2 \dot{N}_{Rt} \ . \tag{1.10}$$

According to this result, the quantity of the resource, which is made extractable by a given R&D investment in extraction technology, is independent of past investments or time. An extractive firm invests an amount of $\dot{N}_{Rt}$ into R&D. This gives her a smaller return on investment in terms of making resources from occurrences of lower grade extractable. However, this smaller advancement in terms of grade makes the same quantity of the resource extractable as she reaches a grade with a higher extractable amount of resources than before.

1.4 The growth model

To illustrate the macroeconomic effect of the analysis in Section 1.3 we extend the standard decentralized endogenous growth model of Acemoglu (2002). One of the two sectors in this model is replaced by an extractive sector. The economy can thus allocate R&D expenditure optimally between the two sectors.

1.4.1 The setup

The basic structure of the model is taken from Acemoglu (2002). We consider an economy with a representative consumer that has constant relative risk aversion preferences:

$$\int_0^\infty \frac{C_t^{1-\theta}-1}{1-\theta}e^{-\rho t}dt\ . \tag{1.11}$$

C_t is consumption of aggregate output at time t, ρ is the discount rate, and θ is the coefficient of relative risk aversion. Her budget constraint is

$$C_t + I_t + M_t \leq Y_t \equiv \left[\gamma Z_t^{\frac{\varepsilon-1}{\varepsilon}} + (1-\gamma)R_t^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}}\ , \tag{1.12}$$

where I_t is aggregate investment in machines by the two sectors and M_t denotes aggregate R&D investment in developing new varieties of machines. For illustrative purposes and to stay in line with the literature we label "technology" as "machines" in the following. The usual no-Ponzi game condition applies. Aggregate output production uses, according to the right hand side of Equation 1.12 two inputs, intermediate goods Z_t and the non-renewable resource R_t. There are two sectors in the economy that produce the inputs to aggregate output production: the intermediate goods sector and the non-renewable resource sector. The distribution parameter γ indicates the respective importance in producing aggregate output Y_t. The R&D expenditure is the sum of R&D expenditure in the intermediate sector and in the extractive sector: $M_t = M_{Zt} + M_{Rt}$.

$\varepsilon > 0$ is the elasticity of substitution. Inputs Z_t and R_t are substitutes for $\varepsilon > 1$. In this case the resource is inessential for aggregate production (see Dasgupta and Heal, 1980). $\varepsilon = 1$ is the Cobb-Douglas case. For $0 < \varepsilon < 1$ the two inputs are complements.

The production function of the intermediate goods sector

The intermediate goods sector follows the basic setup of Acemoglu (2002). It produces intermediate goods Z_t according to the following production function[5]:

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[5] Like Acemoglu (2002) we assume that the firm level production functions of the two sectors exhibit constant returns to scale, so there is no loss of generality in focusing on the aggregate production functions.

$$Z_t = \frac{1}{1-\beta} \left(\int_0^{N_{zt}} x_{zt}(j)^{1-\beta} dj \right) L^{\beta} \ , \tag{1.13}$$

where $\beta \in (0, 1)$. The goods of the intermediate goods sector are produced from aggregate labor L_t, which is in fixed supply, and from machines. $x_{Zt}(j)$ refers to the number of machines that are used of each machine variety j at time t. Machines depreciate fully after use within one period. N_{zt} denotes the number of varieties of machines.

Sector specific technology firms invent and produce machines. They hold fully enforceable patents on the machines and are able to set monopolistic prices $\chi_{Zt}(j)$. Machines depreciate fully after use and the marginal cost of production in terms of the final good ψ is the same for all machines.

The range of machines expands through R&D expenditure by

$$\dot{N}_{Zt} = \eta_Z M_{Zt} \ , \tag{1.14}$$

where M_{Zt} is R&D investment by the technology firms for machines in the intermediate goods sector in terms of the final product and η_Z is a cost parameter. One unit of the final good spent for R&D will generate η_Z new varietes of machines. A technology firm that discovers a new machine receives a patent and becomes its sole supplier.

The production function of the extractive sector

The extractive sector differs from the intermediate goods sector in the production function and in the way technological change takes place.

The extractive sector faces stock constraints which the intermediate goods sector does not. The stock of the non-renewable resource at time t is noted $S_t \geq 0$. R_t notifies the quantity of the non-renewable resource that is sold for aggregate output production. Investing in new machines makes occurrences of lower grades extractable and expands the resource stock by X_t. The evolution of the stock follows:

$$\dot{S}_t = X_t - R_t \ , \qquad S_t \geq 0, X_t \geq 0, R_t \geq 0 \ , \tag{1.15}$$

where $\dot{S}_t$ is the change in the stock in period t, X_t is the inflow through investment in new machines, and R_t the outflow by extracting and selling the resource. Note that for $X_t = 0$ this formulation is the standard Hotelling (1931) setup.

Extractive firms increase the resource stock by

$$X_t = \delta_1 \delta_2 \dot{N}_{Rt} x_R(j) \ , \tag{1.16}$$

which is equal to Equation 1.10 in Proposition 1 with the number of machines $x_R(j)$ that extractive firms purchase from sector specific technology firms added. Each machine $x_R(j)$ makes a specific additional mineral occurrence with a lower grade extractable. In contrast to the intermediate goods sector, the use of the machine variety j is bound to a specific deposit. Each mineral occurrence has the same quantity of the resource but each at a different grade. Once a firm has extracted the resource from a specific mineral occurrence by use of machine variety j, the next deposit - with a lower grade - is not extractable any more by machine variety j. A new machine variety needs to be bought from the sector specific technology firms. As a consequence, each variety of machines in the extractive sector can only be used once, whereas in the intermediate goods sector each variety of machines is used in finitely often. We normalize the size of R&D investment to one, xR(j) = 1. This is mathematically not exactly the same as in the intermediate goods sector, but it provides a comparable micro-foundation by subdividing the growth in technology into units. In the intermediate goods sector a machine is an infinitesimally small variety, whereas in the extractive sector it is a normalized fraction of R&D investment.

The term $\dot{N}_{Rt}$ denotes the range of the new machine varieties invented by the sector specific technology firms. The extractive sector is constantly under constraint to buy newly developed machines as once developed machines are not capable to extract the resource from declining grades. This is in contrast to the intermediate goods sector (see Equation 1.13) which produces from all machine varieties that have ever been developed.

The sector specific technology firms develop $\dot{N}_{Rt}$ new patents for machines of the extractive sector in analogy to the intermediate goods sector according to:

$$\dot{N}_{Rt} = \eta_R M_{Rt} \ , \tag{1.17}$$

where M_{Rt} is spending on R&D in the extractive sector in terms of the final product and η_R is a cost parameter.

Once the patent has been developed, the technology firms produce the new machine variety j at a unit cost of Ψ in terms of the final good. Technology firms can only produce one machine for each patent. They sell machines to the extractive sector in perfect competition, because the machines are perfect substitutes for producing the resource. This implies that the firm which buys the machines from the technology firms is entirely indifferent between the machines. Since sector specific technology firms have no market power, they obtain a price of the machine above marginal cost:

As each machine variety can only be used once in the extractive sector (see above),

$$\chi_R(j) = \frac{1}{\eta_R} + \Psi \ , \tag{1.18}$$

.

The marginal cost on the right hand side consists of two components. The first term, $\frac{1}{\eta_R}$, is the marginal R&D expenditure for developing one patent. This results from the equation $\eta_R M_R = \dot{N}_R$. Setting $\dot{N}_R = 1$ and solving for M_R yields $M_R = \frac{1}{\eta_R}$. The second term, Ψ, notifies the cost of producing the machine.

The production function of the extractive sector is equal to the outflows from the resource stock R_t:

$$R_t = \delta_1 \delta_2 \dot{N}_{Rt} x_R(j) - \dot{S}_t \ . \tag{1.19}$$

It illustrates the fundamental difference between the intermediate goods sector and the extractive sector in the relationship between technological change and the respective production. If technology firms stop investing in R&D in the intermediate goods sector, the intermediate goods sector will still be able to produce the good Z_t by buying machines based on the existing patents. However, if investment in R&D of the extraction technology stops at time T, the quantity of the resource that will still be extractable with the machines from the existing technology is limited to the existing stock

$$S_T = S_0 + \int_0^T X_t dt - \int_0^T R_t dt \ . \tag{1.20}$$

This stock imposes an upper bound on the amount of the extractable non-renewable resource for the entire future given that there is no technological change in the extraction technology:

$$S_T = \int_T^\infty R_t dt \ . \tag{1.21}$$

Patents in the intermediate goods sector can be used infinitely to produce machines once they are created. In contrast, in the extractive sector patents can only be used once since any new machine will lose its usefulness after the initial use. The reason is that each machine is linked to extracting the resource from a specific grade of the occurrences. As the extractable grade of occurrences declines, new R&D in extraction technology is required to access further resources.

1.4.2 Results

We begin the formal analysis with the optimization of the extractive firms. They have full control over inflows and outflows from their resource stock. Inflows X_t depend on R&D investment in the extractive sector and outflows R_t are the sales of the resource to the final good producer. Since the marginal cost for R&D is constant, we obtain the typical result of stock management: inflows and outflows have to balance over time. Proofs for this section can be found in the Appendix.

Proposition 2. *The quantity of the resource used in aggregate production equals the quantity of newly acquired resources through R&D:* $R_t = X_t$.

When the resource stock is zero, $S_t = 0$, it is not possible to extract the non-renewable resource without additional R&D in the extractive sector. An extractive firm needs to buy a new machine and hence trigger investment in R&D by the technology firms. The resulting resource stock can then be extracted and sold to the final good producer. However, another extractive firm may also invest in R&D and also extract and sell the resulting resource. This situation of perfect competition means that resource prices are equal to marginal costs, which is the cost of extraction. This also highlights why the case $S_t > 0$ never occurs under the assumption of no uncertainty: An extractive firm investing in R&D will always extract and sell the newly available resource stock, because the selling price will remain constant.

The result is of course affected by the assumption of no uncertainty. Following the standard in growth models, we have assumed in Equation 1.17 that patents for new machines result in a deterministic way from the respective R&D investments. This reflects a long-term perspective. The model could be made more sophisticated by assuming that R&D is stochastic. Extractive firms would then keep a positive stock of the resource S_t to be on the safe side in the case of a series of bad draws in R&D. This stock would grow over time as the economy grows. But in essence, the result above would remain the same: In the long term, resources used in aggregate production equal those added to the resource stock through R&D.

We turn to the solution of the model:

Proposition 3. *The growth rate of the economy is constant and given by*

$$g = \theta^{-1} \left(\beta \eta_Z L \left[1 - \left(\frac{1-\gamma}{\gamma} \right)^{\frac{\varepsilon}{1-\varepsilon}} \frac{1+\psi\eta_R}{\eta_r \delta_1 \delta_2} \right]^{\frac{1}{\beta}} - \rho \right) .$$

A higher rate of return to R&D investment in new machines of the labor sector, η_Z, increases the growth rate of the economy. We discuss the effects of parameters η_R, δ_1, and δ_2 on the growth rate in Proposition 5.

In order to understand the role of the non-renewable resource in the economy, we determine its relative importance:

Proposition 4. *The resource intensity of the economy is given by*

$$\frac{R}{Y} = \left[(1-\gamma) \frac{\eta_R \delta_1 \delta_2}{1+\psi\eta_R} \right]^{\varepsilon} . \tag{1.22}$$

It depends positively on the distribution parameter for the resource, γ.

The distribution parameter γ indicates the importance of the resource for the economy as shown in the production function in Equation 1.12.

Extractive firms face constant marginal cost of extracting the non-renewable resource, since the resource stock can be expanded due to R&D in extraction technology. The price thus remains constant over time as well:

Proposition 5. *The resource price is*

$$p_{Rt} = \frac{1 + \psi \eta_R}{\eta_r \delta_1 \delta_2} \, .$$

A higher resource price has the following effects: (i) The resource intensity of the economy is lower. (ii) The growth rate of the economy is lower.

This proposition shows that the resource price plays a central role in the model. To understand it we consider first its determinants and then focus on its effects.

The determinants of the price are given by the parameters η_R, δ_1, and δ_2. The productivity of R&D in the extractive sector, defined in Equation 1.17, and given by η_R, determines the number of new machine varieties that are developed by the sector specific technology firms per unit of aggregate output. The higher this parameter, the higher the resource use in the economy. δ_1, defined in Equation 1.6, is a productivity parameter for the marginal effect of R&D investment on the extractability of occurrences of lower grades. δ_2, defined in Equation 1.8, determines the steepness of the distribution of elements over mineral occurrences of various grades in the Earth's crust. If the quantity of the extractable resource increases strongly as the grade of occurrences decreases, the return on investments in R&D for the extraction technology increases, and the economy uses a larger quantity of the resource in proportion to aggregate output.

The resource price is constant, but Proposition 5 shows that the resource price is high when the productivity parameters are low and vice versa. It states quite intuitively that the selling price of the resource is low, if the productivity parameters are high.

Moreover, Proposition 5 in combination with Propositions 3 and 4 shows the effect of a lower resource price on the growth rate and the resource intensity of the economy. Both depend negatively on the resource price. When the price is low, the non-renewable resource is used intensively and the resource constraint on growth is weak. When the price is high, the economy uses substitutes, but this reduces growth.

We compare the growth rates of the technology in the two sectors.

Proposition 6. *The level of technology in the labor intensive sector is*

$$N_Z = \left(\frac{1-\gamma}{\gamma}\right)^{-\varepsilon} \left(\frac{\eta_R \delta_1 \delta_2}{1+\psi\eta_R}\right)^{\varepsilon} \left(\gamma^{-\varepsilon} - \left(\frac{1-\gamma}{\gamma}\right)^{\varepsilon} \frac{\eta_R \delta_1 \delta_2}{1+\psi\eta_R}\right)^{\left(\frac{1}{1-\varepsilon}\right)\left(-\varepsilon+\frac{1-\beta}{\beta}\right)} (1-\gamma)^{\varepsilon} L^{-1} Y \ .$$

The growth rate of technology in the extractive sector

$$\dot{N}_R = (1-\gamma)^{\varepsilon} \frac{\eta_R}{1+\psi\eta_R} Y \ .$$

There is thus a qualitative difference in the growth rate of the two sectors. While the *level* of technology in the intermediate goods sector is proportional to output, the *growth rate* of technology in the extractive sector is proportional to output. N_Z therefore has the *constant* growth rate g, as given in Proposition 3. N_R has an *increasing* growth rate. It is the second derivative $\frac{\partial^2 N_R}{\partial^2 t}$ which is equal to g.

1.4.3 Market structure in the resource market

We have assumed so far that the non-renewable resource is provided competitively so that the resource is priced at marginal cost (see Proposition 5). In this section we first elaborate on the assumption of a fully competitive resource sector. We then consider monopoly power as an alternative assumption in the later part.

As the proof of Proposition 2 shows, the cost of extracting one unit of the resource is given by $\frac{1+\psi\eta_R}{\eta_R\delta_1\delta_2}$. Each extractive firm faces a demand function for R_t from the final good producer and sets the price p_{Rt} optimally. Profits of firms in the extractive sector are thus given by

$$\pi_{Rt} = \left(p_{Rt} - \frac{1+\psi\eta_R}{\eta_R\delta_1\delta_2}\right) R_t \ . \tag{1.23}$$

The use of a patent to produce a new machine decays immediately since the corresponding mineral occurrence is depleted. Any firm willing to invest in a new machine is thus able to extract the resource from a mineral occurrence of lower grade and to sell it to the final good producer. This situation is conducive to competition. Accordingly, profits in the extractive sector are zero and firms price the resource at marginal extraction cost.

For the purpose of illustration, we assume that there is a mass of firms J in the extractive sector, each without resource deposits, $S_{tj} = 0$. Each firm's cost for new machines and their resource output are described by

$$R_{tj} = \delta_1 \delta_2 \eta_R M_{Rtj} \ . \tag{1.24}$$

The final good producer buys the total amount of resources of

$$R_t = \int_j R_{tj} dj \ . \tag{1.25}$$

Each firm in the extractive sector makes profits according to

$$\pi_{Rtj} = \left(p_{Rtj} - \frac{1 + \psi \eta_R}{\eta_R \delta_1 \delta_2} \right) R_{tj} \ . \tag{1.26}$$

Suppose firm A offers a price of $p_{RtA} < \frac{1+\psi\eta_R}{\delta_1\delta_2\eta_R}$. In this case the marginal cost per unit is above the offered price. Firm A would make a loss and would have to leave the market. Suppose instead firm A would offer a price of $p_{RtA} > \frac{1+\psi\eta_R}{\delta_1\delta_2\eta_R}$. In this case firm B offers a price $p_{RtA} > p_{RtB} \geq \frac{1+\psi\eta_R}{\delta_1\delta_2\eta_R}$ and makes a profit or breaks even. The final good producer would buy only from firm B such that firm A would leave the market. Therefore, the only remaining option for firm A is to price at marginal cost: $p_{RtA} = \frac{1+\psi\eta_R}{\delta_1\delta_2\eta_R}$.

We have thus established the price of the resource. The quantity is determined by the final good producer. As we have seen in Equation 1.30 in the Appendix, the demand curve is given by

$$R_t = \frac{Y_t (1-\gamma)^{\varepsilon}}{p_{Rt}^{\varepsilon}} \ . \tag{1.27}$$

There is a unique quantity sold on the market. If existing extractive firms do not offer this unique amount, new etractive firms enter the market and sell the non-renewable resource. By the same means, existing firms may expand their business. If more than the demanded quantity is offered, the final good producer would select some firms, from which to buy. In equilibrium, there is therefore a unique price and a unique quantity in a market without market entry barriers. The number of firms in the extractive sector as well as their size is indeterminate. We therefore use an aggregate production function for the extractive sector.

In the following we assume a monopoly in the extractive sector. In this case the monopolist first maximizes profits from Equation 1.23 without restriction. The resulting resource price has a markup over marginal cost, which depends on the degree of substitutability. Cases where a resource is provided with an intermediate degree of market power are in between the two extreme cases.

Given the central role of the resource price, it is important to analyze the effect of the market structure in the resource sector. To do this we consider a variant of the model, where we assume a monopolist in the resource sector instead of full competition.

Proposition 7. *Let the resource market be dominated by a single monopolist and let $\varepsilon > 1$. Then the price of the non-renewable resource is*

$$p_{Rt}^{Mon} = \frac{1+\psi\eta_R}{\eta_R\delta_1\delta_2}\frac{\varepsilon}{\varepsilon-1} \ .$$

If the resource market is dominated by a single monopolist, the pricing strategy depends strongly on the elasticity of substitution. If Z and R are complements ($0 < \varepsilon < 1$), the economy cannot produce aggregate output without the resource. A resource monopolist could demand an arbitrarily high price in this case. We therefore exclude this case. In the case where the two inputs are substitutes ($1 < \varepsilon$), the pricing becomes a typical monopoly pricing problem: The monopolist imposes the markup $\frac{\varepsilon}{\varepsilon-1}$.

As a corollary of Proposition 7, we note that a stronger market power in the resource sector results in an economy with lower resource intensity and a lower growth rate. The reason is that market power puts a markup on prices. A consequence of a lower resource intensity is also less R&D expenditure in the extractive sector, since less technology is needed when less of the resource is sold.

This result highlights that the market structure in the resource market affects the level of the price, but not its long-term trend. A monopolist simply takes a markup over the competitive price. This allows us to understand the effect of a change in market structure on resource prices. If resource producers form a cartel for example, the price will be higher in the new steady state and the resource intensity of the economy will be lower. In the new steady state, the price will again be constant and the quantity supplied will grow at the same rate as the economy.

1.4.4 The social planner solution

With the help of the social planner solution, we are able to establish that technology firms in the intermediate goods sector cause an inefficiency by their market power.[6] The growth rate of the economy g^{opt} is not constant but growing in the optimum as $\frac{x_Z}{N_Z}$ is not constant in:

$$g^{opt} = \frac{1}{\theta} \left(\frac{1}{\eta_Z (1-\beta)\psi} \frac{x_Z}{N_Z} - \rho \right) . \tag{1.28}$$

As a consequence, there is no balanced growth path in the social planner solution. This is in contrast to the decentralized solution, where the growth rate of the economy is constant (see Equation 3). The reason for this difference is that there are efficiency losses in the decentralized solution due to the monopoly power of the technology firms for machines in the intermediate goods sector. In the decentralised solution the quantity of machines, which is supplied for each variety $x_Z(j)$, is constant as p_Z and $\chi_Z(j)$ are constant (see Equation 1.37 in the Appendix). In contrast, in the social planner solution x_Z is proportional to aggregate output as $x_Z = z_2 Y$ (see Equation 1.74). Furthermore, the decentralized solution features constant returns to scale in the production of Z_t (see Equation 1.13), since firms do not internalize technology in their production technology. For the social planner, however, technology is endogenous so that production has increasing returns in the factors N_Z and x_Z (see Equation 1.51 in the Appendix).

The comparison between the decentralized and the social planner solution illustrates the difference between our model based on Acemoglu (2002) and the Schumpeterian model in Section 5.3.2 in Aghion and Howitt (1998). In the latter model a social planner solution with resources is presented. Aghion and Howitt (1998) make the assumption that "succeeding vintages of goods are increasingly capital intensive" (p. 153) in order to explain an exponent smaller than one on technology. The idea

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[6] Acemoglu (2002) provides only a decentralised solution of his model. The derivation of the central planner solution of our model is in Appendix A1.3.

of Acemoglu (2002) is that there are increasing returns to scale, but these are not exploited due to the inefficiency of the market solution.

The extractive sector does not make a difference to the two solutions. Technology firms are not able to obtain a monopoly price for machines, because machines are linked to the extraction of one specific occurrence while the produced resource is a homogeneous good. There is therefore no efficiency loss in the extractive sector of the decentralized model. The resource production in the decentralized and in the social planner solution functions in the same efficient way. Comparing the respective first order conditions, the first order condition of the decentralized solution is given by the demand of the final good producer for the resource (see Equation 1.30 in the Appendix). When substituting the price from Equation 1.33 to Equation 1.30 in the Appendix, it becomes identical to the respective first order condition in the social planner solution in Equation 1.63 in the Appendix.

There is no straightforward way to correct for the inefficiency in the decentralized model. Technology firms obtain patents for machines. The property right of the patent ensures that only the respective firm is able to produce the machine. However, the patent also entails market power in the intermediate goods sector such that the provided quantity of machines is below the social optimum. There is demand for each variety and each variety is supplied by a single firm. A subsidy on the sale of machines in the intermediate goods sector affects the supply of machines, but does not have an impact on the growth rate of machine supply. To do so, the government needs to apply policy instruments like a subsidy on sales that increases with time, or to modify the market structure by disconnecting R&D investment from the market power created by patents. The latter solution would require government compensation to inventors or some other incentive device. Finally, we have to keep in mind that this inefficiency has also been introduced by Acemoglu (2002) to obtain a balanced growth path in the decentralized solution.

1.4.5 Discussion

We discuss a number of issues that arrive from our model, namely the assumptions made in Section 1.3, the comparison to the other models with non-renewable resources, and the question of the ultimate finiteness of the resource. Function D from Equation 1.7 shows the amount of the non-renewable resource in the Earth's crust for a given occurrence of grade d. Geologists cannot give an exact functional form for D, so we used the form given in Equation 1.8 as a plausible assumption. How would other functional forms affect the predictions of the model? First, the predictions are valid for all parameter values $\delta_2 \in \mathbb{R}_+$. Secondly, if D is discontinuous with a break at d_0, at which the parameter changes to $\delta_2' \in \mathbb{R}_+$, there would be two balanced growth paths: one for the period before and one for the period after the break. Both paths would behave according to the predictions of the model. They would differ in the extraction cost of producing the resource and in the level of extraction and use of the resource in the economy. To see this, recall from Proposition 1 that X_t is a function of δ_2. A non-exponential form of D would produce results that differ from ours. It could feature a scarcity rent as in the Hotelling (1931) model, as an non-exponential form of D could cause a positive trend in resource prices or the extraction from occurrences at a lower ore grade becomes infeasible. In these cases the extractive firms would consider the opportunity cost of extracting the resource in the future in addition to extraction and innovation cost.

How does our model compare to other models with non-renewable resources? We do not assume that resources are finite, as their availability is a function of technological change. As a consequence, resource availability does not limit growth. Substitution of non-renewable resources by capital, technological progress in the use of the resource, and increasing returns to scale are therefore not necessary for sustained growth as in Groth (2007) or Aghion and Howitt (1998). Growth depends on technological change as much as it does in standard growth models without a non-renewable resource.

Our model suggests that the non-renewable resource can be thought of as a form of capital: If the extractive firms invests in new machines and trigger R&D in the extraction technology, the resource is extractable without limits as an input to aggregate production. This feature marks a distinctive difference from models such as the one of Bretschger and Smulders (2003). They investigate the effect of various assumptions on substitutability and a decentralized market on long-run growth, but keep the assumption of a finite non-renewable resource. Without this assumption, the elasticity of substitution between the non-renewable resource and other input factors is not central to the analysis of limits to growth anymore.

Some might argue that the relationship described in Proposition 1 cannot continue to hold in the future as the amount of non-renewable resources in the Earth's crust is ultimately finite. Scarcity will become increasingly important and the scarcity rent will be positive even in the present. However, for understanding current prices and consumption patterns current expectations about future developments are important. Given that the quantities of available resources indicated in Table (1.1) are very large, their ultimate end far in the future does not affect behavior today. Furthermore, when the resources in the Earth's crust are exhausted, so much time will have passed that technology might have developed to a point where the Earth's crust, which makes up one percent of the Earth's mass, is no longer a limit to resource extraction. Deeper parts of the planet or even extraterrestrial sources might be explored. These speculative considerations are not crucial for our model. What is important is that the relation from Proposition 1 has held in the past and looks likely to hold for the foreseeable future. Since in the long term, extracted resources equal the resources added to the resource stock due to R&D in the extraction technology, the price for a unit of the resource will equal the extraction cost plus the per-unit cost of R&D and hence stay constant in the long term. This explains why scarcity rents cannot be found empirically as shown in Hart and Spiro (2011).

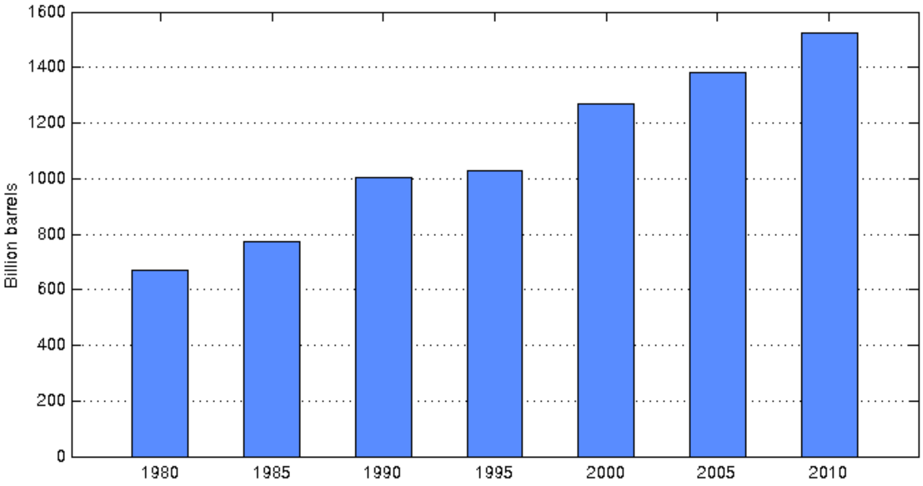
1.5 Conclusion

This paper examines the long-term evolution of prices and production of major non-renewable resources from a theoretical and empirical perspective. We argue that economic growth causes the production and use of a non-renewable resource to increase exponentially and its production costs to stay constant in the long term. Economic growth enables firms to invest more in R&D which makes resources from mineral occurrences of lower grade extractable. We explain the long-term evolution of non-renewable resource prices and world production for more than 200 years. If historical trends in technological progress continue, it is within the realm of possibility that non-renewable resources are, within a time frame relevant for humanity, de facto inexhaustible.

Our model makes four major simplifications, which should be examined in more detail in future extensions. First, there is no uncertainty in R&D development and therefore no need to keep a positive stock of the resource. When R&D development is stochastic (as in Dasgupta and Stiglitz (1981)), there would be a need for firms to keep stocks as we observe it in reality. Second, our model features full competition in the extractive sector. We could obtain a model with monopolistic competition in the extractive sector by introducing privately owned mineral occurrences. A firm would need to pay a certain upfront cost or exploration cost in order to acquire a mineral occurrence (see, e.g., Cairns and Quyen (1998) and Slade (1988)). This upfront cost would give technology firms a certain monopoly power as they develop machines that are specific to single mineral occurrences. Third, extractive firms could face a trade-off between high extraction costs at lower technology levels and R&D investment to lower extraction costs. The general extraction technology function in Equation 1.1 provides the basis to generalize this assumption. Treatment of a similar problem are Farzin, Huisman, and Kort (1998) and Doraszelski (2004). Finally, our model does not include recycling. Recycling will likely become more important for metal production due to the increasing abundance of recyclable materials and the comparatively low energy requirements to recycle the items (see Steinbach and Wellmer, 2010; Wellmer and Dalheimer, 2012). Introducing recycling into our model would further strengthen our argument as it increases the available stock of the non-renewable resource.

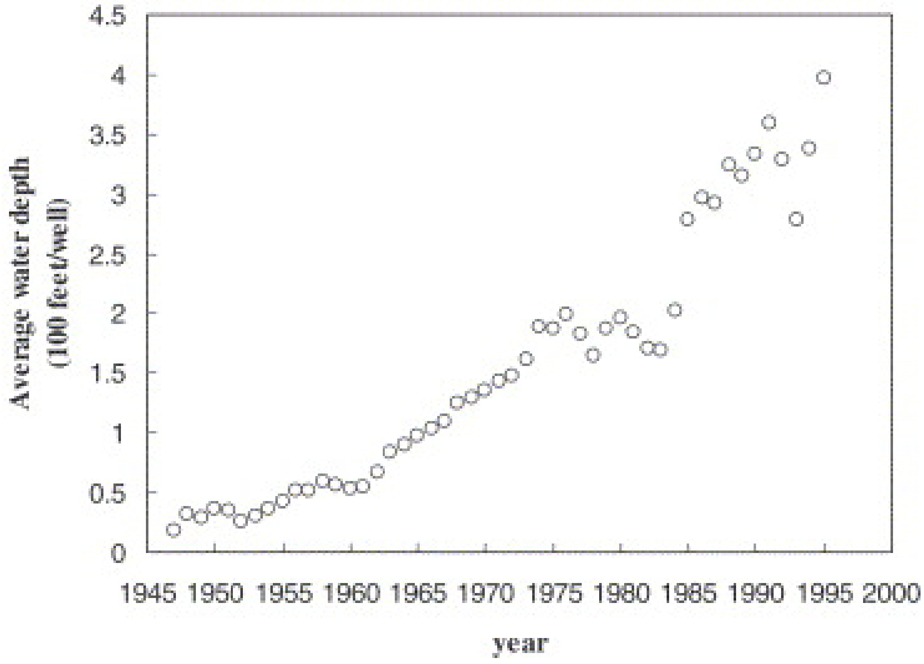
A1 Appendix

A1.1 Additional figures and regression results



Source: British Petroleum (2011).

Figure 1.7: Historical evolution of oil reserves, including canadian oil sands from 1980 to 2010.



Source: Managi et al. (2004).

Figure 1.8: Average water depth of wells drilled in the Gulf of Mexico.

		Aluminum	Copper	Lead	Tin	Zinc	Crude Oil
Range		1905-2009	1792-2009	1792-2009	1792-2009	1824-2009	1862-2009
Constant	Coeff.	-1.774	0.572	0.150	1.800	1.072	8.242
	t-stat.	(-0.180)	(0.203)	(0.052)	(0.660)	(0.205)	(0.828)
Lin.Trend	Coeff.	0.008	0.009	0.016	0.001	0.014	-0.021
	t-stat.	(0.137)	(0.428)	(0.714)	(0.069)	(0.357)	(-0.317)
Range		1905-2009	1850-2009	1850-2009	1862-2009	1850-2009	1850-2009
Constant	Coeff.	-1.299	0.109	-0.268	2.439	1.894	7.002
	t-stat.	(-0.200)	(0.030)	(-0.073)	(0.711)	(0.407)	(1.112)
Lin.Trend	Coeff.	0.008	0.020	0.030	-0.004	0.013	-0.021
	t-stat.	(0.137)	(0.518)	(0.755)	(-0.109)	(0.267)	(-0.317)
Range		1900-2009	1900-2009	1900-2009	1900-2009	1900-2009	1900-2009
Constant	Coeff.	-0.903	-1.428	-0.490	1.068	2.764	-1.974
	t-stat.	(-0.239)	(-0.332)	(-0.102)	(0.269)	(0.443)	(-0.338)
Lin.Trend	Coeff.	0.008	0.055	0.054	0.010	0.010	0.100
	t-stat.	(0.137)	(0.820)	(0.713)	(0.168)	(0.099)	(1.106)
Range		1950-2009	1950-2009	1950-2009	1950-2009	1950-2009	1950-2009
Constant	Coeff.	2.269	1.556	-3.688	-0.061	-0.515	3.445
	t-stat.	(0.479)	(0.240)	(-0.505)	(-0.011)	(-0.062)	(0.354)
Lin.Trend	Coeff.	-0.055	0.041	0.198	0.049	0.103	0.090
	t-stat.	(-0.411)	(0.225)	(0.958)	(0.307)	(0.441)	(0.326)
Range		1875-1975	1875-1975	1875-1975	1875-1975	1875-1975	1875-1975
Constant	Coeff.	-0.549	1.323	0.370	3.719	1.136	-1.111
	t-stat.	(-0.088)	(0.266)	(0.081)	(0.812)	(0.176)	(-0.176)
Lin.Trend	Coeff.	-0.003	0.011	0.030	-0.012	0.051	0.094
	t-stat.	(-0.033)	(0.135)	(0.383)	(-0.152)	(0.468)	(0.875)

Notes: The table presents coefficients and *t*-statistics for regressions of the growth rates on a constant and a linear trend.***, **, and * indicate significance at the 1%, 2.5% and 5% level, respectively.

Table 1.2: Tests of the stylized fact that the growth rates of real prices of mineral commodities equal zero and do not follow a statistically significant trend.

		Aluminum	Copper	Lead	Tin	Zinc	Crude Oil	World GDP
Range		1855-2009	1821-2009	1802-2009	1792-2009	1821-2009	1861-2009	1792-2009
Constant	Coeff.	48.464	4.86	16.045	4.552	30.801	35.734	0.128
	t-stat.	*** 3.810	*** 2.694	*** 3.275	* 2.231	** 2.58	*** 4.365	0.959
Lin.Trend	Coeff.	-0.221	-0.006	-0.087	-0.016	-0.174	-0.182	0.018
	t-stat.	** -2.568	-0.439	** -2.294	-0.999	* -1.975	*** -3.334	*** 16.583
Range		1855-2009	1850-2009	1850-2009	1850-2009	1850-2009	1861-2009	1850-2009
Constant	Coeff.	48.464	5.801	6.032	3.569	5.579	25.198	0.995
	t-stat.	*** 3.810	*** 3.461	***3.371	* 2.185	*** 3.774	*** 4.81	*** 5.49
Lin.Trend	Coeff.	-0.221	-0.018	-0.038	-0.015	-0.021	-0.182	0.019
	t-stat.	** -2.568	-1.007	-1.938	-0.833	-1.308	*** -3.334	*** 9.797
Range		1900-2009	1900-2009	1900-2009	1900-2009	1900-2009	1900-2009	1900-2009
Constant	Coeff.	19.703	5.965	2.980	2.844	4.44	9.883	2.004
	t-stat.	*** 5.498	*** 2.651	* 2.043	1.361	* 2.225	*** 6.912	*** 7.8
Trend	Coeff.	-0.l78	0.035	-0.019	-0.015	-0.018	-0.083	0.018
	t-stat.	*** 3.174	-0.995	-0.853	-0.464	-0.592	***-3.711	***4.549
Range		1950-2009	1950-2009	1950-2009	1950-2009	1950-2009	1950-2009	1950-2009
Constant	Coeff.	10.781	5.043	13.205	0.051	5.675	9.897	4.729
	t-stat.	*** 7.169	*** 4.979	*** 2.936	0.028	*** 4.619	*** 9.574	*** 12.89
Lin.Trend	Coeff.	-0.171	-0.057	-0.48	0.04	-0.078	-0.196	-0.028
	t-stat.	*** -3.999	-1.978	-1.553	0.768	* -2.255	*** -6.64	*** -2.724
Range		1875-1975	1875-1975	1875-1975	1875-1975	1875-1975	1875-1975	1875-1975
Constant	Coeff.	50.75	6.307	3.851	3.762	4.384	12.272	1.244
	t-stat.	*** 4.846	** 2.543	1.938	1.664	* 2.032	*** 4.060	*** 5.509
Lin.Trend	Coeff.	-0.53	-0.024	-0.018	-0.026	-0.005	-0.072	0.027
	t-stat.	*** -2.974	-0.566	-0.536	-0.66	-1.26	-1.403	***7.045

Notes: The table presents coefficients and *t*-statistics for regressions of the growth rates on a constant and a linear trend. ***, **, and * indicate significance at the 1%, 2.5% and 5% level, respectively.

Table 1.3: Tests for the stylized facts that growth rates of world primary production and world GDP are equal to zero and trendless.

		Aluminum	Copper	Lead	Tin	Zinc	Crude Oil	World GDP
Range		1855-2009	1821-2009	1802-2009	1792-2009	1821-2009	1861-2009	1792-2009
Constant	Coeff.	48.301	5.474	20.57	4.427	30.7	35.689	0.032
	t-stat.	*** 3.824	*** 3.06	*** 3.845	* 2.181	** 2.584	*** 4.379	0.276
Lin.Trend	Coeff.	-0.229	-0.018	-0.125	-0.023	-0.182	-0.19	0.01
	t-stat.	*** -2.677	-1.367	*** -3.025	-1.457	* -2.071	*** -3.499	*** 11.066
Range		1855-2009	1850-2009	1850-2009	1850-2009	1850-2009	1861-2009	1850-2009
Constant	Coeff.	48.301	5.399	5.629	3.179	5.18	24.681	0.628
	t-stat.	*** 3.824	*** 3.254	***3.169	1.961	*** 3.541	*** 4.733	*** 4.052
Lin.Trend	Coeff.	-0.229	-0.027	-0.047	-0.024	-0.03	-0.19	0.01
	t-stat.	*** -2.677	-1.523	** -2.442	-1.348	-1.895	*** -3.499	*** 5.876
Range		1900-2009	1900-2009	1900-2009	1900-2009	1900-2009	1900-2009	1900-2009
Constant	Coeff.	18.595	4.985	2.028	1.903	3.473	8.869	1.071
	t-stat.	*** 5.242	* 2.241	1.41	0.918	1.763	*** 6.306	*** 4.862
Trend	Coeff.	-0.184	-0.042	-0.027	-0.023	-0.026	-0.09	0.01
	t-stat.	*** -3.315	-1.214	-1.186	-0.694	-0.404	*** -4.084	*** 3.01
Range		1950-2009	1950-2009	1950-2009	1950-2009	1950-2009	1950-2009	1950-2009
Constant	Coeff.	8.583	2.952	1.141	-1.954	3.578	7.716	2.632
	t-stat.	*** 5.742	*** 2.892	1.04	1.086	*** 2.87	*** 7.493	*** 7.444
Lin.Trend	Coeff.	-0.156	-0.044	-0.35	0.051	-0.065	-0.18	-0.016
	t-stat.	*** -3.667	-1.515	-1.129	0.997	-1.819	*** -6.14	-1.551
Range		1875-1975	1875-1975	1875-1975	1875-1975	1875-1975	1875-1975	1875-1975
Constant	Coeff.	50.004	5.854	3.413	3.317	3.942	11.789	0.834
	t-stat.	*** 4.81	** 2.386	1.738	1.480	1.851	*** 3.933	*** 4.509
Lin.Trend	Coeff.	-0.542	-0.038	-0.032	-0.039	-0.019	-0.086	0.013
	t-stat.	*** -3.06	-0.908	-0.959	-1.028	-0.517	-1.691	***4.004

Notes: The table presents coefficients and t-statistics for regressions of the growth rates on a constant and a linear trend. ***, **, and * indicate significance at the 1%, 2.5% and 5% level, respectively.

Table 1.4: Tests for the stylized fact that growth rates of world per capita primary production and world per capita GDP are equal to zero and trendless.

A1.2 Proofs

Proof of Proposition 1

$$\begin{aligned} D(d_{N_{Rt}}) &= -\delta_2 \ln(d_{N_{Rt}}) \\ &= -\delta_2 \ln(e^{-\delta_1 N_{Rt}}) \\ &= \delta_1 \delta_2 N_{Rt} \end{aligned}$$

□

Proof of Proposition 2

The final good producer demands the resource for aggregate production. The price of the final good is the numeraire. The first order condition with respect to the resource from production (see Equation 1.12) is

$$Y^{\frac{1}{\varepsilon}}(1-\gamma)R^{-\frac{1}{\varepsilon}} - p_R = 0 \ , \tag{1.29}$$

so that the demand for the resource is

$$R = \frac{Y(1-\gamma)^{\varepsilon}}{p_R^{\varepsilon}} \ . \tag{1.30}$$

Assume that initially, the resource stock available to the extractive firms is zero, $S_t = 0$. Revenues are given by $p_R R$ and expenses are given by $M_R = \frac{1}{\eta_R}\dot{N}_R$ in terms of the final good. Given the machine price from Equation 1.18, the per-unit production cost of the resource is

$$\left(\frac{1}{\eta_R} + \psi\right)\frac{1}{\delta_1\delta_2} = \frac{1+\psi\eta_R}{\eta_R\delta_1\delta_2} \ . \tag{1.31}$$

The resource firms make profits

$$\pi_{Rt} = p_R R_t - \frac{1+\psi\eta_R}{\eta_R\delta_1\delta_2} X_t \ . \tag{1.32}$$

Since the stock of resources S cannot be negative, newly acquired resources cannot be less than resources sold to the final good producer: $X_t \geq R_t$. Newly acquired resources in excess of those sold could be stored. In a world without uncertainty, however, this would not be profitable. The price therefore must be equal to marginal cost:

$$p_R = \frac{1+\psi\eta_R}{\eta_R\delta_1\delta_2} \ . \tag{1.33}$$

It remains to consider the case of a positive initial stock of the resource, $S_t > 0$. Under perfect competition, this stock is immediately sold off to the final good producer sucht that the case of $S_t = 0$ returns. ☐

Proof of Proposition 3

The first order conditions (FOC) of the final good producer for the optimal input of Z and R are $Y^{\frac{1}{\varepsilon}}\gamma Z^{-\frac{1}{\varepsilon}} - p_Z = 0$ and $Y^{\frac{1}{\varepsilon}}(1-\gamma)R^{-\frac{1}{\varepsilon}} - p_R = 0$, where the final good is the numeraire. From this the relative price is

$$p = \frac{p_R}{p_Z} = \frac{1-\gamma}{\gamma}\left(\frac{R}{Z}\right)^{-\frac{1}{\varepsilon}} \ . \tag{1.34}$$

Setting the price of the final good as the numeraire gives (for the derivation of the price index see the derivation of Equation (12.11) in Acemoglu (2009)):

$$\left[\gamma^{\varepsilon} p_Z^{1-\varepsilon} + (1-\gamma)^{\varepsilon} p_R^{1-\varepsilon}\right]^{\frac{1}{1-\varepsilon}} = P = 1 \ . \tag{1.35}$$

The intermediate goods sector

As in Acemoglu (2009), the maximization problem in the intermediate goods sector is:

$$\max_{L,\{x_Z(j)\}} p_Z Z - w_Z L - \int_0^{N_Z} \chi_Z(j) x_Z(j) dj \ . \tag{1.36}$$

The FOC with respect to $x_Z(j)$ is $p_Z x_Z(j)^{-\beta} L^{\beta} - \chi_Z(j) = 0$ so that

$$x_Z(j) = \left(\frac{p_Z}{\chi_Z(j)}\right)^{\frac{1}{\beta}} L \ . \tag{1.37}$$

From the FOC with respect to L we obtain the wage rate

$$w_Z = \frac{\beta}{1-\beta} p_Z \left(\int_0^{N_Z} x_Z(j)^{-\beta} dj\right) L^{\beta-1} \ . \tag{1.38}$$

The profits of the technology firms are:

$$\pi_Z(j) = (\chi_Z(j) - \psi)x_Z(j) \ . \tag{1.39}$$

Substituting Equation 1.37 into Equation 1.39 we calculate the FOC with respect to the price of a machine $\chi_Z(j)$: $\left(\frac{p_Z}{\chi_Z(j)}\right)^{\frac{1}{\beta}} L - (\chi_Z(j) - \psi)p_Z^{\frac{1}{\beta}}\frac{1}{\beta}\chi_Z(j)^{\frac{1}{\beta}-1}L = 0$. Solving this for $\chi_Z(j)$ yields $\chi_Z(j) = \frac{\psi}{1-\beta}$. Following Acemoglu (2002) we normalize $\psi = 1-\beta$ so that $\chi_Z(j) = 1$. Combining this result with Equations 1.37 and 1.39 we write profits as

$$\pi_Z(j) = \beta p_Z^{\frac{1}{\beta}} L \ . \tag{1.40}$$

The present discounted value is:

$$rV_Z - \dot{V}_Z = \pi_Z \ . \tag{1.41}$$

The steady state ($\dot{V} = 0$) is:

$$V_Z = \frac{\beta p_Z^{\frac{1}{\beta}} L}{r} \ . \tag{1.42}$$

Substituting Equation 1.37 into Equation 1.13 yields

$$Z = \frac{1}{1-\beta} p_Z^{\frac{1-\beta}{\beta}} N_Z L \ . \tag{1.43}$$

Solving for the variables of the intermediate goods sector

Solving Equation 1.35 for p_Z yields

$$p_Z = \left(\gamma^{-\varepsilon} - \left(\frac{1-\gamma}{\gamma}\right)^{\varepsilon} p_R\right)^{\frac{1}{1-\varepsilon}} \ . \tag{1.44}$$

This can be used, together with the expression for R from Equation 1.30 and the expression for p_R from Equation 1.33 to determine Z as a function of Y from Equation 1.34. We obtain the range of machines N_Z as a function of Y from Equation 1.43.

The growth rate

The consumer earns wages from working in the sector which produces good Z and earns interest on investing in the technology N_Z. The budget constraint thus is $C = w_Z L + rM$. Maximizing utility in Equation 1.11 with respect to consumption and investments yields the first order conditions $C^{-\theta}e^{-\rho t} = \lambda$ and $\dot{\lambda} = -r\lambda$ so that the growth rate of consumption is

$$g_c = \theta^{-1}(r - \rho) \; . \tag{1.45}$$

This will be equal to output growth on the balanced growth path. We can thus solve for the interest rate and obtain $r = \theta g + \rho$. The free entry condition for the technology firms imposes that profits from investing in patents must be zero. Revenue per unit of R&D investment is given by V_Z, cost is equal to $\frac{1}{\eta_Z}$. Consequently, we have $\eta_Z V_Z = 1$. Substituting Equation 1.42 into it we obtain $\frac{\eta_Z \beta p_Z^{\frac{1}{\beta}} L}{r} = 1$. Solving this for r and substituting into Equation 1.45 we obtain

$$g = \theta^{-1}(\beta \eta_Z L p_Z^{\frac{1}{\beta}} - \rho) \; . \tag{1.46}$$

Plugging this in Equation 1.44 yields the growth rate. □

Proof of Proposition 4

Substitute Equation 1.33 into Equation 1.30. □

Proof of Proposition 5

The total cost of extracting resources can be split into the price of the new machine and the extraction cost. The technology costs have been derived in Proposition 1 as proportional to R&D in extraction technology. The extraction cost isgiven by the constant E. Since the extraction cost is constant and this model focusses on the innovation side, we make the simplifying assumption of zero extraction cost, $E = 0$. Therefore the total cost is given by the cost for the new machine.

The extractive firms sell the resource R, to the final good producer at price p_R. Its total revenues are thus Rp_R. The expenses are given by the price of a machine, $\chi_R(j)$ times the number of machines bought, $\dot{N}_{Rt}x_R(j)$ with $x_R(j) = 1$. Total expenses are thus $\frac{1}{\chi_R(j)}\dot{N}_{Rt}$. The extraction firms are in perfect competition, just like firms in the intermediate goods sector. Therefore profits are zero, its revenues must equal expenses: $Rp_R = \chi_R(j)\dot{N}_{Rt}$. Inserting Equation 1.16 we obtain $\delta_1\delta_2\dot{N}_{Rt}x_R(j)p_R = \chi_R(j)\dot{N}_{Rt}$, so that $p_R = \frac{1+\psi\eta_R}{\eta_R\delta_1\delta_2}$. □

Proof of Proposition 6

We use Equation 1.44, together with the expression for R from Equation 1.30 and the expression for p_R from Equation 1.33 to determine Z as a function of Y from Equation 1.34. This can then be used to obtain the range of machines N_Z as a function of Y from Equation 1.43.

The expression for $\dot{N}_R$ follows from Equation 1.10, Proposition 2 as well as equation 1.30. □

Proof of Proposition 7

The resource monopolist maximizes Equation 1.32. A monopolist will spread a potential endowment of $S_t > 0$ over time, but will drive it down to zero nevertheless. In any case, inflow and outflow will have to be balanced in the long run so that $X_t = R_t$. Substituting the expression for R from Equation 1.30 into Equation 1.32, the FOC for p_R is

$$\frac{Y(1-\gamma)^\varepsilon}{p_R^\varepsilon} + \left(p_R - \frac{1+\psi\eta_R}{\eta_R\delta_1\delta_2}\right)(-\varepsilon p_R^{-\varepsilon-1}Y(1-\gamma)^\varepsilon) = 0 \;, \tag{1.47}$$

which gives

$$p_R^{Mon} = \frac{1+\psi\eta_R}{\eta_R\delta_1\delta_2}\frac{\varepsilon}{\varepsilon-1} \;. \tag{1.48}$$

□

A1.3 The social planner solution

We present a social planner solution of the model for comparison. Since production has increasing returns to scale as apparent in Equation 1.52, there is no constant growth rate. This can be seen in Equation 1.76 below when considering the two preceding equations.

Preferences and budget

Household preferences are

$$\int_0^\infty \frac{C(t)^{1-\theta}-1}{1-\theta} e^{-\rho t} dt \ , \tag{1.49}$$

where ρ is the discount rate and θ is the coefficient of relative risk aversion.

The budget constraint is

$$C + I + M \leq Y = \left[\gamma Z^{\frac{\varepsilon-1}{\varepsilon}} + (1-\gamma) R^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}} \ , \tag{1.50}$$

where I is aggregate investment into new machines and M is aggregate R&D expenditure. The R&D expenditure is used for research in the production of Z and R: $M = M_Z + M_R$. Aggregate production uses two inputs, intermediate goods Z and resources R, with elasticity of substitution ε and distribution parameter γ.

The production function of good Z

The production function of Z is

$$Z = \frac{1}{1-\beta}\left(\int_0^{N_Z} x_Z(j)^{1-\beta} dj\right) L^\beta \ , \tag{1.51}$$

where L is labor. Production inputs are therefore labor and machines $x_Z(j)$ of variety j. The range of machine varieties is denoted N_Z. The social planner chooses the $x_Z(j)$ identical, so that we can write

$$Z = \frac{1}{1-\beta} N_Z x_Z^{1-\beta} L^\beta \ . \tag{1.52}$$

Intermediates x_Z depreciate fully after use and the marginal cost of production is the same for all machine varieties and equal to ψ in terms of the final good. Investment in machines is thus given by

$$x_Z \psi = I \ . \tag{1.53}$$

The range of intermediates expands through investment in R&D by the following production function

$$\dot{N}_L = \eta_Z M_Z \ , \tag{1.54}$$

where M_Z is spending on R&D and η_Z is a cost parameter. One unit of the final good spent for R&D will generate η_Z new varieties of machines.

Production of the resource

The evolution of the resource stock follows:

$$\dot{S}_t = X_t - R_t \ , \qquad S_t \geq 0, X_t \geq 0, R_t \geq 0 \ . \tag{1.55}$$

The per unit production cost of the resource is as in equation (1.31):

$$\frac{1}{\eta_R \delta_1 \delta_2} \ . \tag{1.56}$$

The cost for R&D in the extractive sector is analogous to R&D in the intermediate goods sector and follows:

$$\dot{N}_R = \eta_R M_R \ . \tag{1.57}$$

The social planner chooses $X = R$ such that

$$R_t = X_t = \delta_1 \delta_2 \dot{N}_{Rt} = \frac{1}{\eta_R \delta_1 \delta_2} M_R \ . \tag{1.58}$$

The objective function and first order conditions

The social planner maximizes the intertemporal utility from consumption as defined in equation 1.49 with respect to the endogenous variables C, N_Z, x_Z, R, and M_Z, and subject to the budget constraint:

$$\left[\gamma Z^{\frac{\varepsilon-1}{\varepsilon}} + (1-\gamma) R^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}} - C - I - M_Z - \frac{1}{\eta_R \delta_1 \delta_2} R = 0 \ , \tag{1.59}$$

where $M = M_Z + \frac{1+\psi\eta_R}{\eta_R \delta_1 \delta_2} R$ is the aggregate R&D expenditure and $I = \psi x_Z + \psi x_R$ is the aggregate expenditure on machines.

The Hamiltonian to be maximized by the social planner is therefore

$$\begin{aligned} H &= \frac{C(t)^{1-\theta}-1}{1-\theta} \\ &+\lambda\Big(\left[\gamma\left(\frac{1}{1-\beta}N_Z x_Z^{1-\beta}L^{\beta}\right)^{\frac{\varepsilon-1}{\varepsilon}} + (1-\gamma)R^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}} - C - \psi x_Z - \psi x_R - \\ &-M_Z - \frac{1}{\eta_R\delta_1\delta_2}R\Big) \\ &+\mu\eta_Z M_Z \ . \end{aligned}$$

The first order conditions are

$$\frac{\partial H}{\partial C} = C^{-\theta} - \lambda = 0 \ , \tag{1.60}$$

$$\frac{\partial H}{\partial N_Z} = \lambda Y^{\frac{1}{\varepsilon}}\gamma Z^{\frac{\varepsilon-1}{\varepsilon}} N_Z^{-1} = \mu\rho - \dot{\mu} \ , \tag{1.61}$$

$$\frac{\partial H}{\partial x_Z} = \lambda Y^{\frac{1}{\varepsilon}}\gamma Z^{\frac{\varepsilon-1}{\varepsilon}}(1-\beta)x_Z^{-1} - \lambda\psi = 0 \ , \tag{1.62}$$

$$\frac{\partial H}{\partial R} = \lambda Y^{\frac{1}{\varepsilon}}(1-\gamma)R^{-\frac{1}{\varepsilon}} - \lambda\frac{1}{\eta_R\delta_1\delta_2} = 0 \ , \tag{1.63}$$

$$\frac{\partial H}{\partial M_Z} = -\lambda + \mu\eta_Z = 0 \ . \tag{1.64}$$

$$\tag{1.65}$$

Derivation of the growth rate

The FOC for C in growth rates is

$$g_\lambda = -\theta g_C \ . \tag{1.66}$$

Substituting the FOC for M_Z into the FOC for N_Z gives

$$g_\mu = \rho - \eta_Z Y^{\frac{1}{\varepsilon}}\gamma Z^{\frac{\varepsilon-1}{\varepsilon}} N_Z^{-1} \tag{1.67}$$

and

$$g_\lambda = g_\mu \ . \tag{1.68}$$

From the FOC for x_Z we obtain

$$Y^{\frac{1}{\varepsilon}}\gamma Z^{\frac{\varepsilon-1}{\varepsilon}} = \frac{x_Z\psi}{(1-\beta)} \ . \tag{1.69}$$

The FOC for R shows that the ratio of resource use and output is constant

$$\frac{R}{Y} = \big(\eta_R\delta_1\delta_2(1-\gamma)\big)^{\varepsilon} \tag{1.70}$$

and consequently that they have the same growth rate:

$$g_R = g_Y \ . \tag{1.71}$$

Substituting (1.70) into the production function (1.50) yields

$$\Big[1-(1-\gamma)\big(\eta_R\delta_1\delta_2(1-\gamma)\big)^{\varepsilon-1}\Big] Y^{\frac{\varepsilon-1}{\varepsilon}} = \gamma Z^{\frac{\varepsilon-1}{\varepsilon}} \tag{1.72}$$

such that

$$Z = z_1 Y \ , \tag{1.73}$$

where $z_1 = [\frac{1}{\gamma}(1-(1-\gamma)(\eta_R\delta_1\delta_2(1-\gamma))^{\varepsilon-1})]^{\frac{\varepsilon}{\varepsilon-1}}$ is a constant.

Substituting this into (1.69) yields

$$x_Z = z_2 Y \ , \tag{1.74}$$

where $z_2 = \gamma z_1^{\frac{\varepsilon-1}{\varepsilon}}(1-\beta)\frac{1}{\psi}$ is again a constant.

Substituting this in Equation 1.52 yields

$$N_Z \ = z_1(1-\beta)L^{-\beta}Y^{\beta} \ . \tag{1.75}$$

Therefore $\frac{x_Z}{N_Z}$ is not constant.

Combining Equations 1.66, 1.67, 1.68, and 1.69, we obtain the growth rate of the economy

$$g^{opt} = \frac{1}{\theta}\left(\frac{1}{\eta_Z(1-\beta)\psi}\frac{x_Z}{N_Z} - \rho\right) \ . \tag{1.76}$$

Chapter 2

150 years of boom and bust - What drives mineral commodity prices?[1]

2.1 Introduction

The prices of mineral commodities, including fuels and metals, have repeatedly undergone periods of boom and bust over the last 150 years. These long-term fluctuations affect the macroeconomic conditions of developing and industrialized countries (World Trade Organization, 2010; IMF, 2012b). Moreover, strong booms have raised the issue of "security of supply" to the top of governmental agendas again and again.

However, the literature is far from conclusive on the driving forces behind these long-term fluctuations.[2] Extensions of the Hotelling (1931) model explain price fluctuations by referring to irregular exploration for deposits and so focus on the supply side (Arrow and Chang, 1982; Fourgeaud, Lenclud, and Michel, 1982; Cairns and Lasserre, 1986). Competitive storage models usually interpret shocks as supply driven, but ultimately leave the source of shocks open. (Gustafson, 1958a,b; Wright and Williams, 1982; Cafiero et al., 2011). Another strand of literature on the subject stresses the role of storage in the presence of expected supply shortfalls in explaining price fluc-

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[1] A different version has been published as a Discussion Paper of the German Development Institute (see Stürmer, 2013).

[2] See Carter, Rausser, and Smith (2011) for a detailed summary of theories on fluctuations in commodity markets.

tuations (Alquist and Kilian, 2010). Frankel and Hardouvelis (1985), Barsky and Kilian (2002) and other authors point to monetary policy as a major driving force. Finally, Dvir and Rogoff (2010) and other authors argue that price booms are due to persistent demand shocks combined with supply constraints.

What empirical work there is tends to focus on the oil market. According to Kilian (2009) and Kilian and Murphy (2012), fluctuations in the price of oil are driven mainly by demand shocks due to the global business cycle. In contrast, Hamilton (2008) stresses the role of supply shocks as a driver of crude oil prices. Thomas, Muehleisen, and Pant (2010) find that a combination of supply and demand shocks determines the price of oil. Pindyck and Rotemberg (1990) claim that such macroeconomic variables as inflation and money supply help to explain the concurrent movements of various commodity prices. In the same direction, Belke, Bordon, and Volz (2012) present empirical evidence that monetary aggregates drive various commodity price indices. Frankel and Rose (2010) find that, while global output and inflation have positive effects on the prices of several agricultural and mineral commodities, they are outstripped by volatility and inventories. Regarding storage models, Deaton and Laroque (1992, 1996) show that supply shocks and storage are not sufficient to explain price fluctuations and autocorrelation of commodity prices. They come to the conclusion that "demand shocks are a more plausible source of price fluctuations than has usually been supposed in the literature" (Deaton and Laroque, 1996, p. 899). Cafiero et al. (2011) use a different estimation methodology and find empirical evidence in favour of the predictions of the empirical storage model.

This paper identifies the dynamic effects of demand and supply shocks on mineral commodity prices from 1840 to 2010. It covers a far longer time period than most previous work, thus allowing me to include a long series of boom and bust in prices. Commodities have always shown greater price volatility than manufactures (Jacks, O'Rourke, and Williamson, 2011), and booms and busts are not a new phenomenon (see, e.g., Cuddington and Jerrett, 2008). In contrast to Erten and Ocampo (2012), who examine "super-cycles" of a metal price index over the period from 1865 to 2009, I am able to include data on the supply side of the mineral commodity markets examined here and hence to pin-down the contribution of shocks to the fluctuation of prices. In addition, I provide a detailed historical account for each price.

To obtain empirical evidence from such a long time period, I use a new set of annual data which includes prices, world production of copper, lead, tin, zinc, and crude oil, and world GDP. I chose copper, lead, tin, and zinc because they were traded on the London Metal Exchange and its predecessors as fungible and homogeneous goods in an integrated world market over the long period considered here. The four mineral commodities studied exhibit a substantial track record in industrial use and are still among the top twenty-five in value of world production. Hence, these four mineral commodity markets exhibit long-term characteristics that other mineral commodities such as iron ore or coal have only gained in recent times. To ease comparison to the literature, I also present regression results for the crude oil market. In contrast to the other four mineral commodities, the market has undergone major structural changes (Kilian and Vigfusson, 2011; Dvir and Rogoff, 2010) which make it difficult to obtain regression results that are robust across sub-periods.

I use a structural vector autoregressive (VAR) model to decompose demand and supply shocks to fluctuations in the real price of the commodity concerned. To do so, I assume the existence of three different types of shock to commodity prices: "supply shocks", e.g., a disruption in physical production due to strikes; "world output-driven demand shocks", which include shocks in global demand for all commodities due to, e.g., an unexpected strong growth of world output; and "other demand shocks". The latter include all other shocks that have no correlation with the aforementioned two shocks. I interpret them as mainly capturing unexpected changes in inventories driven by the market power of producers, government stocking programs, and changing expectations of consumers. My identification is based on long-run restrictions, which allows me to leave short-run relationships unrestricted.

My paper is to my knowledge the first to provide long-term evidence on demand and supply shocks in mineral commodity markets. The main conclusion drawn in this paper is that price fluctuations of the four mineral commodities studied here were basically driven by demand shocks rather than by supply shocks over the period from 1840 to 2010. My results point to the importance of models that take into account demand shocks due to world output like in Kilian (2009); Kilian and Murphy (2012). Dvir and Rogoff (2010), Mitraille and Thille (2009), Bodenstein and Guerrieri (2011), and others have only recently begun to develop such theoretical models.

My analysis suggests that extensions of the seminal Hotelling (1931) model such as those by Arrow and Chang (1982), Fourgeaud, Lenclud, and Michel (1982), and Cairns and Lasserre (1986) which explain price fluctuations by supply shocks must be rethought. It also questions the usual interpretation of shocks in competitive storage models (Gustafson, 1958a,b; Wright and Williams, 1982), which views supply shocks as a key to explaining commodity price fluctuations. Supply shocks are only of some importance in explaining fluctuations of tin and copper prices. Such shocks appear to increase with the importance of concentrated industry structures and government intervention in the markets. This evidence is in contrast to industrial organization models which predict that higher product market concentration will reduce price volatility (see Slade and Thille, 2006).

In contrast to the classical competitive storage models, my findings point to inventories as a source of fluctuations rather than a calming agent. My results provide long-term evidence in support of Alquist and Kilian (2010) and others who maintain that storage in the presence of expected supply shortfalls explains price fluctuations. Narrative evidence in this paper, however suggests that shocks due to changes in inventories are rather driven by producer cartels and government stockpiling, and only in recent times by "precautionary" behaviour of consumers or investors in the markets examined here.

Impulse response functions show that "world output-driven demand shocks" have had a large and statistically significant effect on the prices of all the commodities considered, reaching their peak after one or two years. They persist for five to ten years. "Other demand shocks" have direct and significant effects on all commodities and are quite persistent. "Supply shocks" exhibit a significant impact only on the prices of tin and copper. Whereas "world output-driven demand shocks" have a strong, significant, persistent and positive effect on the production of copper, lead and tin, they have a positive, but only insignificant effect on the production of zinc.

In contrast to the other mineral commodities examined in this study, the results for crude oil are not robust for different sub-periods and lag lengths. This is possibly due to multiple structural changes in the time series for price and production (see Dvir and Rogoff, 2010) and the strong change of importance of oil in the economy over time. At the same time, my results show that during earlier periods supply shocks have played an important role in driving the price of crude oil, whereas they confirm the empirical evidence provided by Kilian (2009), which indicates that demand shocks have been the main driving force for the period from 1973 to 2007.

My results have important policy implications both for commodity exporting and commodity importing countries. For optimal fiscal and macroeconomic policy responses in commodity exporting, developing countries, it is important to know, first, whether a price change is temporary or permanent, and second, to identify the driving source behind the price change (see IMF, 2012b). My results suggest that the current price boom is temporary rather than permanent: the long-term trends are significantly negative or statistically insignificant for the commodities examined. Hence, commodity exporters should take a countercyclical policy stand rather than increasing long-term public investment based on the assumption of a permanent price increase. Since the current boom is mainly driven by "world output-driven demand shocks", which exhibit strong effects on the external and fiscal balances of commodity exporting countries, preparation for a down-swing of mineral commodity prices is all the more important. Finally, my results illustrate that self-imposed supply restrictions by a group of exporting countries are at most only temporarily effective in the copper and tin market but are ineffective, as history shows, in increasing prices over the long-run.

For countries which import mineral commodities, my results indicate that apprehensions about the security of the supply are exaggerated in the light of historical evidence for broadly used mineral commodities. Various forms of subsidies for overseas mining and the reduction of import dependencies as well as "resource diplomacy", are questionable in effect given the fact that these mineral commodities are traded on world markets, while prices react only moderately to supply restrictions in the short-run.

I have organized the remainder of this paper as follows. In section 2.2 I introduce my interpretation of the shocks studied here. In section 2.3 I describe the construction of my data set. Section 2.4 focuses on the econometric model and the scheme used to identify and distinguish the different structural shocks. In sections 2.5 and 2.6, I present empirical results and robustness checks for copper, lead, tin, and zinc. Section 2.7 gives empirical results and robustness checks for the case of crude oil. Section 2.8

offers conclusions.

2.2 Interpretation of shocks to mineral commodity prices

I classify the key determinants of mineral commodity prices close to Kilian (2009). This allows me to distinguish three shocks, notably "world output-driven demand shocks", "supply shocks" and "other demand shocks".

I define "world output-driven demand shocks" in such a way as to capture shocks to the global demand for all mineral commodities due to unexpectedly strong expansions or contractions of the world economy. They thus also include unexpectedly strong periods of industrialization such as those of Great Britain, Germany and the U.S. in the 19th century, Japan in the 20th century, and China and other emerging economies at the beginning of the 21st century. "World output-driven demand shocks" result from both non-persistent aggregate demand shocks (e.g., monetary policy shocks) and persistent aggregate supply shocks (e.g., productivity changes).

"Supply shocks" are shocks to the production of mineral commodities due to unexpected changes in production caused by cartels, strikes, or natural catastrophes.

I do not directly include "other demand shocks" in this model due to missing long-term data on inventories and on the world use of the mineral commodities. Instead, controlling for "world output-driven demand shocks" and "supply shocks" allows me to pin down the "other demand shocks" as the residual of a structural dynamic simultaneous-equation model. They mainly reflect changes in the demand for inventories of mineral commodities which stem from three different sources: first, government stocking programs, second, producers with market power who increase their inventories in an attempt to increase prices, and finally, shifts in expectations of the downstream processing industry about the future supply and demand balance (see Kilian, 2009; Kilian and Murphy, 2012, on the last point).

As "other demand shocks" capture all shocks that are uncorrelated to "world output-driven demand shocks" and "supply shocks", they also include unexpected changes in the intensity of use of the respective mineral commodity in the production of world output. The intensity of use reflects the quantity of a mineral commodity which an economy needs to produce one unit of output. The intensity of use is driven by several factors: first, technical improvements that either decrease or increase the quantity of a mineral commodity used to produce a specific good, second, substitution by other materials, third, changes in the structure of world output (e.g., a higher share of services), fourth, saturation of markets, and finally, government regulations that change the use of materials (for example the phase-out of lead additives in gasoline see (Cleveland and Szostak, 2008)). However, all of these processes are rather longterm, especially on the world level. Even government regulation, such as that imposed on lead additives, has become set in a continuous process of phasing-out over several decades. Narrative historical evidence suggests that "other demand shocks" rather capture unexpected changes in inventories rather than changes in the intensity of use. The latter are rather captured in the linear trends in the regressions.

2.3 A new data set

I have compiled annual data for real prices and world production of copper, lead, tin, and zinc as well as world GDP over the time period from 1840 to 2010. For crude oil, data is only available from 1861 onwards.[3]

With respect to world market prices, I make use of annual nominal price data for copper, lead, tin, and zinc from the London Metal Exchange (LME) and its predecessors. The LME was the principal price setter in these non-ferrous metals markets outside of the U.S. during most of the study period (Schmitz, 1979; Rudolf Wolff & Co Lt., 1987; Slade, 1991). The prices are in British-£ for most of the period covered in this study. Since the middle of the 1970s they have been given in U.S.-$, and I have transformed them to British-£ by using annual exchange rates. For robustness checks I have also collected U.S.-American prices. I obtained nominal world market prices for crude oil from British Petroleum (2011). This price series reaches back to 1861. Please note that there have been some gradual changes in the quality of products over time.

Following Krautkraemer (1998) and Svedberg and Tilton (2006), I deflate all

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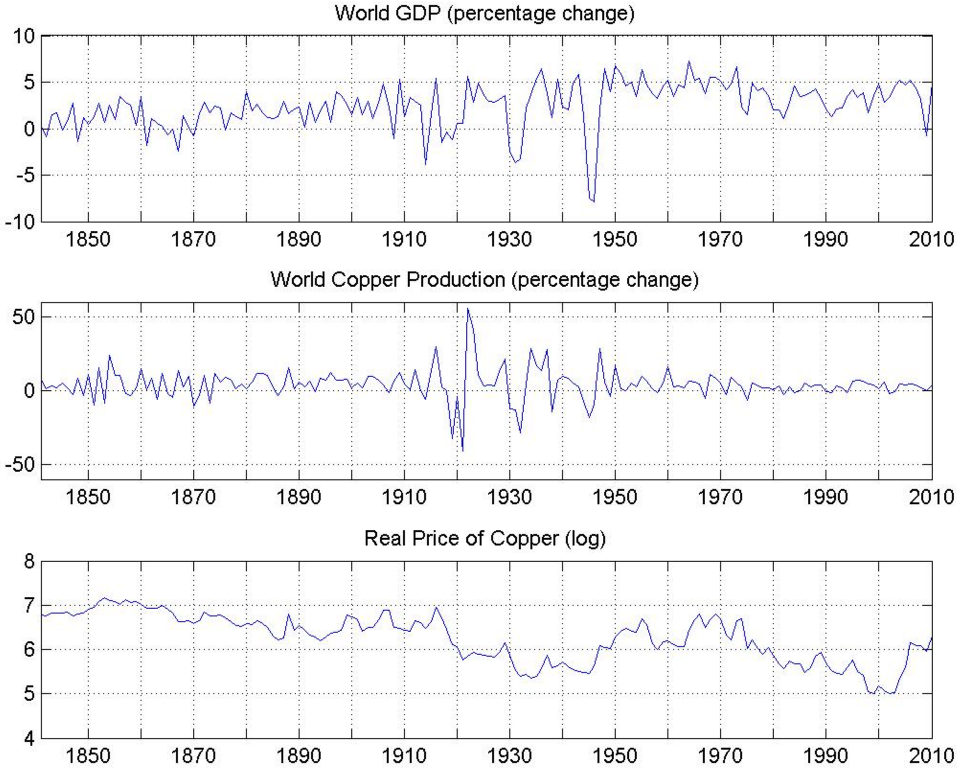
[3] See also the chapter on data sources and description.

nominal prices by the respective consumer price indices (CPI) for the U.K. and the U.S. I also use producer price indices (PPI) as a robustness check. To obtain the U.S.-PPI, I have spliced together the wholesale price index for all commodities by Hanes (1998) and the producer price index for all commodities from the U.S. Bureau of Labor Statistics (2011). I have constructed the U.K.-PPI based on data from Mitchell (1988) and the World Bank (2012) in the same way.

A common definition for the existence of a world market is that prices for a homogeneous good strongly co-move across different areas of the world. This implies that price movements are in accordance with the law of one price, even though the levels of prices might differ due to transportation costs or trade barriers. Klovland (2005) shows that British and German markets for copper, lead, tin, and zinc were integrated from 1850 until World War I, whereas price gaps for pig iron and coal remained quite significant due to trade policies and high transport costs. O'Rourke and Williamson (1994) find a strong convergence of U.S. and British copper and tin prices between 1870 and 1913.

Unfortunately, there is to my knowledge no empirical evidence regarding historical integration of the oil market. However, narrative evidence from Yergin (2009) suggests that American kerosene rapidly became an internationally traded good after the first discovery of oil in Titusville in 1859. In the 1870s and 1880s it was even the 4th largest U.S. export in value. By the 1880s competition was already strong from Russian oil. Hence, I assume in the following sections that world oil markets have been as integrated over time as the non-ferrous metal ones described above and leave it to future research to find statistical evidence for this assumption.

According to Findlay and O'Rourke (2007), commodity markets disintegrated during the First and Second World War. Price and supply controls for mineral commodities tend to characterize war-time economies (see Backman and Fishman (1941) regarding the example of Great Britain). Unfortunately, no systematic study of price convergence for the above metals in the inter-war period has been carried out. I account for the disintegration of world markets during the two World War periods by using yearly dummies for the war periods and the three consecutive years. For the period after the Second World War until today, Labys (2008) finds evidence for strong market integration.



Notes: For other mineral commodities see the Appendix.

Figure 2.1: Historical evolution of world GDP, world copper production, and the real price of copper from 1841 to 2010.

I have assembled data on the world production of the four mineral commodities from several sources. I use mine output or smelter output for earlier times and refined output where available for the 20th century. World production includes production from primary as well as secondary materials. However, the differentiation between primary and secondary materials is not easy, since so-called “new scrap” accrues across the different stages of the production process. “New” and “old” scrap are also fed back in the production process at different stages according to quality. Overall, I have tried to keep the data series as consistent as possible.

In contrast to Kilian (2009) and Kilian and Murphy (2012) I do not create a freight rate index to measure global economic activity but use world GDP from Maddison (2010) and The Conference Board (2012). Unfortunately, Maddison’s data set only provides annual world GDP data from 1950 onwards. Therefore, I sum up country based annual data. For those years where country based annual data is missing, I generally interpolate the data with linear trends. For European countries and Western offshoots, I compute their respective shares of output related to neighboring countries, where data is available. I then interpolate these shares and multiply them with the data from those countries, where annual data is available. This process assumes that the business cycle of these countries moves in tandem to that of their neighboring countries.

2.4 Identification

I use a three-variable, structural VAR model with long-run restrictions to decompose unpredictable changes in the real mineral commodity prices into three mutually uncorrelated shocks, notably “world output-driven demand shocks”, “supply shocks”, and “other demand shocks”. Blanchard and Quah (1989) have introduced this methodology to explain fluctuations in GNP and unemployment, while I use this methodology to explain fluctuations in mineral commodity prices. It is therefore important to keep in mind that Blanchard and Quah (1989) identify and interpret demand and supply shocks at the aggregate level, wheras I do so at the level of a specific commodity market.

The basic idea of the variance decomposition is to find what amount of information each variable, notably world total output and world mineral production, contributes to the world mineral commodities price in the autoregression. It hence shows how much of the predicted error variance of the mineral commodity price can be explained by exogenous shocks to world total output and world mineral production.

The vector of endogenous variables is $z_t = (\Delta Y_t, \Delta Q_t, P_t)^T$, where ΔY_t refers to the percentage change in world GDP, ΔQ_t denotes the percentage change in world primary production of the respective mineral commodity, and P_t is the log of the respective real commodity price. D_t denotes a matrix of deterministic terms, notably a constant, a linear trend, and annual dummies during World War I and II periods and the three years immediately after. The structural VAR representation is

$$Az_t = \Gamma_1^* z_{t-1} + ... + \Gamma_p^* z_{t-p} + \Pi^* D_t + B\epsilon_t. \tag{2.1}$$

The reduced form coefficients are $\Gamma_j = A^{-1}\Gamma_j^*$ for $(j = 1, ..., p)$. ϵ_t is a vector of serially and mutually uncorrelated structural innovations. The relation to the reduced form residuals is given by $u_t = A^{-1}B\epsilon_t$. p is the number of lags, which I choose according to the Akaike information criterion (AKI) for the benchmark regressions.

To compute the structurally identified impulse responses, I estimate the contemporaneous impact matrix $C = A^{-1}B$ by $\hat{C} = \hat{\Phi}^{-1}\hat{\Psi} = \hat{\Phi}^{-1}\text{chol}[\hat{\Phi}\hat{\Sigma}_u\hat{\Phi}']$. Φ is the matrix of accumulated effects of the impulses, namely $\Phi = \sum_{s=0}^{\infty} \Phi_s = (I_K - \Gamma_1 - ... - \Gamma_p)^{-1}$. Ψ is the long-run impact matrix of structural shocks. We need $K(K-1)/2 = 3$ restrictions to identify the structural shocks of the VAR. I hence assume that Ψ is lower triangular and obtain it from a Choleski decomposition of the matrix $\hat{\Phi}\hat{\Sigma}_u\hat{\Phi}'$. (See Lütkepohl and Krätzig, 2004)

Assuming that Ψ is lower triangular means that I place zero restrictions on the upper-right hand corner of the long-run impact matrix. Thereby, I make the assumption that shocks to the supply of mineral commodities and "other demand shocks" exhibit transitory but not permanent effects on world total output. These two shocks thus affect world total output in the short-run but not in the long-run. Furthermore, "other demand shocks" exhibit only a transitory effect on mineral commodity production. These assumptions lead to the identification of the following three shocks:

World output-driven demand shocks

I refer to “world output-driven demand shocks” as those shocks to global real GDP that are neither explained by the short-run effects of shocks to the supply of the respective mineral commodity nor by the short-run effects of “other demand shocks”. I hence impose the restriction that shocks to the production of the mineral commodity which are not driven by “world output-driven demand shocks” (see below) have no long-term effect on global real GDP. This assumption seems strong as one might argue that a reduction in inputs of a certain commodity might affect productivity and hence world total output in the long-term. However, Barsky and Kilian (2004) state that U.S. productivity losses due to the search for substitutes for oil are too small to be of relevance. They sum up that none of the models which establish a link from oil price shocks to productivity changes “can claim solid empirical support”. Kilian (2009) demonstrates that unanticipated oil supply shocks exhibit a statistically significant impact on the level of U.S. GDP only for the first two years and then become insignificant. Since the other mineral commodities examined here are of even less importance to world output than crude oil, I believe that my assumption is reasonable.

Moreover I assume that shocks to mineral commodity prices due to “other demand shocks” exhibit no long-term effect on total world output. Certainly an increase in a commodity price decreases the income of consumers in the importing countries. At the same time, it increases the income of consumers in exporting countries so that there is no effect on global real GDP from the aggregate demand side. Even in the case of crude oil, Rasmussen and Roitman (2011) have shown that oil price shocks on a global scale exhibit only small and transitory negative effects on a slight majority of countries.

I do not distinguish between the different sources of “world output-driven demand shocks”, be they transitory aggregate demand shocks due, e.g. to unexpected changes in unemployment, or persistent aggregate supply shocks due, e.g., to increases in productivity (see Blanchard and Quah, 1989). However, it is important to keep these different sources of “world output-driven demand shocks” in mind when it comes to explaining mineral commodity production.

Supply shocks

I define "supply shocks" as those innovations to the production of the respective commodity that are neither driven by the short and long-term effects of "world output-driven demand shocks" nor by the short-term effects of "other demand shocks". I hence assume that "supply shocks" and "world output-driven demand shocks" affect the world's primary production of the respective commodity in the long run. In contrast, price changes driven by "other demand shocks" exhibit only a transitory effect on world primary production. They hence affect only capacity utilisation of the extractive sector but not long-term investment decisions. This is plausible, given the fact that expanding extraction and first-stage processing capacities exhibits high upfront costs and takes many years (Radetzki, 2008; Wellmer, 1992). This makes it likely that "other demand shocks" affect world primary production only in the short term.

Other demand shocks

Other demand shocks encompass all innovations to the respective real mineral commodity price that are neither driven by "world output-driven demand shocks" nor "supply shocks". It hence captures all shocks that are uncorrelated to these two latter shocks. These in turn mainly capture changes in the demand for inventories due to government stocking programs, producer market power, and shifts in expectations of the downstream processing industry about the future supply and demand balance (see on the last point Kilian, 2009; Kilian and Murphy, 2012).

Overall, this methodology allows me to identify the effects of demand and supply shocks on mineral commodity prices and to estimate long-run price trends. Theoretical models make different predictions on the long-term trends and the type of shocks that drive fluctuations in prices. The seminal Hotelling (1931) model predicts an increasing trend in prices, while it makes no statement on price fluctuations. Extensions of the Hotelling (1931) model such as those by Arrow and Chang (1982), Fourgeaud, Lenclud, and Michel (1982), and Cairns and Lasserre (1986) introduce the exploration of deposits which causes sudden price changes. Following this literature, I would expect "supply shocks" to mainly drive price fluctuations. These models predict different short-term price trends, but mainly point to increasing trends in the long term.

Competitive storage models (Gustafson, 1958a,b; Wright and Williams, 1982) usually assume supply shocks as the source of uncertainty.[4] Storage smoothes these shocks intertemporally and explains the empirically observed autocorrelation in prices. Commodity storage model do not make a prediction concerning the trend. Based on this literature I would expect supply shocks to drive fluctuations in prices. Alquist and Kilian (2010) and Kilian and Murphy (2012) extent the storage model in a way that storage in the presence of expected supply shortfalls explains price fluctuations. These shocks would show up in the "other demand shocks" in our model. Finally, some scholars have explicitely modelled demand shocks. Dvir and Rogoff (2010) introduce persistent demand shocks to a competitive storage model. In this model storage amplifies rather than smoothes these shocks if supply is restricted. Mitraille and Thille (2009) endogenize production and therefore regard demand shocks as the source of uncertainty in a competitive storage model. Bodenstein and Guerrieri (2011) introduce several types of demand shocks in a two-country DSGE model. Overall, these models seem to suggest that demand shocks drive price fluctuations.

2.5 Empirical results

I employ ordinary least squares to consistently estimate the reduced-form coefficients of the VAR models of each of the four mineral commodity markets. On the basis of these estimates, I obtain the contemporaneous and long-run matrices by the Cholesky decomposition described above. I use a recursive-design wild bootstrap with 2000 replications for inference, following Goncalves and Kilian (2004). See Tables 2.2 to 2.12 in the Appendix for the estimated coefficients.

In the following, I set out the main results for each of the mineral commodities examined. For each mineral commodity, I first present the respective impulse response functions which plot the respective responses of world GDP, world mineral commodity production, and real copper prices to a one-standard deviation of the three respective structural shocks. I use accumulated impulse response functions for the shocks to

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[4] However, these models ultimately leave the source of shocks open, since shocks to demand and supply are "isomorphic" in the model setup (Dvir and Rogoff, 2010, p. 10).

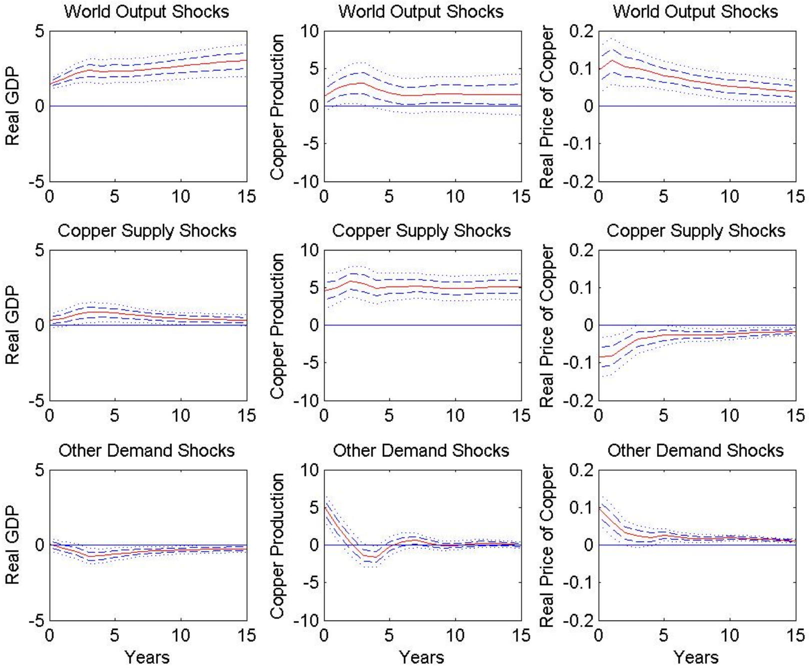
world mineral commodity production and world GDP to trace the long-term effects on the levels of these variables.

I compare the identified structural shocks to evidence from economic history. This helps to better understand the dynamics of the markets and to give the identified shocks a proper interpretation. I do so with the help of two figures: First, I present the evolution of the three structural shocks to the respective mineral commodity price (see Figure 2.3 for the example of copper). Second, I show the historical decomposition of each mineral commodity price which quantifies the contribution of the three structural shocks to the deviation of the respective price from its base projection (see Figure 2.4 for the example of copper). Since the vertical scales across the three sub-panels are identical, they show the relative importance of a given shock. The two figures are related as, e.g., a positive structural shock as in Figure 2.3 drives upwards the curve of the cumulative effect of the shocks in the historical decomposition in Figure 2.4.

2.5.1 Copper market

My results show that the major fluctuations in the price of copper are mainly driven by “world output-driven demand shocks”. “Supply shocks” and “other demand shocks” also play a pronounced role in determining medium-term swings in price. The narrative evidence suggests that the copper market is characterized by a long history of oligopolistic structures. Chandler (1990) points out that the five largest U.S. copper producers in 1917 were still under the top five in 1930 and in 1948. In addition, copper production has also always been strongly concentrated, with the main producers in Chile and the U.S. (Schmitz, 1979).

The impulse response functions in Figure 2.2 show that a positive “world output-driven demand shock” exhibits a strong, positive, and persistent effect on world GDP. It causes a positive significant increase in copper production that lasts for about three years. Finally, it triggers a major increase in the real price of copper for a maximum of about one year after the shock. The shock continues to persist significantly over a period of more than ten years.

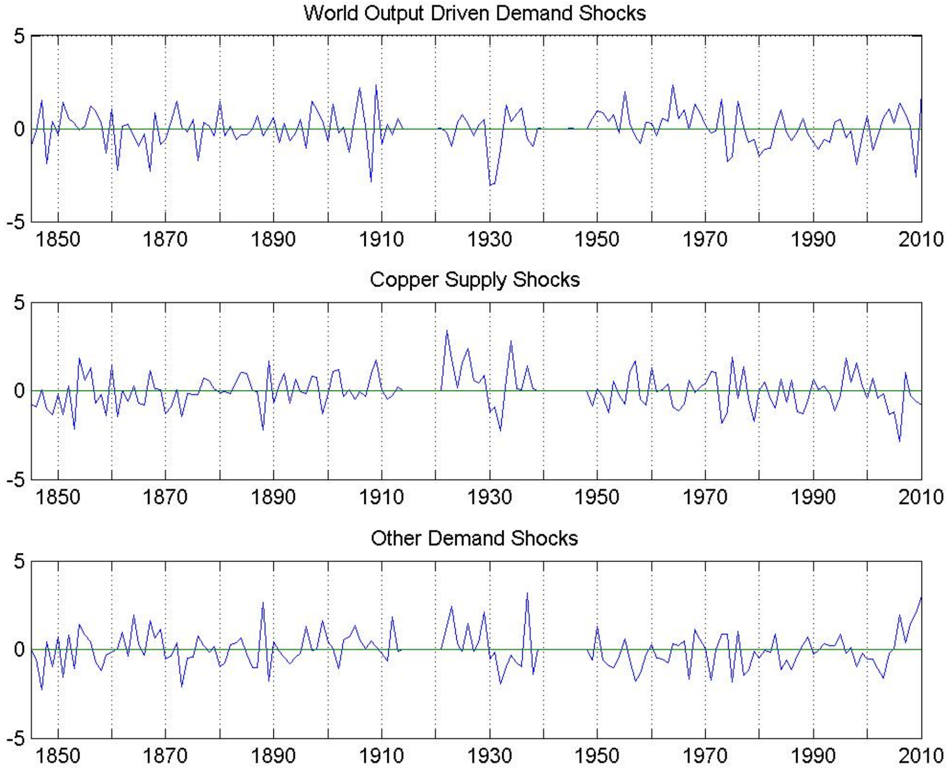


Notes: Point estimates with one- and two-standard error bands based on Model (2.1). I use accumulated impulse response functions for the shocks to world mineral commodity production and world GDP to trace the effects on the level of these variables. For the other mineral commodities see the Appendix.

Figure 2.2: Impulses to one-standard-deviation structural shocks for copper.

A positive shock to the supply of copper has a positive significant effect on GDP for three to ten years and then approaches zero, in accordance with our identifying assumptions. The supply shock affects copper production strongly and persistently. Moreover, it reduces the real price of copper significantly for more than ten years, with an insignificant period of three to five years after the shock.

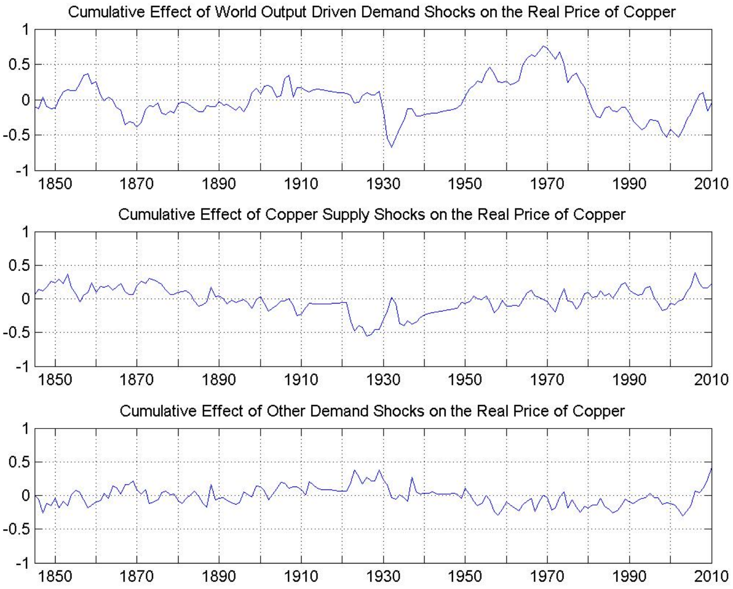
A positive "other demand shock" has by assumption only a transient effect on world GDP and copper production. Its impact on the real price of copper is immediate and statistically significant for the first two years and then again five to ten years after the shock.



Notes: Structural residuals implied by Model (2.1). For other mineral commodities see the Appendix.

Figure 2.3: Historical evolution of structural shocks to copper.

In the late 1840s the price of copper was low owing to the British railway crisis from 1847 to 1848 (see Kindleberger and Aliber, 2011), which caused negative "world output-driven demand shocks". In the 1850s the price underwent a major upswing, driven mainly by positive “world output-driven demand shocks” due to the world economic boom at that time (see Kindleberger and Aliber, 2011). In the mid 1850s, prices stopped rising even though “world output-driven demand shocks” still persisted. Large positive supply shocks due to the “copper mania” (Richter, 1927, p. 246), the opening of copper mines in the Southern Appalachians of the U.S., put downward pressure on the price of copper, which experienced a long downturn during the 1860s, reaching a trough around 1870. This was due to negative “world output-driven demand shocks” triggered by the Panic of 1857, the American Civil War from 1861 to 1865, and the Overend-Gurney Crisis in 1866 and their respective economic aftermaths (see Kindleberger and Aliber, 2011). At the same time, there was some downward pressure caused by positive “supply shocks” due to the opening of new mines in Arizona and Michigan - despite the problems posed by the Civil War - and a substantial increase in production in Chile and elsewhere in the world, especially in the late 1860s (Richter, 1927).



Notes: Estimates derived from Model (2.1). The historical decomposition quantifies the contribution of the three specific shocks to the deviation of the actual copper price data from its base projection. Since the vertical scales are identical, the panels show not only the positive and negative effects, but also the relative importance of a given shock. Please note that I have not included data for the two World War periods and the three subsequent years because of the price controls and other major market distortions at that time.

Figure 2.4: Historical decomposition of the real price of copper.

After the price peaked at the end of the 1870s owing to positive "world output driven demand shocks", it fell until the mid 1880s. This was caused by two shocks. First, the Long Depression beginning in 1873 led to strong negative "world output driven demand shocks" (Kindleberger and Aliber, 2011) . Second, major, positive "supply shocks" drove prices down. Between 1875 and 1885, annual U.S. copper production rose by more than 500 percent. The Anaconda mine in Montana "proved fabulously rich and enormously productive" (Richter, 1927, p. 255), and several others mines opened in Arizona.

The mines in Michigan, which had already created a selling pool in the 1870s, reacted to the low prices with an aggressive rise in production and a sales policy aimed at driving out the new competitors (Richter, 1927, p. 256). This explains the major positive copper "supply shock" that drove prices down further in the first half of the 1880s. As many mines were unable to continue operating at a profit at these low prices, world production fell from 229,600 mt in 1885 to 220,500 mt in 1886 (Richter, 1927, p. 257). This explains the negative "supply shock" at that time.

In response, the new Secrétan copper syndicate, which controlled up to eighty percent of world production, became active from 1887 to 1889 (Richter, 1927; Herfindahl, 1959), driving up the world market price to a high in 1887 by stockpiling copper (Richter, 1927; Herfindahl, 1959), as reflected in the strong "other demand shocks" at the time. However, the high prices led to increased production and oversupply, which the syndicate tried to compensate for by stockpiling even more (Richter, 1927; Herfindahl, 1959). This led to the syndicate's collapse in 1889. The Société Industrielle et Commerciale des Métaux, which handled the operations of the syndicate, and the main financing bank, Comptoir d'Escompte, were forced into bankruptcy, and the manager responsible committed suicide (Richter, 1927; Herfindahl, 1959). The copper from the inventories was sold over a period of three to four years, driving prices down until the mid 1890s (Richter, 1927, p. 259), as the accumulated effects of the "other demand shocks" show. "World output-driven demand shocks" also had a waning impact on prices over this period.

Prices increased again at the end of the 1890s, then experienced a downturn reaching a low around 1904, followed by another boom in the mid 1900s and then a further downturn. These cycles of boom and bust were driven by all three kinds of shock. After gradual economic recovery in the 1890s, positive "world output-driven demand shocks" peaked at the beginning of the 20th century, followed by recessions in 1904 and 1907, which were triggered by a financial crisis in the U.S as described by Kindleberger and Aliber (2011) (see also data provided by Crafts, Leybourne, and Mills, 1989; National Bureau of Economic Research, 2010). "Other demand shocks" and "supply shocks" also affected prices over that period. In the late 19th century, the Amalgamated Copper Company, which controlled about one fifth of world copper production, and a number of other firms tried to stabilize the price of copper by withholding stocks from the markets and restricting output (Herfindahl, 1959, p. 81). This is also revealed by spikes in the cumulative effects of both "other demand shocks" and "supply shocks". In late 1901 the company changed course by releasing copper from its stocks in order to undersell its competitors, which resulted in negative "other demand shocks" to the market. Subsequently, there were renewed attempts at price manipulation through the withholding of stocks from 1904 to 1905, 1906 to 1907 and, finally, 1912 to 1913 (Herfindahl, 1959, pp. 83-91). These manipulations played a major part in the fluctuations in the price of copper, as the accumulated effects of "other demand shocks" show. Finally, from 1910 onwards the introduction of fine grinding methods and milling by flotation made large-scale mine production from low-grade ores possible (Richter, 1927, p. 278-281). The consequent positive supply shocks helped to drive down prices, as copper production in Alaska and the South-West of the U.S. surged (Richter, 1927, pp. 278-281).

The price of copper stayed relatively flat during the 1920s, with a small peak in 1929. According to my analysis, this was due to upward pressure by "other demand shocks" and downward pressure by "supply shocks" that roughly balanced each other out. On the one hand, strong positive "supply shocks" followed the sharp increases in production capacity during the First World War owing to improved mining technology (Radetzki, 2009) and war-time demand. The increased mining capacities were temporarily abandoned in the first few-years after the war in coordinated action by the Copper Export Association[5]. In 1917 world refined production totalled 1.4 million metric tons. It slumped to 0.5 million metric tons in 1921, but then rebounded

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[5] Please note that I have not included the three years after the First and Second World Wars in my regressions.

to 1.3 million metric tons in 1923, after the cartel operation ceased. From 1927 to 1929 production leapt again (for the aforementioned data see U.S. Geological Survey, 2011a). On the other hand, there were strong positive "other demand shocks" that put upward pressure on the price of copper owing to the build-up of inventories and price manipulations by two cartels: the Copper Export Association (Herfindahl, 1959, pp. 93-4) in the early 1920s and later by the Copper Exporters Inc. (Herfindahl, 1959, pp. 100-6).

The Great Depression that began in 1929 caused a major negative "world output-driven demand shock" that drove down the price of copper. In response, the Copper Exporters Inc. cartel, which controlled about 85 percent of world output, succeeded in firmly restricting copper production by taking collective action (Herfindahl, 1959, pp. 100-6). This resulted in strong accumulated effects of "supply shocks" that counterbalanced the "world output-driven demand shocks" to some extent. However, diverging interests and declining discipline among its members brought Copper Exporters Inc. to an end in 1932, and world copper production rebounded (Herfindahl, 1959, p. 105). In 1935 the International Copper Cartel emerged and succeeded in driving up the price of copper in the late 1930s (Herfindahl, 1959, p. 110), as the cumulative effects of "other demand shocks" reveal.

In the period from the end of the Second World War until the mid 1970s, the price of copper rose sharply, with peaks in 1955, 1966, 1969, and 1974. During this time post-war reconstruction and the economic rise of Japan generated strong, positive "world output-driven demand shocks", which mainly determined price fluctuations. Interventions by the U.S. government in the form of price controls, import and export restrictions, and government stockpiling were quite common in this period (see Herfindahl, 1959; Sachs, 1999) and are largely reflected in "other demand shocks". Their accumulated effect was, however, rather transient and insignificant. Voluntary production cutbacks in 1963 and strikes in the U.S. from 1959 to 1960 and 1967 to 1968 explain most of the supply shocks during this period (see Sachs, 1999). The nationalization of mines in Chile, Zambia, and elsewhere in the 1960s, and as well as the attempts by the Intergovernmental Council of Copper Exporting Countries (CIPEC) to limit production in 1975 aggravated the negative "supply shocks" (see Mardones, Silva, and Martinez, 1985; Sachs, 1999). Overall, the cumulative effects of “supply shocks” were rather limited compared to the “world output-driven demand shocks” during this period.

The price of copper reached its peak in 1974. This was due to several kinds of shocks. On the one hand, the CIPEC cartel reduced its exports by fifteen percent (Mikesell, 1979, p. 205), as is evident from the strong accumulative effects of “supply shocks” and “other demand shocks”. On the other hand, the recession in 1974 caused strong negative “world output-driven demand shocks”, which led to a serious decline in the price in 1975, since the CIPEC could not sustain its action. In the following three decades prices fell mainly because of the negative “world output-driven demand shocks” caused by the recession in 1981, the economic impact of the breakup of the U.S.S.R., and the Asian crisis. There were two small peaks in the late 1980s and the mid 1990s due to the interplay of positive “world output-driven demand shocks” and “supply shocks”.

The sharp rise in copper prices from 2003 to 2007 was basically driven by the cumulative effects of large “world output-driven demand shocks” due to the booming economy. Supply shocks also played a role. In 2005 and 2006 in particular, global copper mine production grew far less than expected owing to strikes, equipment shortages, and other production problems (U.S. Geological Survey, 2007, 2008).

Since the onset of the Great Recession in 2008 “world output-driven demand shocks” have had a negative effect on the real price of copper. This has been offset by strong “other demand shocks”, which have had a positive effect on price since 2005. These shocks reflect changes in inventories (see data provided by the International Copper Study Group, 2010a, 2012a). However, while consumers’ and producers’ inventories have stayed roughtly constant, inventories at exchanges grew more then fourfold between 2004 and 2010. At the same time, Chinese firms imported significant quantities in 2009 and 2010, but their inventories are not transparent (see U.S. Geological Survey, 2010b, 2011c).

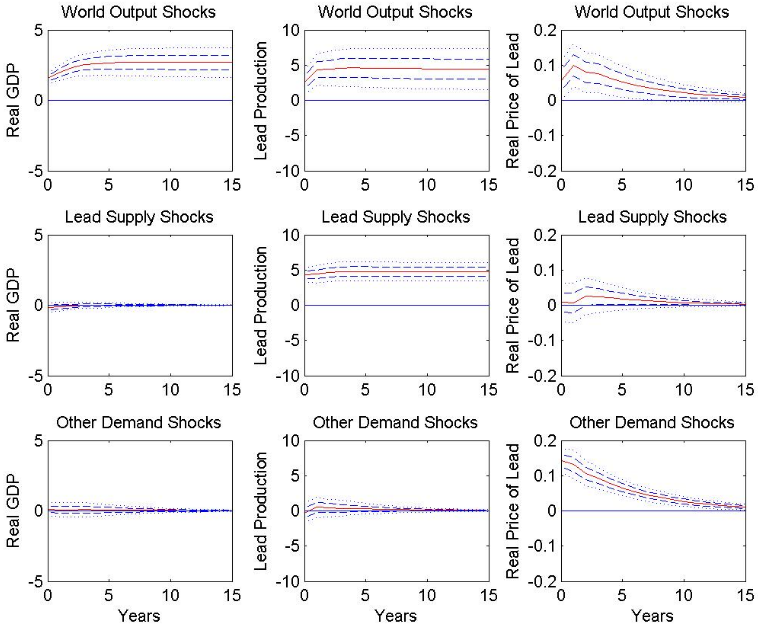
Overall, my results demonstrate that the major fluctuations in the price of copper are mainly driven by “world output-driven demand shocks”. “Supply shocks” and “other demand shocks” also play a pronounced role in determining medium-term swings in price. The narrative evidence suggests that the copper market is characterized by a long history of oligopolistic structures. Recurrently appearing cartels were able to influence prices by both restricting output and by stocking. The evidence points to inventory changes by producer cartels, governments, and in the most recen years by investors as key drivers of "other demand shocks"

2.5.2 Lead market

My results show that the fluctuations in the real price of lead have basically been driven by "world output-driven demand shocks" and "other demand shocks". "Supply shocks" do not play a role. My historical account reveals that the lead market does not have a strong oligopolistic structure so that supply is quite elastic. This is due to the fact that lead resources are relatively widespread and production takes mainly place in the industrialized countries (BGR, 2007). As a consequence, the formation of cartels to restrict output has not been successful in the history of the lead market.

Figure 2.5 plots the impulse response functions for lead. An unexpected positive rise in demand due to an increase in world output triggers a persistent and significant positive increase in world GDP and in lead production. Its impact on the real price of lead is positive and significant for a period of about five years. This is far less than in the cases of copper and tin but relatively similar to the case of zinc.

A positive unexpected shock to the supply of lead exhibits no significant change in world GDP but a strong, significant, and persistent effect on the world production of lead. It exhibits a slighly positive but not significant effect on the real price of lead. This result is in line with my finding for zinc, where the effect of a "supply shock" on the real price of lead is also insignificant. In contrast, in the copper and tin market positive "supply shocks" have a strong and significant effect on price. I explain this difference through market structures. The production of copper and tin is horizontally more concentrated than that of zinc and lead (BGR, 2007; Rudolf Wolff & Co Lt., 1987). In addition, mine production of copper and tin takes rather place in developing countries, while lead and zinc are mainly mined in industrialized countries, which also use lead and zinc as an input to manufacturing (Rudolf Wolff & Co Lt., 1987; Schmitz, 1979; BGR, 2007). As a consequence, shocks to the supply, e.g., in the form of coordinated production decreases by a cartell, have an impact on



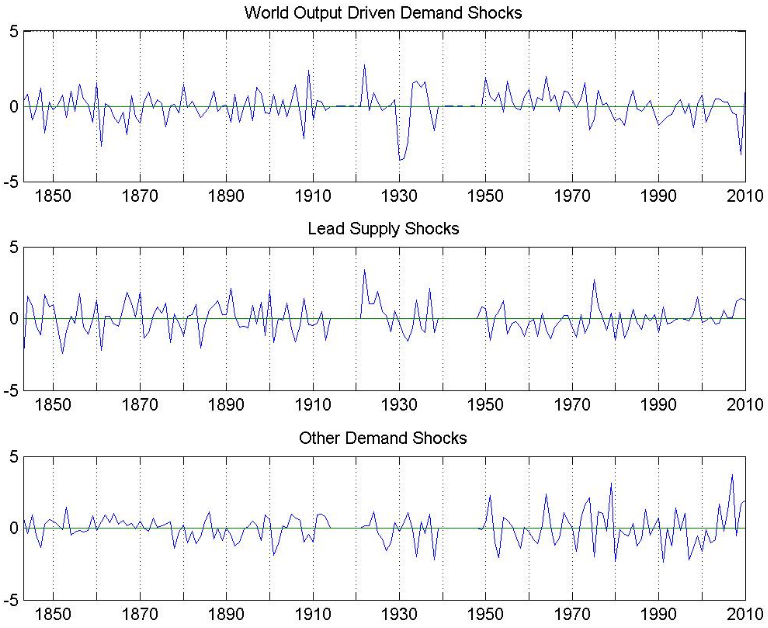
Notes: Point estimates with one- and two-standard error band based on Model (2.1). I use accumulated impulse response functions for the shocks on world mineral commodity production and world GDP to trace out the effects on the levels of these variables.

Figure 2.5: Impulses to one-standard-deviation structural shocks for lead.

copper and tin prices but do not affect the zinc and lead market.

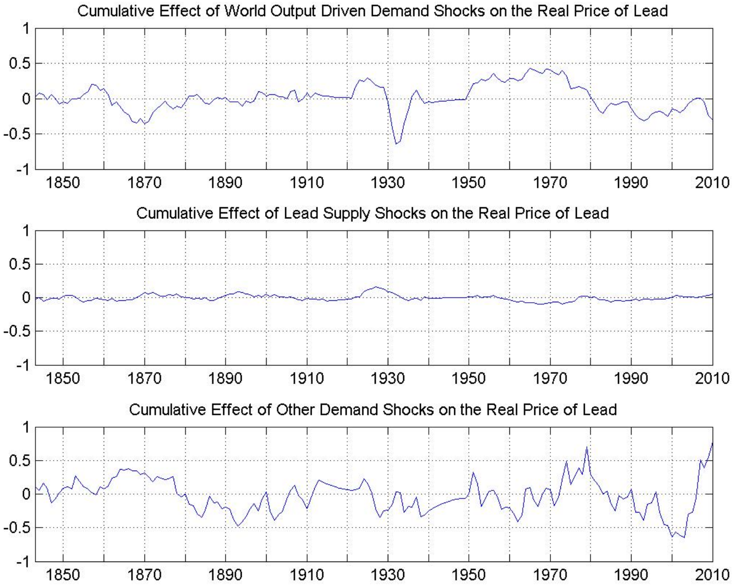
The impulse response functions in Figure 2.5 show that a positive “other demand shock” exhibits no significant impact on world GDP and lead production. There is no long term impact due to my identifying assumptions. However, it has a strong positive effect on the real price of lead that is persistent for a period of about ten years.

Lead prices were mainly driven by “world output-driven demand shocks” and “other demand shocks” in the period considered. Prices went up at the beginning of the 1850s and remained at this level for the next decade. Overall, prices were relatively stable until the 1880s, compared to the other threemineral commodities examined. McCune-Lindsay (1893) comes to the conclusion that the price of lead was far less affected by a “twist of fate” (German original: “schicksalsreiche Laufbahn” (McCune-Lindsay, 1893, p. 150). McCune-Lindsay (1893) also adds that it is not possible to find data on stocks in order to explain price movements for lead.



Notes: Structural residuals implied by Model (2.1).

Figure 2.6: Historical evolution of structural shocks for lead.



Notes: Please see notes to Figure 2.4.

Figure 2.7: Historical decomposition of the real price of lead.

Unfortunately, not much is known about the lead market in the 19th century. The "other demand shocks" in the mid 1860s may be due to the high uncertainty in the market about the German War that probably affected the trade in zinc from its main production sites in Silesia. Moreover, according to (Gibson-Jarvie, 1983) the zinc industry has always been prone to producer cartels in the main producing country Germany, where "the cartel "rationale" generally was both established and indeed encouraged..." (Gibson-Jarvie, 1983, p. 73). Through the last decade of the 19th century there were "repeated rumours in circulation as to a potential zinc cartel (...) sufficiently strong as to have an unsettling effect on prices." (Gibson-Jarvie, 1983, p. 73) However, as producers were not able to agree on or sustain production limits, these rumours faded again (Gibson-Jarvie, 1983, p. 73). The Metallgesellschaft (1904) mentions that the Lead Trust, a large cartel in the U.S., limited its production, and stocks increased so sharply that prices rose for a time. Overall, these ups and downs in cartel action may explain the "other demand shocks" that drove up prices in the mid 1890s, then vanished, and had a strong positive impact on prices again in the mid 1910s.

In 1909 the Metallgesellschaft which controlled most German and non-U.S. output led a successful attempt at market manipulation by creating the Lead Smelters' Association together with the main Belgian and Spanish lead mining companies (Gibson-Jarvie, 1983). Instead of production controls, the members agreed to leave the entire marketing of lead to the Metallgesellschaft, which could use stocks to withhold lead from the market (Gibson-Jarvie, 1983). The "other demand shocks" show that the Association was in line with the historical account relatively successful in driving up prices from 1910 to 1913 (Gibson-Jarvie, 1983).

In the interwar period, prices increased and peaked in 1924 owing to the accumulated effects of "world output-driven demand shocks". However, prices came under pressure from strong negative "other demand shocks", probably caused by extensive stockpiling (Gibson-Jarvie, 1983). As a reaction to stocks that "had amassed to an alarming degree" (Gibson-Jarvie, 1983, p. 79) non-U.S. producers established the Lead Producers' Reporting Association in 1931. It tried to increase prices by both production restrictions and stocking (Gibson-Jarvie, 1983). As the accumulated effects of "other demand shocks" show, it had considerable positive impact in the first year as it partly compensated for the strong negative "world output-driven demand shocks" due to the Great Depression. However, it collapsed when Great Britain imposed import tariffs in 1932 (Gibson-Jarvie, 1983). This put downward pressure on the price as stocks were dissolved (Gibson-Jarvie, 1983). Besides positive "world output-driven demand shocks", "other demand shocks" drove the market in the following years. The latter shocks included actions by goverments to protect their zinc producers with import tariffs and other measures as well as speculation on the London Metal Exchange (Gibson-Jarvie, 1983; Hughes, 1938).

After the Second World War prices rose sharply reaching a peak in 1951 due to "world output-driven demand shocks" triggered by postwar reconstruction and "other demand shocks". These "other demand shocks" were caused by several factors. First, after the Second World War the U.S. enacted the Strategic and Critical Minerals Stock Piling Act leading to heavy stockpiling, which can be seen in the sharp rise in the accumulative effects of "other demand shocks", especially during the Korean War (see Mote and den Hartog, 1953, p. 684). In 1951 the U.S. government imposed a price ceiling (see Bishop and den Hartog, 1954, p. 752). As foreign importers were not willing to sell their lead at the low mandatory U.S. price and foreign consumers could not absorb these quantities, stocks of non-U.S. producers accumulated, as evident from the positive "other demand shocks". As these stocks were sold on the market in the following two years, they extend downwards pressure on the real price of lead.

From 1961 to 1969 the U.S. government enacted the Lead and Zinc Mining Stabilization Program, which paid subsidies to mining companies when prices dropped below a certain threshhold (Smith, 1999). This kept prices fairly stable over this period (Smith, 1999). From 1971 to 1973 the U.S. government imposed price limits, which were lifted in 1973 and then strongly increased the price of lead (Smith, 1999), which was followed by a strong negative "other demand shock" due to destocking. The price peak in 1979 was mainly attributed to a wordwide shortage of lead concentrates and a strong demand from centrally planned economic countries (Smith, 1999). However, my analysis suggests that it was rather the strong demand from centrally planned economies as shown in the "other demand shocks" that drove the price then supply shortages. There were also strong increases in stocks of refined lead at consumers' and producers' sites (see data by U.S. Geological Survey, 2011a) that might be captured by these shocks.

In the 1980s there were strong downward pressures on the price of lead owing to the recession in 1981, as evident in the accumulated effects of “world output-driven demand shocks”, and owing to the phasingout of lead from many appliances, which caused strong negative “other demand shocks” (see Smith, 1999). However, demand picked up again in the late 1980s with the growth of the battery industry (Smith, 1999).

From 2003 prices recovered. This was partly driven by positive “world output-driven demand” until 2007, but mostly by positive “other demand shocks” in 2005, 2007, 2009, and 2010. While the positive demand shocks in 2009 and 2010 are attributable to a quadrupling of stocks at commercial exchanges, reflecting mainly demand by institutional investors (see data by International Lead and Zinc Study Group, 2011), the strong demand shocks from 2005 to 2007 probably reflect the lead intensive growth in rapidly industrializing countries such as China (Guberman, 2009).

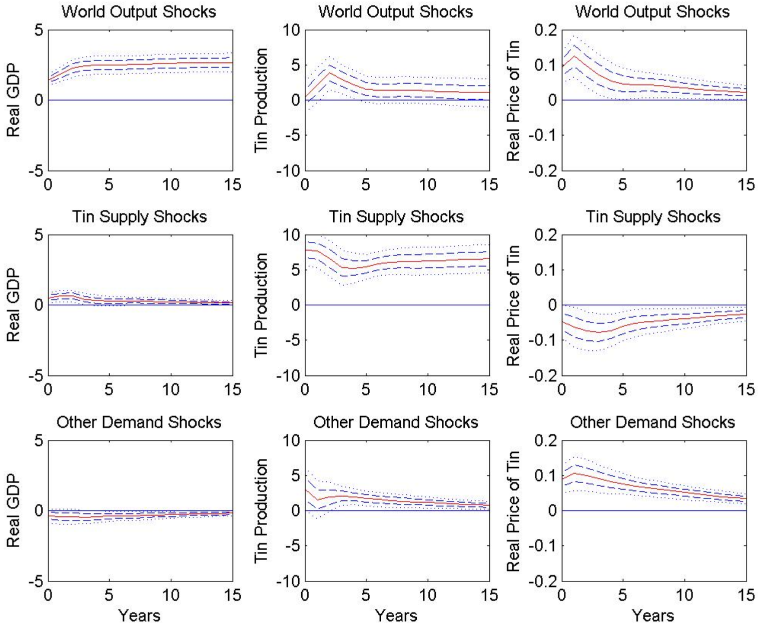
To conclude, fluctuations in the real price of lead have basically been driven by “world output-driven demand shocks” and “other demand shocks” but not by “supply shocks”. Historical evidence shows that the formation of cartels to restrict output has not been successful in the history of the lead market. This is due to the fact that lead resources are relatively widespread and production takes mainly place in the industrialized country (BGR, 2007). “Other demand shocks” have been basically driven by changes in inventories by producers, the U.S. government, and in recent times probably also by investors. “Other demand shocks” also encompasse shocks to the use of lead due to environmental regulation in the 1970s and 1980s.

2.5.3 Tin market

The price of tin has experienced large fluctuations in the past 170 years. According to my results these fluctuations are mainly driven by “world output-driven demand shocks” and “other demand shocks”, but “supply shocks” also play a role. The tin market has been characterized by a long history of oligopolistic structures. Governments have attempted to control the market since after the First World War. There is a strong geographic narrowness of supplies in the Earth’s crust (Gibson-Jarvie, 1983).

During history supplies shifted from England, to the Straits and Australia, and then to the South-East Indies (Gibson-Jarvie, 1983). Today, the main mine producers are China, Indonesia, and Peru (U.S. Geological Survey, 2013). "Tin is unusual among minerals in that the world is dependent on less developed countries for the bulk of its supplies" (Thoburn, 1994, p. 1)

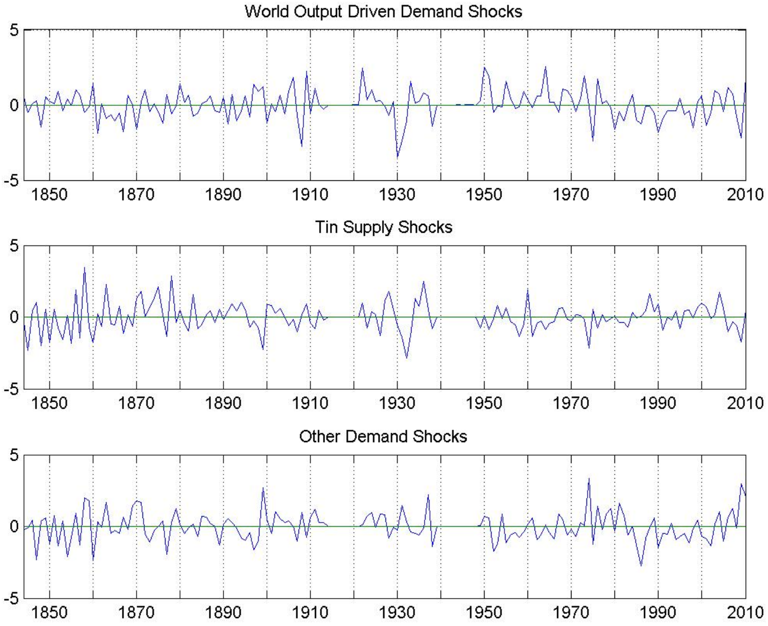
A positive unexpected shock to supply significantly increases GDP slighly for the first three years, but then subsides. It has a strong, significant, and persistent affect on the tin production. It exerts a strong and negative effect on the real price of tin that persists significantly for more than fifteen years. This effect is similar to the effect of a copper supply shock on price but different to the respective effects for zinc and lead.



Notes: Point estimates with one- and two-standard error bands based on Model (2.1). I use accumulated impulse response functions for the shocks on world mineral commodity production and world GDP to trace out the effects on the levels of these variables.

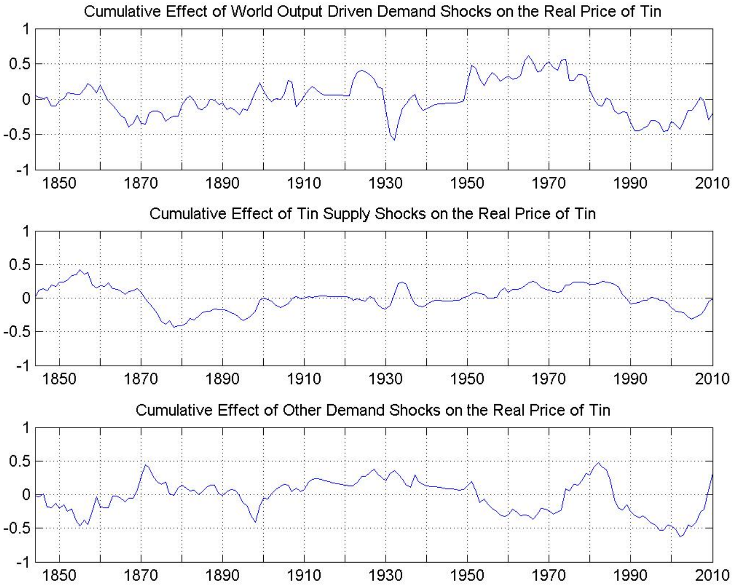
Figure 2.8: Impulses to one-standard-deviation structural shocks for tin.

Finally, I find that positive “other demand shocks” have no statistically significant impact on world GDP, but exert a positiv and rather minor effect on tin production, which turns statistically significant about three years after the shock hits. Owing to the long-run restrictions, the effects level off over time. An unexpected increase in “other demand shocks” leads to a strong and positive increase in the real price of tin, which remains statistically significant for more than fifteen years.



Notes: Structural residuals implied by Model (2.1).

Figure 2.9: Historical evolution of structural shocks for tin.



Cumulative Effect of World Output Driven Demand Shocks on the Real Price of Tin

Cumulative Effect of Tin Supply Shocks on the Real Price of Tin

Cumulative Effect of Other Demand Shocks on the Real Price of Tin

Notes: Please see notes to Figure 2.4.

Figure 2.10: Historical decomposition of the real price of tin.

The rise in the prices from the 1840s until the late 1850s was due to positive "world output-driven demand shocks", as the world economy boomed in the 1850s (Kindleberger and Aliber, 2011). At the same time, there were unexpected negative "supply shocks" due to partly simultaneous production shortfalls in the main mining areas of Cornwall and Banka, which drove up prices (see data provided by Neumann, 1904, pp. 251-2). "Other demand shocks" also exerted downward pressure on the price, but their sources are not identifiable from the literature.

The price of tin slumped in the following years, reaching a trough in 1867. Britain, whose industry was the main user of tin at that time, lifted the restrictive import policies it had adopted to protect tin producers in Cornwall (Thoburn, 1994), which opened the market to tin from South-East Asia and led to positive "supply shocks" that drove prices down as the structural shocks in Figure 2.9 show. At the same time, several negative "world output-driven demand shocks" triggered by the Panic of 1857, the American Civil War and the Overend-Gurney crisis exerted downward pressure on the price (see Kindleberger and Aliber, 2011).

In the late 1860s and early 1870s, conflicts between Chinese clans that controlled mining production on the Malayan peninsula turned into war (Thoburn, 1994). Britain intervened and took control of important parts of the Malayan peninsual by 1874 (Thoburn, 1994). My analysis suggests that this event triggered major “other demand shocks”, since it increased uncertainty in the tin market, which led to a rise in pre-cautionary stockholding by consumers. The resulting high price resulted in greater production elsewhere. Tin production in Cornwall reached a high in 1871, and Australian production rose significantly in the early 1870s (Thoburn, 1994). This caused positive supply shocks that put downward pressure on the price, which rose even higher after the British consolidated their control of the Malayan peninsula. The result was a significant increase in production and the Malayan peninsula became the most important producer in the world by the late 1870s (Thoburn, 1994). Moreover, the Long Depression in the industrializing world began in 1873 and exerted further downward pressure on the price of tin. Prices recovered from their low levels, reaching a peak in the late 1880s owing to the economic recovery after the Long Depression, which triggered positive “world output-driven demand shocks”. From 1889 to the late 1890s prices fell again because of sluggish economic growth and further positive “supply shocks”.

At the end of the 1890s prices rose dramatically. This was due to several factors. First, positive accumulative effects of “world output-driven demand shocks” peaked at the beginning of the 20th century (see also data provided by Crafts, Leybourne, and Mills, 1989; National Bureau of Economic Research, 2010), which led to unexpectedly high rises in the demand for tin. Second, labor shortages and equipment problems caused negative “supply shocks”. These problems were also linked to the need to produce tin from deposits of lower ore grades and of greater depths (Thoburn, 1994) and were exacerbated by the decision of local authorities to stop the exploration for new deposits in Kinta Valley, the most important tin-mining area (Thoburn, 1994).

Until the outbreak of the First World War, the price of tin was essentially driven by positive and negative “world output-driven demand shocks” due to the business cycles of the two major economies at the time, the U.S. and the U.K. (see data provided by Crafts, Leybourne, and Mills, 1989; National Bureau of Economic Research, 2010).

Price fluctuations in the inter-war period were mainly influenced by the economic recovery after the First World War, the effects of the Great Depression, and attempts to form cartels. In 1921 the governments of the Federated Malay States and the Dutch East Indies establishd the Bandoeng Pool and agreed to stabilize the price of tin by jointly managing inventories (Thoburn, 1994). The Bandoeng Pool controlled more than fifty percent of world production at the time (Thoburn, 1994, p. 77). From 1921 to 1923 it withheld some fifteen percent of world tin production from the market and sold it gradually when prices rose in the mid of the 1920s owing to positive "world output-driven demand shocks" (Thoburn, 1994). The action taken by the cartel is evident form the "other demand shocks". The Bandoeng Pool reaped a "substantial profit from the operation" (Thoburn, 1994, p. 77) and was dissolved in 1924 with its stocks exhausted (Baldwin, 1983).

The Great Depression caused strong negative "world output-driven demand shocks" to the price of tin, which coincided with a major expansion of world production (Thoburn, 1994). In response, a number of tin producers tried to withhold tin from the markets by stockpiling it, which explains the positive "other demand shocks" at the time. However, as these attempts were unsuccesssful, the International Tin Agreement was drawn up. It encompassed the major producers and introduced formal restrictions on output (Thoburn, 1994). This caused a large negative supply shock in 1932, evident from the accumulative effects of the "supply shocks", which drove the price up again. In 1938 a buffer stock was formed under the International Tin Agreement to stabilize prices (Thoburn, 1994). While the International Tin Agreement inventories were increased in the first year, causing prices to rise, it was soon exhausted in the run-up to the Second World War (Thoburn, 1994).

The high price from the end of the Second World War until the early 1970s was driven mainly by upward pressure from strong "world output-driven demand shocks" and mild "supply shocks". The "world output-driven demand shocks" reflected post-war reconstruction, followed by South-Korea's and Japan's industrial expansion. Downward pressure at that time resulted from "other demand shocks" due to the U.S. stockpiling programme. After the Second World War the U.S. passed the Strategic and Critical Minerals Stock Piling Act and bought tin into government inventories because of fears about supplies due to the spread of communism in South-East Asia (Thoburn, 1994). After the Korean War it stopped buying and gradually reduced its inventories during a period of high prices (Smith and Schink, 1976). Purchases from government stocks help to explain the downward pressure on prices by "other demand shocks" until the mid 1950s.

In 1956 the main producing and consuming countries, with the exception of the U.S., concluded a new International Tin Agreement with a view to stabilizing prices. It provided for both export restrictions and an international buffer stock (Thoburn, 1994). It imposed export restrictions, which are visible in the accumulative effects of "supply shocks" until they were lifted in 1960 (Thoburn, 1994). The resulting oversupply is clear from the structural shocks. The buffer stock formed under the International Tin Agreement also exerted some influence on the market in this period (see Thoburn, 1994; Smith and Schink, 1976). From an examination of "other demand shocks" it seems that the downward pressure of subsequent releases from the U.S. stockpiling programme was offset by the upward pressure of action under the International Tin Agreement during the 1960s.

The recessions of 1974 and the early 1980s caused large negative "world output driven demand shocks" to the price of tin (Thoburn, 1994). However, the price rose sharply in 1974 and continued at this high level because of action taken under the International Tin Agreement. Export restrictions were imposed, and the buffer stock was increased (Thoburn, 1994). This strategy worked until the famous collapse of the buffer stock and the suspension of the trade of tin on the London Metal Exchange (see Kestenbaum, 1991, for a detailed account). The collapse and dissolution of the buffer stock caused a serious slump in the price of tin, which levelled-off slowly in the 1990s. During this time, the Association of Tin Producing Countries was established and tried to restrict supplies (Thoburn, 1994).

From the beginning of the new millennium until 2010 the price of tin rose sharply as a result of positive "world output-driven demand shocks" caused by the rise of China and, to a far larger extent, by "other demand shocks". This accords with data on inventories at the London Metal Exchange, which more than doubled from 2008 to 2010, according to data released by the BGR, 2013. This reveals the strong part played by inventory changes in the current price hike, and especially in compensating for the negative "world output-driven demand shock" in 2009. These changes have not only been been due to restocking at producers and consumers, but also, according to industry observers, due to stockpiling by investment funds as attribute (U.S.

Geological Survey, 2011c).

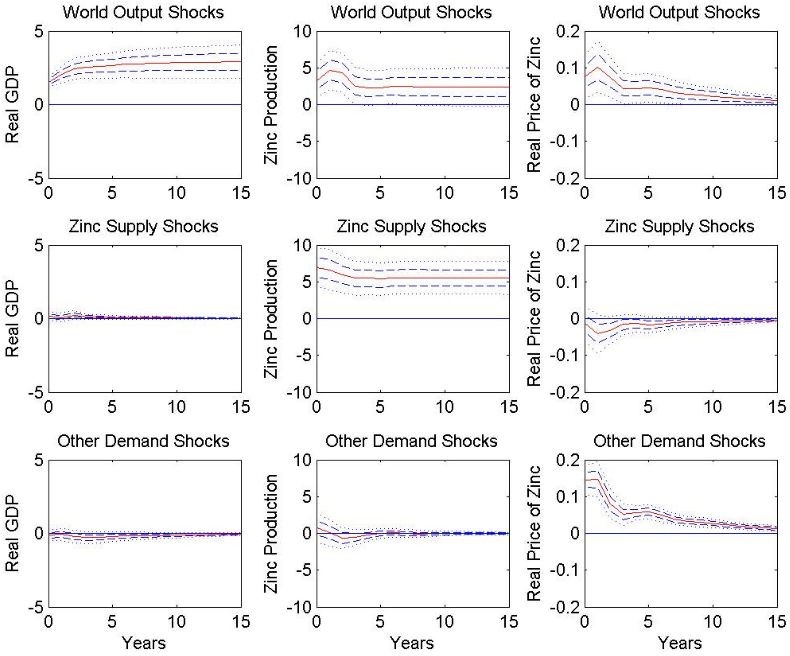
Overall, my results provide evidence that fluctuations in the price of tin are mainly driven by "world output-driven demand shocks" and "other demand shocks", but "supply shocks" also play an important role. The tin market is characterized by a long history of oligopolistic structures and continuous attempts to manipulate prices since after the First World War. Cartels were able to do so by restricting output but also by stockpiling. My account shows that "other demand shocks" were mainly driven by government stockpiling programs, the change in stocks of different cartels, and recently by increases in demand for inventories at metal exchanges. A special feature has been the build-up and collapse of the International Tin Agreement, which influenced the price strongly over several decades.

2.5.4 Zinc market

My results show that "world output-driven demand shocks" and "other demand shocks" are the main drivers of fluctuations in the real price of zinc. As it is the case for lead, zinc is basically produced in industrialized countries and resources are found all across the world. The market is therefore not prone to functioning cartels and does not have an oligopolistic structure (BGR, 2007).

The impulse response functions in Figure 2.11 show that the behaviour of the zinc market is very similar to that of the one for lead. An unexpected rise in demand due to an increase in world output is causing a strong and persistent increase in zinc production. While the effect on world output is of considerable statistical significance, the effect on zinc production is statistically significant in only the four following years. Later it becomes a borderline case. Its effect on the price of zinc is substantial and continues to be significant for about five years.

An unexpected increase in zinc supply does not have an effect on world GDP, but has a strong positive impact on zinc production, as expected. It leads to a statistically insignificant fall in the real price of zinc. In this respect, zinc is similar to lead, but different from copper and tin, which are affected by "supply shocks". I attribute this difference to market structures. Copper and tin production are horizontally more concentrated than zinc and lead production (BGR, 2007; Rudolf Wolff & Co Lt.,



Notes: Point estimates with one- and two-standard error bands based on Model (2.1). I use accumulated impulse response functions for the shocks on world mineral commodity production and world GDP to trace out the effects on the levels of these variables.

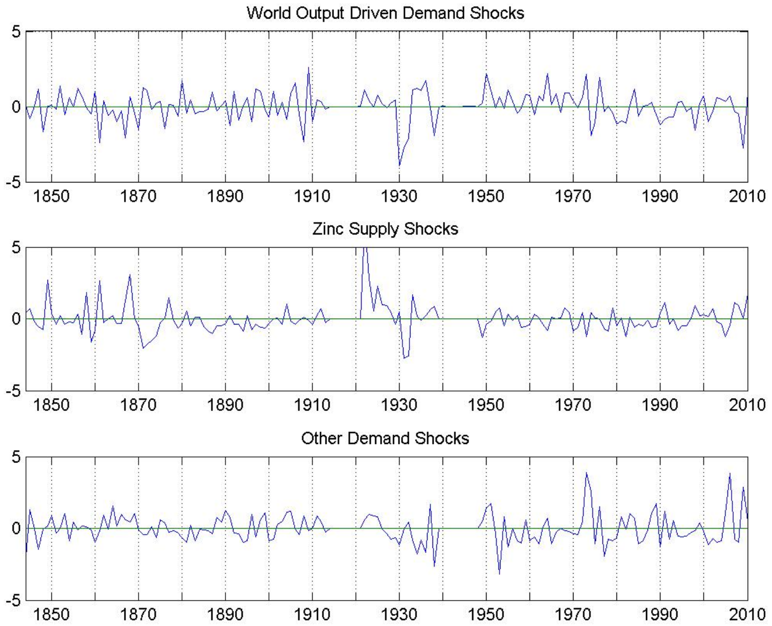
Figure 2.11: Impulses to one-standard-deviation structural shocks for zinc.

1987). In addition, copper and tin are generally mined in developing countries, while lead and zinc are mined mainly in industrialized countries, which also use lead and zinc as manufacturing inputs (Rudolf Wolff & Co Lt., 1987; Schmitz, 1979; BGR, 2007). As a consequence, shocks to supply in the form of coordinated production decreases by a cartell, for example, have an impact on copper and tin prices, without affecting the markets of lead and zinc.

A positive "other demand shock" has no impact on world GDP or zinc production. It has an immediate, major, highly significant, and persistent positive effect on the real price of zinc for a period of up to fifteen years.

The price of zinc has been driven mainly by "world output-driven demand shocks" and "other demand shocks" in the course of history as Figure 2.13 shows. Prices rose sharply in the 1850s and peaked in 1857, driven by the accumulative effects of "positive output-driven demand shocks" as the world economy boomed in the 1850s (see Kindleberger and Aliber, 2011). Prices then slumped due to the accumulative effects of negative “world output-driven demand shocks” caused by the Panic of 1857 and the American Civil War (see Kindleberger and Aliber, 2011). Even though “world output-driven demand shocks” continued to put pressure on zinc prices, strong positive “other demand shocks” supported them in the mid-1860s as the structural shocks in Figure 2.12 show. Unfortunately, I have not been able to find a conclusive explanation for these shocks. A possible explanation is the German War of 1866, which may have affected the trade in zinc from the main mining area in Silesia and so caused “precautionary demand” for inventories. I leave it to future research to delve deaper into the history of the zinc market around that time.

Prices recovered in the early 1870s owing to “world output-driven demand shocks” and then reached a peak in 1875. This peak was mainly driven by market manipulations of U.S. producers, which are evident from the strong positive “other demand shocks” at the time (Jolly, 1997). The high price caused production increases elsewhere, which sent prices down again (Jolly, 1997). The falling prices led to attempts by German producers in 1979 and by a number of other European producers in 1882 to form cartels and to put upwards pressure on prices by limiting production (Jolly, 1997; Cocks and Walters, 1968). These attempts failed, since local production decreases were offset by production elsewhere (Jolly, 1997; Cocks and Walters, 1968). As a result, negative “other demand shocks” in combination with “world output-driven demand shocks” due to the Long Depression exerted downward pressure on prices, which reached their lowest level in the mid-1880s.



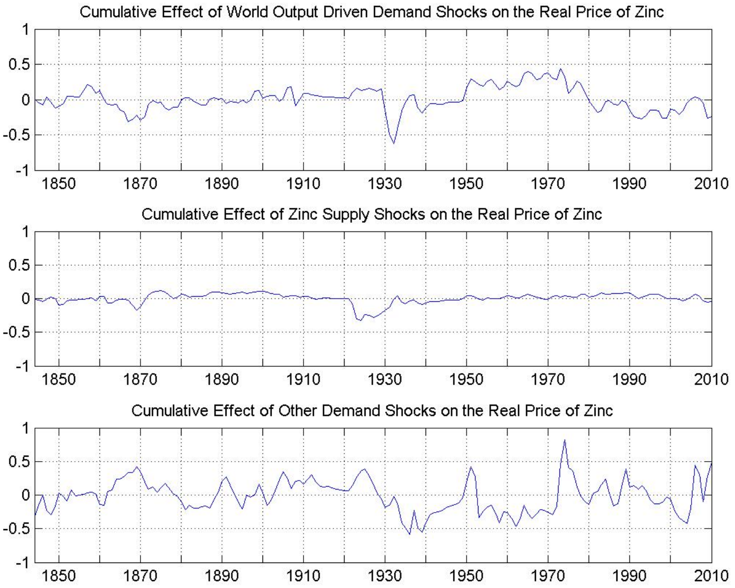
World Output Driven Demand Shocks

Zinc Supply Shocks

Other Demand Shocks

Notes: Structural residuals implied by Model (2.1).

Figure 2.12: Historical evolution of structural shocks for zinc.



Cumulative Effect of World Output Driven Demand Shocks on the Real Price of Zinc

Cumulative Effect of Zinc Supply Shocks on the Real Price of Zinc

Cumulative Effect of Other Demand Shocks on the Real Price of Zinc

Notes: Please see notes to Figure 2.4.

Figure 2.13: Historical decomposition of the real price of zinc.

As a reaction to the low prices in the 1880s, major European producers joined the “first significant international zinc cartel” (Jolly, 1997, p. 116), which accounted for about 85 percent of world production (Jolly, 1997). The accumulative effects of “other demand shocks” show that it succeeded in temporarily increasing the price, which reached a peak in 1890. There were also supply cuts, which are evident from the structural supply shocks, but did not have a major impact on prices, as can be seen from the accumulative effects. However, the cartel lost its power when new production came on to the market in reaction to the high prices (Jolly, 1997). Subsequent destocking inhibited strong negative “other demand shocks” and exerted additional downward pressure on the price.

The price rose sharply in the late 1890s owing to “world output-driven demand shocks”, reflecting the booming world economy, but also due to “other demand shocks”, which may reflect not only growing stocks at smeltering plants but also attempts by U.S. producers to form a trust (Metallgesellschaft, 1904). In the following years, the price was driven mainly by “other demand shocks”, possibly reflecting the “cartel mentality” (Cocks and Walters, 1968, p. 16) of the German metal industry at the time. In 1909 another major attempt was made by European producers to form a cartel, known as the Spelter Convention, which drove up prices in the period until the outbreak of the First World War, as can be seen from the accumulated effects of the “other demand shocks” (Jolly, 1997).

In the inter-war period, prices began by falling, then rose to a peak in the mid-1920s, slumped sharply during the Great Depression and did not recover from this low level until the end of the Second World War. My analysis shows the peak in the mid-1920s to be the result of positive “world output-driven demand shocks” due to the booming world economy and “other demand shocks” probably due to industry stockpiling (see data provided by U.S. Geological Survey, 2011a). Positive supply shocks also exerted significant downward pressure on prices. I attribute these to the widespread introduction of flotation extraction and the electrolytic technique of smelting which made the zinc production from complex sulphide ores possible (Gupta, 1982). These new techniques increased production especially in non-European areas such as Canada, Australia, Mexico, Rhodesia, and Indochina (Gupta, 1982). As a result the production of flotation concentrate in the U.S. for example increase from

34,000 tons in 1921 to 500,000 tons in 1928 (Jolly, 1997, p. 39).

The new competition from outside Europe triggered the formation of the European zinc cartel in 1928 but which was dissolved in 1929 due to disparate interests of its members (Jolly, 1997; Gupta, 1982). The Great Depression caused a major negative "world output-driven demand shock" in 1930 and send prices down. As a reaction, the European zinc cartel was revived and imposed a 45 percent cutback of production in 1931 which was raised to 55 percent in the following year (Jolly, 1997). This explains the negative "supply shocks" during these two years. However, the cartel dissolved in 1934 as some participants cheated on their production and sales. Problems with the treatment of inventories, which started to be released on the market as "other demand shocks" show, were also not solved (Jolly, 1997; Gupta, 1982). Several attempts to renew the cartel failed until a cartel called the International Sheet Zinc Cartel was founded at the end of the 1930s. It had a short impact on the market as the "other demand shocks" suggest but was dissolved by the start of Second World War (Jolly, 1997).

The high price level from the end of the Second World War until the beginning of the 1970s was mainly driven by upwards pressure due to strong "world output-driven demand shocks" fueled by post-war reconstruction and the following industrial expansion in South-Korea and Japan. After Second World War the U.S. enacted the Strategic and Critical Minerals Stock Piling Act which led to heavy stockpiling, visible in the sharp rise of accumulated "other demand shocks" and driving up prices enormously (Gupta, 1982, p. 32). The following years were characterized by price controls and sales and purchases into the government stockpile in the U.S. This economic policy strongly influenced the price in the rest of the world and had a rather destabilizing effect (Gupta, 1982, p. 32). It is also visible in the "other demand shocks". Furthermore, a new informal cartel was founded in 1964, known as the "Zinc Club" (Jolly, 1997, p. 117). Its members, mainly European, Canadian, and Australian zinc companies aimed at supporting the newly introduced European Producer Price and to restrain the influence of the London Metal Exchange (Jolly, 1997). They used inventories as a tool to set the European Producer Price (Jolly, 1997). .

At the beginning of the 1970s the zinc price increased dramatically. My analysis shows that this was mainly driven by "other demand shocks". The U.S. government imposed a stabilization program in 1971 which fixed prices at a low level (Jolly, 1997). After lifting the fixed price in 1973, both the U.S. producers and the "Zinc Club" increased their prices sharply by more than 225 percent (Gupta, 1982, p. 30). As producers withhold stocks, visible in the strong accumulated response of the "other demand shocks", the price of the London Metal Exchange also increased drastically. In 1974 the recession had a strong negative shock on the price and producers were not able to support prices anymore such that prices dropped again (Gupta, 1982). The governments of the U.S., Japan, and France helped zinc companies to reduce inventories in these times of a low zinc price by increasing government stocks in 1975 and 1976 (Gupta, 1982). After investigations of the U.S. department of Justice, the informal "Zinc Club" collapsed in 1976 (Jolly, 1997).

In the 1980s the zinc price reached peaks in the middle of the 1980s and at the end of the 1980s. Both are explainable by a combination of positive "world output-driven demand shocks" due to economic expansions of the world economy (U.S. Geological Survey, 2011a) and "other demand shocks". I attribute these "other demand shocks" to the introduction of the zinc penny by the U.S. government (Jolly, 1997). This led to irregular purchases of zinc by the U.S. mint which influenced the zinc price over the decade (see Jolly, 1984, 1986, 1989).

In the 1990s the real price of zinc was driven by negative "world output-driven demand shocks" due to the breakup of the U.S.S.R. and the Asian Crisis later on. The price increase at the beginning of the 2000s was fueled by positive "world output-driven demand shocks" until the Great Recession starting in late 2007 caused strongest negative "world output-driven demand shocks". However, strong positive "other demand shocks" partly compensated for these negative shocks. They reflect a strong change in warehouse inventories of the London Metal Exchange and the Shanghai Futures Exchange, which have increased eightfold and sixfold in the period from 2007 to 2010 (International Lead and Zinc Study Group, 2011). Interestingly data on inventories at consumers' and producers' sites have not increased over the time period (International Lead and Zinc Study Group, 2011), which points to the role of institutional investors in buying inventories.

Overall, the price of zinc was mainly driven by "world output-driven demand shocks" and "other demand shocks" over the course of history. Cartels have not had success in restricting output. Historical evidence points to changes in inventories by firms, government, and investors as an interpretation of the “other demand shocks”.

2.5.5 Long-term trends

The estimated coefficients of the linear trends in the five estimated VAR models show that prices - with the exception of copper - have basically been trendless from 1840 to 2010. The negative linear trend is statistically significant at the 5 percent level in the case of the price of copper and only statistically significant at the 10 percent level in the cases of the prices of lead and zinc. The estimated coefficients for the linear trends in the prices of tin and crude oil (since 1861) are zero. These results partly differ to those presented in chapter 1 as price data has been deflated by the producer price index and not by the consumer price index as in 1

	Est. coefficient	t-stat.	t-prob.
Copper	-0.002	-2.811	0.006
Lead	-0.001	-1.871	0.063
Tin	0.000	0.315	0.753
Zinc	-0.001	-1.777	0.077
Crude Oil	0.001	0.698	0.486

Table 2.1: Estimated coefficients of the linear trends.

2.6 Sensitivity analysis

I have employed several robustness checks, including an alternative identification scheme, and different time periods and alternative price data to test whether my main results still hold. To ease comparison, I present the results of forecast error variance decompositions for each of the respective specifications. The respective regression results are available from the author upon request. Table 2.17 shows the respective contributions of the three shocks for my baseline specification.

In order to check the robustness of the results over that of an alternative identification, I use Kilian’s identification scheme, which is based on short-run restrictions. I postulate a vertical short-run supply shape and no effect of price changes driven by "other demand shocks" on world GDP within the first year. I describe the identification in detail in the Appendix. Even if it is not clear how reasonable the identifying restrictions on annual data are, the empirical results are relatively similar. As table 2.18 shows, my results stand up with respect to the overall strong impact of demand shocks on the prices of copper, lead, tin, and zinc. However, the effect of supply shocks on the prices of tin and copper do not show up due to the restrictions that I apply regarding the instantaneous impact of world output shocks and other demand shocks on supply.

My results are also robust regarding alternative price data. Table 2.19 illustrates the empirical results obtained from using the producer price index instead of the consumer price index for disinflation.

Employing New York prices instead of London based prices (see Table 2.21) increases the contribution of supply shocks and reduces the contribution of demand shocks due to unexpected changes in world output significantly in the cases of tin and copper prices. In the cases of the lead and zinc market, "other demand shocks" strongly dominate other shocks. These results illustrate how strong government intervention and stockpiling, the imposing of restrictions on trade policies, and producer prices have dominated non-ferrous metals markets in the U.S. most of the time, whereas the market in London was basically the market-based price setter on a global scale (see also Slade, 1989).

Finally, I check the results for robustness with respect to different subperiods. Starting the observation period in 1900 or 1925 does not change the general results in the cases of copper, lead, tin and zinc (see table 2.20).

2.7 The case of crude oil

While the empirical results are quite robust and relatively homogeneous across the four mineral commodities, the results for the crude oil market are less compelling due to structural breaks in the time series. As a comparison, I present the empirical results in the following.

The structural shocks evolve in a plausible way. "World output-driven demand shocks" develop in relatively similar fashion for the examined other mineral commodities. “Supply shocks” are quite pronounced in the pre-World War I and interwar period, but have decreased in amplitude after the Second World War. “Other demand shocks” are also plausible. All in all the structural shocks are in line with those identified by Kilian (2009) over the period from 1973 to 2007. However, impulse response functions raise questions. The cumulative effects of positive “world output-driven demand shocks” have strong negative effects on the real price. This seems to be an anomaly, since they should feature positive effects. An explanation for this behaviour is the still unsettled issue of causality in the relationship between the oil price and economic growth (see, e.g., Ozturk (2010) for an overview). All other impulse response functions behave as expected. The historical decomposition reveals again the problem with the “world output-driven demand shocks”. As expected from the impulse response function, their contribution is turned on its head with a large accumulation of positive shocks during the Great Depression and a large accumulation of negative shocks during the 1950s and 60s. As in Kilian (2009) supply shocks are not important and other demand shocks make a strong contribution to the crude oil price especially during the 1970s. This is in line with the argumentation of Kilian (2009) that the political uncertainty in the Middle East caused a strong increase in the precautionary demand for oil. Overall, the evolution of supply and other demand shocks is plausible and in line with the empirical evidence presented by Kilian (2009).

The results for crude oil are not robust with respect to different subperiods due to the familiar structural changes in the oil market (see Kilian and Vigfusson, 2011; Dvir and Rogoff, 2010; Hamilton, 2011). My results show that supply shocks played an important role in shaping oil prices before the structural break in 1973. This is in contrast to the time period from 1973 to 2007, where the oil price was shaped by demand shocks (as also examined by Kilian (2009)). I use annual GDP data instead of the freight rates in Kilian’s regressions and find that it generates relatively similar results over the period from 1973 to 2007 when I use his identification (see figures 2.20 to 2.23). However, the results change when his identification is used over the entire time period from 1861 to 2010. Whereas “other demand shocks” are quite strong, “world output-driven demand shocks” do not play a role and supply shocks have some effect on the oil price.

2.8 Conclusion

This paper has examined the dynamic effects of demand and supply shocks on the real prices of copper, lead, tin, zinc, and crude oil from 1840 to 2010. Using a historical decomposition based on a structural VAR model with long-term restrictions, my results show that these prices are mainly driven by persistent "world output-driven demand shocks" and "other demand shocks", namely shocks to inventory demand. "Supply shocks" play a role only in the cases of tin and copper, possibly due to the oligopolistic structure of these markets.

My results contribute to the literature by providing long-term empirical evidence from a new data set on mineral commodity prices. Two major limitations to my analysis may guide further research. First, my model does not include asymmetric responses of prices to positive or negative shocks. This may be particularly important for the effect of positive and negative supply shocks on prices and vice versa. For example, Radetzki (2008) describes an experience which is common in the extractive sector, namely that firms keep their utilization rates high even after negative price and demand shocks hit the market. Second, "other demand shocks" capture all shocks that are orthogonal to "supply shocks" and "world output-driven demand shocks". Disentangling these shocks by explicitly controling for changes in inventories or the resource intensity of the economy would shed further light on the sources of these shocks.

A2 Appendix

A2.1 An alternative identification

As a robustness check and to ease comparison, I provide an identification scheme following Kilian (2009). I use a structural VAR model with short-run restrictions to decompose unpredictable changes in the real mineral commodity prices into mutually orthogonal components.

The vector of endogenous variables is $z_t = (\Delta Q_t, \Delta Y_t, P_t)^T$, where ΔQ_t denotes the percentage change in world production of the respective mineral commodity, ΔY_t refers to the percentage change in world GDP, and P_t is the log of the respective real commodity price. D_t denotes the deterministic terms, notably a constant, a linear trend, and the annual dummies during the World War I and II periods and the three consecutive years. The structural VAR representation is

$$Az_t = \Gamma_1 z_{t-1} + ... + \Gamma_p z_{t-p} + \Pi D_t + \epsilon_t. \tag{2.2}$$

ϵ_t is a vector of serially and mutually uncorrelated structural shocks. Assuming that A^{-1} has a recursive structure, I decompose the reduced-form structural errors e_t according to $e_t = A^{-1}\epsilon_t$:

$$e_t \equiv \begin{bmatrix} e_t^Q \\ e_t^Y \\ e_t^P \end{bmatrix} = \begin{bmatrix} a_{11} & 0 & 0 \\ a_{21} & a_{22} & 0 \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} \epsilon_t^Q \\ \epsilon_t^Y \\ \epsilon_t^P \end{bmatrix}$$

.

I use the same restrictions on the short-term relations as Kilian (2009) to identify the model. However, since he uses monthly and I annual data, I explain my restrictions as follows:

I define "supply shocks" as unpredictable changes to the global production of the respective mineral commodity. The underlying assumption is a vertical short-run supply curve of that commodity. Shocks to demand or supply instantaneously change the price, inasmuch they shift the demand curve or the vertical supply curve. Hence, I assume that innovations due to neither world output nor price affect supply within the same year. This assumption seems plausible as an explanation for expanding extraction and first-stage processing capacities, which are highly capital-intensive. Thus it takes five or more years before new capacities become operational (see Radetzki, 2008; Wellmer, 1992).

However, firms might also respond to demand shocks by increasing capacity utilization, which would make the above assumption implausible. At the same time, Kilian (2008) states that capacity utilization rates in world crude oil production were around 90 percent from 1974 to 2004, so that major expansions in capacity utilization within the space of a month were not possible. He states that firms run their oil production facilities only at 90 percent of nominal capacity - and not at full nominal capacity -, because there is uncertainty about the threshold of sustainable production. Exceeding that threshold might permanently damage an oil field. I find similarly high utilization rates in U.S.-data for the oil extraction, mining and primary metals industries from 1967 to 2011 (U.S. Federal Reserve, 2011). In the case of the mining and primary metals industries, maintenance and repairs make a capacity utilization rate higher than 90 percent also unlikely. To sum up, there is some evidence that the assumption of a vertical supply curve in the short-run is reasonable, but for the annual data that I use it is nevertheless contestable.

I define “world output-driven demand shocks” as shocks to global GDP that cannot be explained by “supply shocks”. Hence, I impose the restriction that price changes driven by “other demand shocks” do not affect global GDP within a year. Kilian (2009) shows that price increases due to oil market specific demand shocks do not result in a statistically significant decline in the level of even the U.S.-GDP. Furthermore, on a global scale a price increase is only a redistribution of income from importing to exporting countries such that global output should not be affected in the short-run.

A2.2 Additional figures

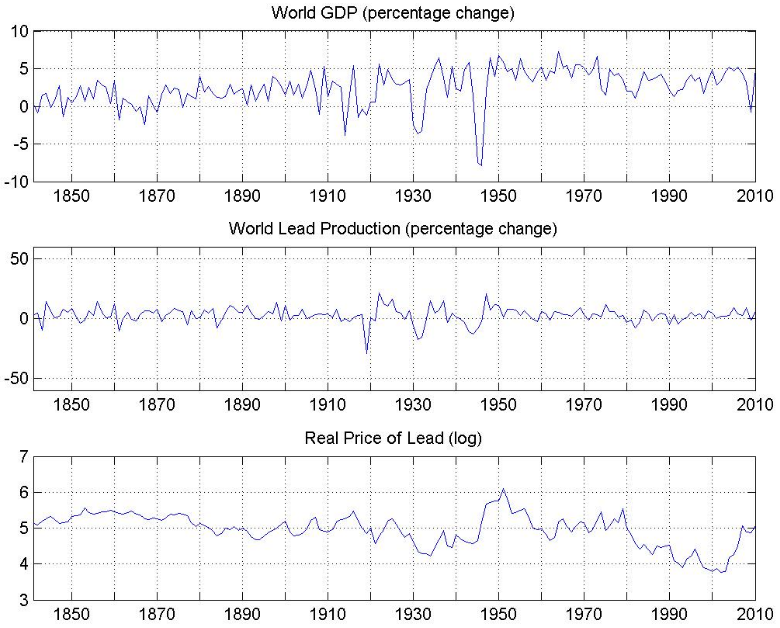


Figure 2.14: Historical evolution of world GDP, world lead production, and the real price of lead from 1841 to 2010.

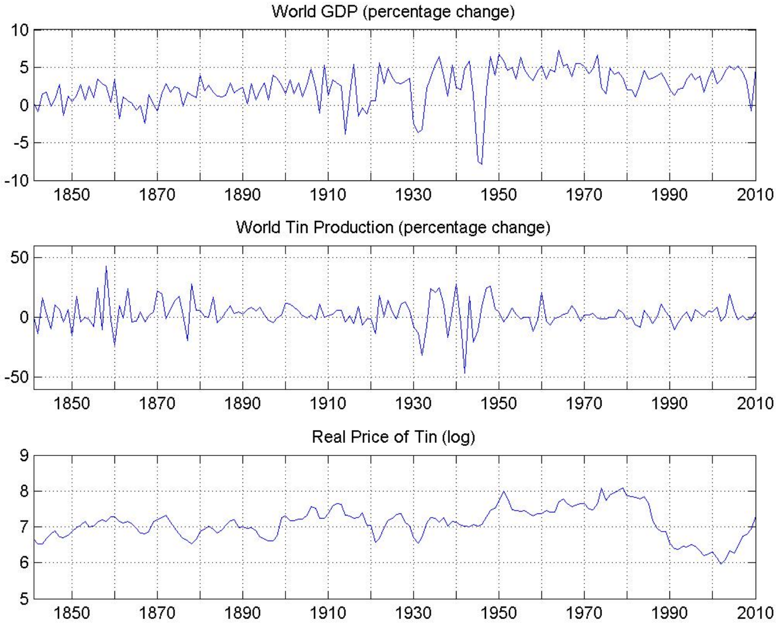


Figure 2.15: Historical evolution of world GDP, world tin production, and the real price of tin from 1841 to 2010.

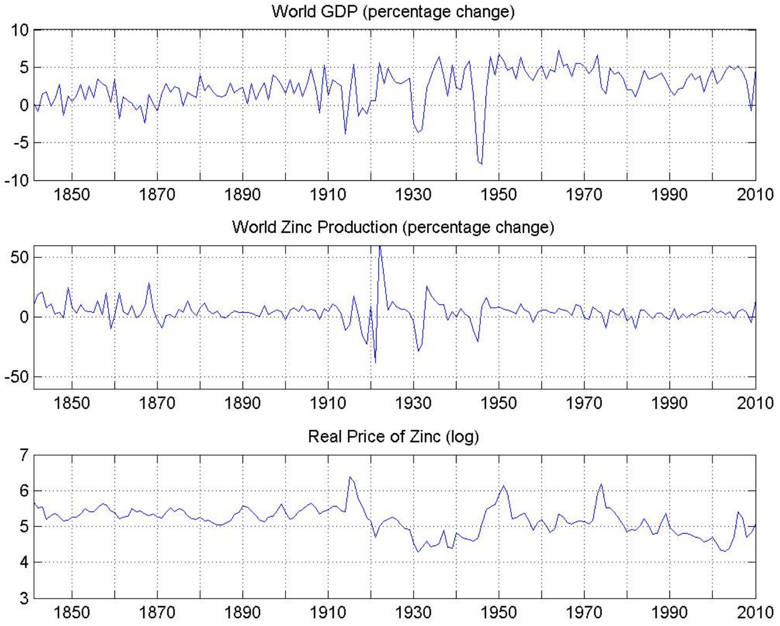


Figure 2.16: Historical evolution of world GDP, world zinc production, and the real price of zinc from 1841 to 2010.

A2.3 Regression results

Indep. variable	**Coefficient**	**t-statistic**	**t-probability**
Dependent variable: World GDP (percentage share)			
World GDP lag1	0.375	3.964	0.000
World GDP lag2	0.353	3.281	0.001
World GDP lag3	0.149	1.603	0.111
World GDP lag4	-0.196	-2.340	0.021
Production lag1	-0.025	-1.547	0.124
Production lag2	-0.008	-0.518	0.605
Production lag3	-0.035	-2.345	0.021
Production lag4	-0.003	-0.206	0.837
Price lag1	-1.539	-1.661	0.099
Price lag2	-0.544	-0.436	0.663
Price lag3	0.206	0.170	0.865
Price lag4	1.790	2.122	0.036
Constant	1.267	0.344	0.731
Trend	0.005	0.660	0.510
Dependent variable: Copper production (percentage share)			
World GDP lag1	1.950	4.366	0.000
World GDP lag2	1.706	3.355	0.001
World GDP lag3	0.810	1.848	0.067
World GDP lag4	-0.258	-0.650	0.517
Production lag1	-0.287	-3.701	0.000
Production lag2	-0.258	-3.493	0.001
Production lag3	-0.374	-5.245	0.000
Production lag4	-0.245	-3.333	0.001
Price lag1	-13.522	-3.088	0.002
Price lag2	-2.990	-0.507	0.613
Price lag3	3.053	0.533	0.595
Price lag4	4.787	1.200	0.232
Constant	68.142	3.916	0.000
Trend	-0.184	-5.172	0.000
Dependent variable: Price of copper (logs)			
World GDP lag1	0.031	3.024	0.003
World GDP lag2	0.009	0.756	0.451
World GDP lag3	0.011	1.044	0.299
World GDP lag4	-0.002	-0.171	0.865
Production lag1	-0.004	-2.273	0.025
Production lag2	-0.002	-1.122	0.264
Production lag3	-0.001	-0.597	0.552
Production lag4	-0.001	-0.604	0.547
Price lag1	0.850	8.366	0.000
Price lag2	-0.164	-1.198	0.233
Price lag3	0.063	0.474	0.636
Price lag4	0.086	0.929	0.355
Constant	1.130	2.801	0.006
Trend	-0.002	-2.811	0.006

Notes: I choose a lag length of 4 according to the Akaike IC). Sample range: 1845-2012, t=166. The coefficients for the World War periods are available from the author upon request.

Table 2.2: Estimated coefficients for the copper market.

	World GDP	Production	Price
World GDP	1.533	0.325	0.055
	(6.383)	(0.917)	(0.185)
Production	1.298	4.805	5.488
	(1.602)	(4.295)	(3.930)
Price	0.102	-0.091	0.105
	(1.859)	(-2.990)	(5.100)

Notes: World GDP and production reflect the percentage changes of world GDP and of the annual copper production. Price is the average annual real price of copper in logs. Estimates for the structural version of Model (2.1). Bootstraped standard errors are in brackets. Maximum likelihood estimation, scoring algorithm (see Amisano and Giannini (1992)).

Table 2.3: Estimated contemporaneous impact matrix for the copper market.

	World GDP	Production	Price
World GDP	4.002	0	0
	(2.623)	—	—
Production	1.394	5.496	0
	(0.714)	(3.919)	—
Price	1.744	-0.818	0.633
	(1.785)	(-2.378)	(3.958)

Notes: World GDP and production reflect the percentage changes of world GDP and of the annual copper production. Price is the average annual real price of copper. Estimates for the structural version of Model (2.1). Bootstraped standard errors are in brackets. Maximum likelihood estimation, scoring algorithm (see Amisano and Giannini (1992)).

Table 2.4: Estimated identified long-term impact matrix for the copper market.

	Coefficient	**t-statistic**	**t-probability**
Dependent variable: World GDP (percentage share)			
World GDP lag1	0.265	2.762	0.007
World GDP lag2	0.130	1.289	0.199
Production lag1	0.019	0.665	0.507
Production lag2	0.017	0.649	0.517
Price lag1	-0.466	-0.500	0.618
Price lag2	0.341	0.405	0.686
Constant	1.173	0.522	0.602
Trend	0.011	2.229	0.027
Dependent variable: Lead production (percentage share)			
World GDP lag1	0.958	3.102	0.002
World GDP lag2	-0.457	-1.409	0.161
Production lag1	0.039	0.426	0.670
Production lag2	0.031	0.363	0.717
Price lag1	4.933	1.645	0.102
Price lag2	-4.592	-1.695	0.092
Constant	1.321	0.183	0.855
Trend	-0.013	-0.814	0.417
Dependent variable: Price of lead (logs)			
World GDP lag1	0.031	3.257	0.001
World GDP lag2	-0.021	-2.053	0.042
Production lag1	0.001	0.303	0.763
Production lag2	0.004	1.422	0.157
Price lag1	0.888	9.597	0.000
Price lag2	-0.040	-0.474	0.636
Constant	0.782	3.506	0.001
Trend	-0.001	-1.871	0.063

Notes: The table presents estimated coefficients for the reduced form Model (2.1) with a lag length of 2 (chosen according to the Akaike Information Criterion). Sample range: 1843-2010, t=168. The coefficients for the World War periods are available from the author upon request.

Table 2.5: Estimated coefficients for the lead market.

	World GDP	Production	Price
World GDP	1.644	-0.156	0.127
	(7.052)	(-0.819)	(0.397)
Production	2.664	4.604	-0.344
	(3.192)	(6.399)	(-0.324)
Price	0.060	0.008	0.153
	(1.700)	(0.247)	(6.149)

Notes: World GDP and production reflect the percentage changes of world GDP and of the annual lead production. Price is the average annual real price of lead in logs. Estimates for the structural version of Model (2.1). Bootstraped standard errors are in brackets. Maximum likelihood estimation, scoring Algorithm (see Amisano and Giannini (1992)).

Table 2.6: Estimated contemporaneous impact matrix for the lead market.

	World GDP	Production	Price
World GDP	2.844	0	0
	(0.620)	—	—
Production	4.666	5.028	0
	(1.584)	(0.834)	—
Price	0.732	0.209	1.010
	(0.365)	(0.241)	(0.304)

Notes: World GDP and production reflect the percentage changes of world GDP and of the annual lead production. Price is the average annual real price of lead. Estimates for the structural version of Model (2.1). Bootstrapped standard errors are in brackets. Maximum likelihood estimation, scoring algorithm (see Amisano and Giannini (1992)).

Table 2.7: Estimated identified long-term impact matrix for the lead market.

	Coefficient	**t-statistic**	**t-probability**
Dependent variable: World GDP (percentage share)			
World GDP lag1	0.263	2.840	0.005
World GDP lag2	0.159	1.612	0.109
World GDP lag3	-0.020	-0.249	0.803
Production lag1	0.002	0.128	0.898
Production lag2	-0.008	-0.523	0.602
Production lag3	-0.026	-1.817	0.071
Price lag1	0.428	0.424	0.672
Price lag2	0.533	0.352	0.726
Price lag3	-0.705	-0.736	0.463
Constant	-1.056	-0.442	0.659
Trend	0.011	2.868	0.005
Dependent variable: Tin production (percentage share)			
World GDP lag1	1.664	3.278	0.001
World GDP lag2	0.418	0.773	0.441
World GDP lag3	-1.098	-2.527	0.013
Production lag1	-0.164	-1.961	0.052
Production lag2	-0.141	-1.766	0.080
Production lag3	-0.124	-1.583	0.116
Price lag1	-5.369	-0.971	0.333
Price lag2	15.807	1.906	0.059
Price lag3	-12.616	-2.406	0.017
Constant	20.780	1.588	0.115
Trend	-0.046	-2.115	0.036
Dependent variable: Price of tin (logs)			
World GDP lag1	0.007	0.866	0.388
World GDP lag2	-0.017	-1.930	0.056
World GDP lag3	0.001	0.140	0.889
Production lag1	-0.001	-0.727	0.468
Production lag2	-0.001	-0.733	0.465
Production lag3	-0.001	-0.586	0.559
Price lag1	1.262	14.265	0.000
Price lag2	-0.421	-3.174	0.002
Price lag3	0.098	1.166	0.246
Constant	0.466	2.225	0.028
Trend	0.000	0.316	0.753

Notes: The table presents estimated coefficients for the reduced form Model (2.1) with a lag length of 3 (chosen according to the Akaike Information Criterion). Sample range: 1844-2010, t=167. The coefficients for the World War periods are available from the author upon request.

Table 2.8: Estimated coefficients for the tin market.

	World GDP	Production	Price
World GDP	1.507	0.532	-0.390
	(5.824)	(1.469)	(-0.911)
Production	0.376	8.364	3.322
	(0.317)	(6.501)	(1.294)
Price	0.097	-0.050	0.094
	(2.219)	(-1.444)	(3.575)

Notes: World GDP and production reflect the percentages change of world GDP and of the annual tin production. Price is the average annual real price of tin in logs. Estimates for the structural version of Model (2.1). Bootstrapped standard errors are in brackets. Maximum likelihood estimation, scoring algorithm (see Amisano and Giannini (1992)).

Table 2.9: Estimated contemporaneous impact matrix for the tin market.

	World GDP	Production	Price
World GDP	2.981	0	0
	(3.975)	—	—
Production	0.575	7.589	0
	(0.258)	(4.231)	—
Price	1.141	-1.139	1.525
	(1.137)	(-1.494)	(2.727)

Notes: World GDP and production reflect the percentage changes of world GDP and of the annual tin production. Price is the average annual real price of tin. Estimates for the structural version of Model (2.1). Bootstrapped standard errors are in brackets. Maximum likelihood estimation, scoring algorithm (see Amisano and Giannini (1992)).

Table 2.10: Estimated identified long-term impact matrix for the tin market.

	Coefficient	**t-statistic**	**t-probability**
Dependent variable: World GDP (percentage share)			
World GDP lag1	0.333	3.432	0.001
World GDP lag2	0.151	1.497	0.137
World GDP lag3	-0.017	-0.209	0.835
Production lag1	-0.017	-1.029	0.305
Production lag2	0.024	1.420	0.158
Production lag3	-0.028	-1.776	0.078
Price lag1	0.814	0.964	0.337
Price lag2	-1.911	-1.654	0.100
Price lag3	1.247	1.511	0.133
Constant	-0.115	-0.039	0.969
Trend	0.010	2.067	0.041
Dependent variable: Zinc production (percentage share)			
World GDP lag1	1.285	2.629	0.010
World GDP lag2	-0.077	-0.151	0.880
World GDP lag3	-1.052	-2.532	0.012
Production lag1	-0.085	-0.100	0.319
Production lag2	-0.104	-1.245	0.215
Production lag3	-0.113	-1.455	0.148
Price lag1	-2.860	-0.673	0.502
Price lag2	-2.627	-0.451	0.652
Price lag3	4.647	1.118	0.266
Constant	13.170	0.876	0.383
Trend	-0.036	-1.412	0.160
Dependent variable: Price of zinc (logs)			
World GDP lag1	0.025	2.415	0.017
World GDP lag2	-0.001	-0.098	0.922
World GDP lag3	-0.008	-0.878	0.382
Production lag1	-0.005	-2.555	0.012
Production lag2	0.001	0.472	0.637
Production lag3	-0.001	-0.596	0.552
Price lag1	1.064	11.846	0.000
Price lag2	-0.563	-4.581	0.000
Price lag3	0.337	3.834	0.000
Constant	0.890	2.799	0.006
Trend	-0.001	-1.777	0.078

Notes: The table presents estimated coefficients for the reduced form Model (2.1) with a lag length of 3 (chosen according to the Akaike Information Criterion). Sample range: 1844-2010, t=167. The coefficients for the World War periods are available from the author upon request

Table 2.11: Estimated coefficients for the zinc market.

	World GDP	Production	Price
World GDP	1.622	0.163	-0.142
	(7.054)	(0.860)	(-0.390)
Production	3.447	7.449	0.800
	(3.212)	(4.847)	(0.483)
Price	0.080	-0.014	0.154
	(1.820)	(-0.394)	(5.597)

Notes: World GDP and production reflect the percentage changes of world GDP and of the annual zinc production. Price is the average annual real price of zinc in logs. Estimates for the structural version of Model (2.1). Bootstrapped standard errors are in brackets. Maximum likelihood estimation, scoring algorithm (see Amisano and Giannini (1992)).

Table 2.12: Estimated contemporaneous impact matrix for the zinc market.

	World GDP	Production	Price
World GDP	3.149	0	0
	(3.976)	—	—
Production	2.555	5.888	0
	(1.801)	(5.040)	—
Price	0.731	-0.256	0.952
	(1.749)	(-1.071)	(3.056)

Notes: World GDP and production reflect the percentage changes of world GDP and of the annual zinc production. Price is the average annual real price of zinc. Estimates for the structural version of Model (2.1). Bootstrapped standard errors are in brackets. Maximum likelihood estimation, scoring Aagorithm (see Amisano and Giannini (1992)).

Table 2.13: Estimated identified long-term impact matrix for the zinc market.

A2.4 The case of crude oil: Figures and regression results

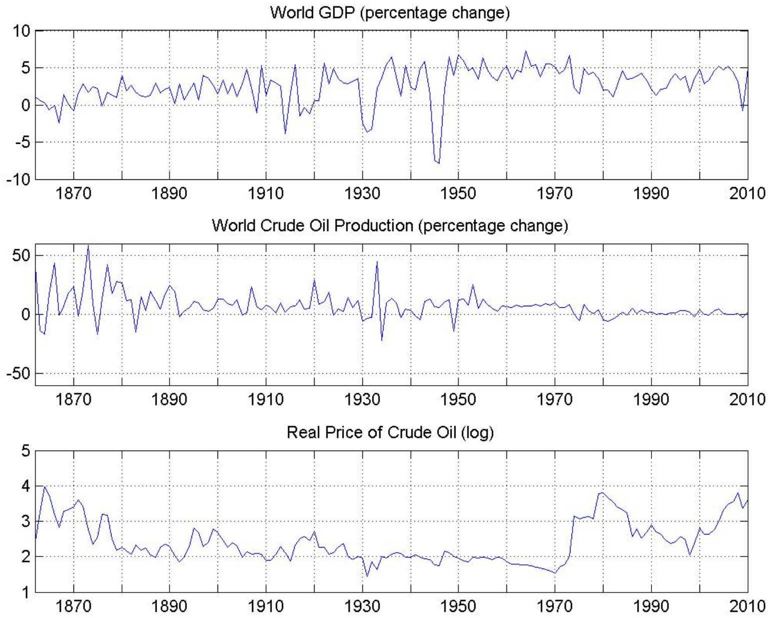
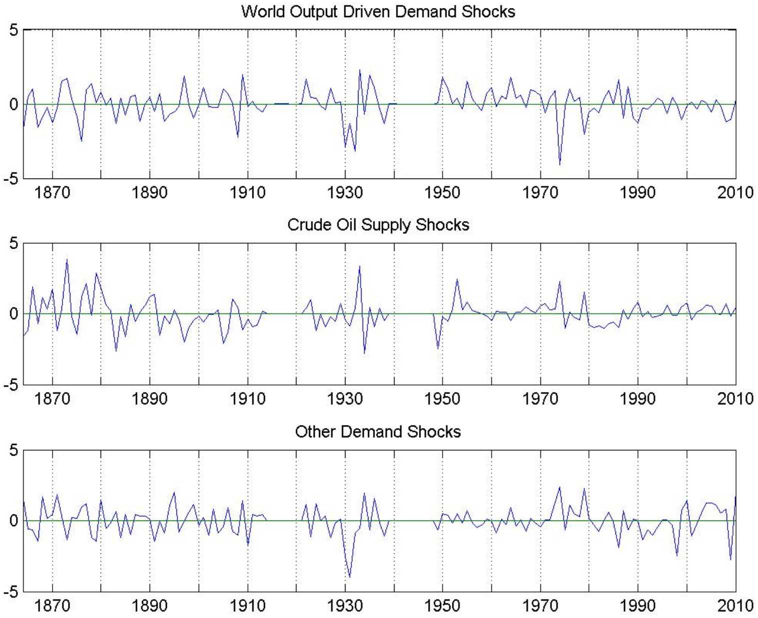
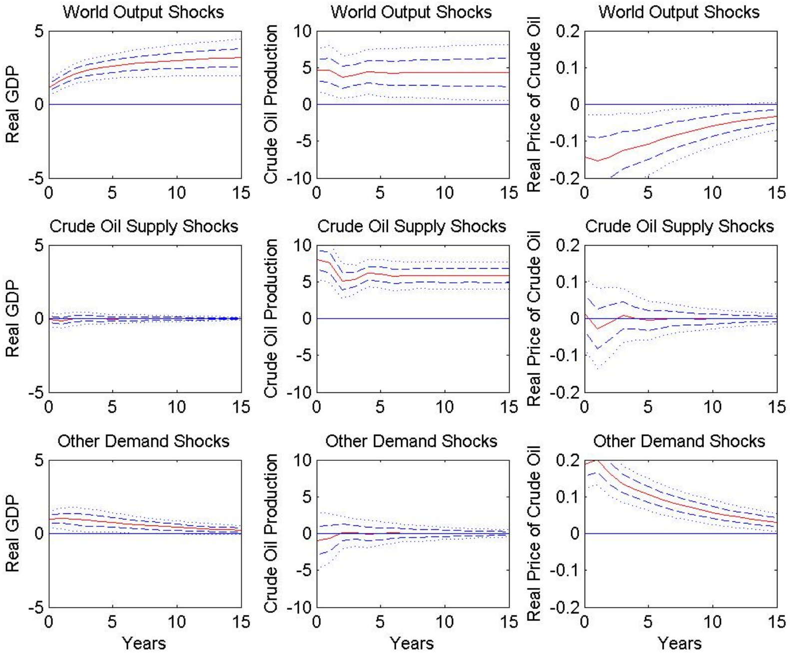


Figure 2.17: Historical evolution of world GDP, world crude oil production, and the real price of oil from 1862 to 2010.



Notes: Structural residuals implied by Model (2.1).

Figure 2.18: Historical evolution of the structural shocks for crude oil.



Notes: Point estimates with one- and two-standard error band based on Model (2.1). I use accumulated impulse response functions for the shocks on world mineral commodity production and world GDP to trace out the effects on the level of these variables.

Figure 2.19: Impulses to one-standard-deviation structural shocks for crude oil.

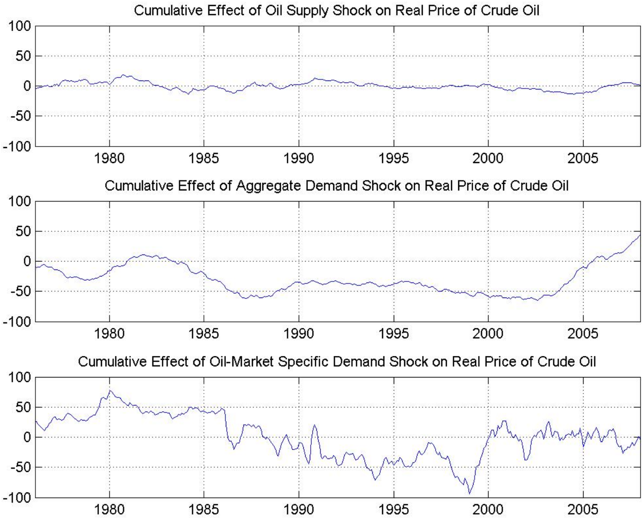
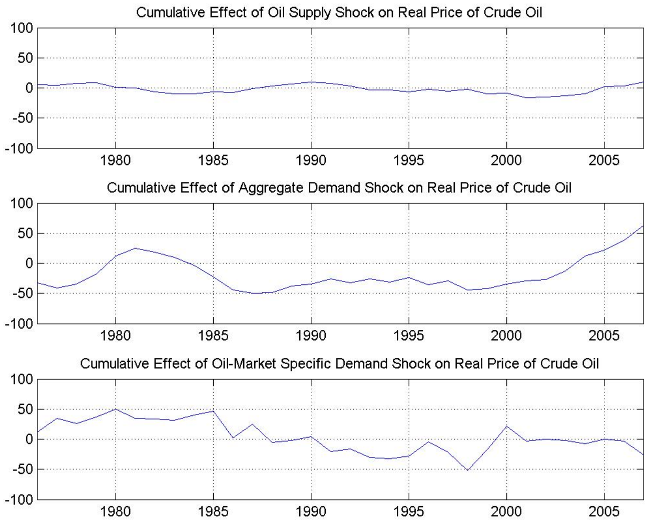


Figure 2.20: Historical decomposition of the real price of crude oil using the original monthly dataset from Kilian (2009).



Notes: The data has been annualized to illustrate that his results are not due to frequency and that his identification strategy produces the same results for annual data.

Figure 2.21: Historical decomposition of the real price of crude oil using an annualised version of the dataset of Kilian (2009).

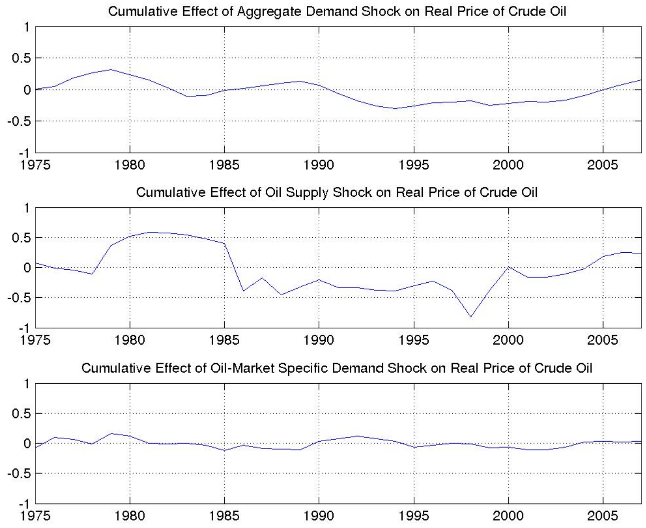


Figure 2.22: Historical decomposition of the real price of crude oil using my dataset and the first identification scheme for the period from 1973 to 2007.

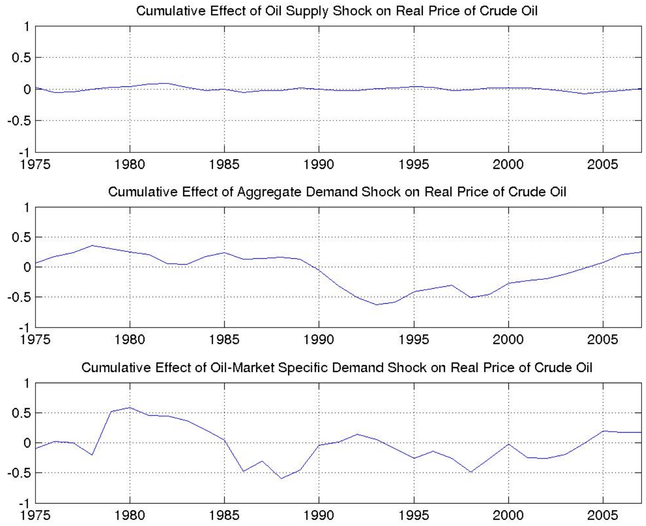
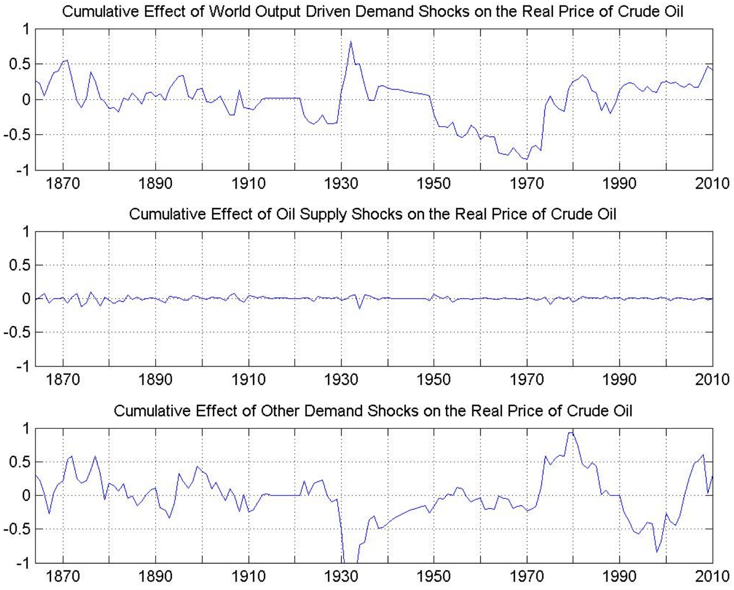


Figure 2.23: Historical decomposition of the real price of crude oil using my dataset and the identification scheme of Kilian (2009) for the period from 1973 to 2007.



Notes: Estimates derived from model (2.1).

Figure 2.24: Historical decomposition of the real price of crude oil.

	Coefficient	**t-statistic**	**t-probability**
Dependent Variable: World GDP (percentage share)			
Variable	Coefficient	t-statistic	t-probability
World GDP lag1	0.317986	3.458524	0.000751
World GDP lag2	0.071221	0.787402	0.432586
Production lag1	-0.007504	-0.497782	0.619541
Production lag2	0.016091	1.200206	0.232404
Price lag1	-1.385274	-2.381678	0.018793
Price lag2	0.820845	1.367192	0.174100
Constant	2.055494	2.562365	0.011623
Trend	0.014000	3.047203	0.002837
Dependent Variable: Crude Oil Production (percentage share)			
World GDP lag1	0.209041	0.365172	0.715620
World GDP lag2	0.431103	0.765509	0.445459
Production lag1	-0.050558	-0.538683	0.591095
Production lag2	-0.311928	-3.736971	0.000286
Price lag1	0.218645	0.060377	0.951955
Price lag2	0.331791	0.088760	0.929420
Constant	17.250599	3.453922	0.000762
Trend	-0.144032	-5.035084	0.000002
Dependent Variable: Price of Crude Oil (logs)			
World GDP lag1	0.010816	0.743631	0.458541
World GDP lag2	-0.016559	-1.157210	0.249466
Production lag1	-0.005225	-2.190927	0.030373
Production lag2	0.002072	0.976797	0.330618
Price lag1	0.992449	10.785610	0.000000
Price lag2	-0.101103	-1.064446	0.289246
Constant	0.267617	2.108760	0.037027
Trend	0.000508	0.698426	0.486251

Notes: World GDP and production reflect the percentage change of world GDP and of the annual crude oil production. Price is the average annual real price of crude oil in logs (CPI deflated). The table presents estimated coefficients for the reduced form Model (2.1) with a lag length of 2 (according to the Akaike Information Criterion). Sample range: 1864-2010, t=147. The coefficients for the annual dummies during the periods 1914-1921 and 1939-1948 are available from the author upon request.

Table 2.14: Estimated coefficients for the crude oil market.

	World GDP	Production	Price
World GDP	1.2153	-0.0732	1.0432
	(4.4925)	(-0.2981)	(2.4170)
Production	4.9795	8.5917	-1.0173
	(3.3926)	(5.5415)	(-0.4712)
Price	-0.1541	0.0162	0.2008
	(-2.1241)	(0.3243)	(4.8525)

Notes: World GDP and production reflect the percentage change of world GDP and of the annual crude oil production. Price is the average annual real price of crude oil. Estimates for the structural version of Model (2.1). Bootstrapped standard errors are in brackets. Maximum likelihood estimation, scoring algorithm (see Amisano and Giannini (1992)).

Table 2.15: Estimated contemporaneous impact matrix for the crude oil market.

	World GDP	Production	Price
World GDP	3.6707	0	0
	(3.4743)	—	—
Production	4.6732	6.2922	0
	(1.7918)	(6.4412)	—
Price	-1.7479	-0.0339	1.8482
	(-1.4078)	(-0.0794)	(2.9159)

Notes: World GDP and production reflect the percentage change of world GDP and of the annual crude oil production. Price is the average annual real price of crude oil. Estimates for the structural version of Model (2.1). Bootstrapped standard errors are in brackets. Maximum likelihood estimation, scoring algorithm (see Amisano and Giannini (1992)).

Table 2.16: Estimated identified long-term impact matrix for the crude oil market.

A2.5 Sensitivity analysis

Comm.	**Model**	**Time**	**Market Place** P	**Deflator**	**Lag length**	**Forecast error variance decomp. (%)**								
						horizon: 1			horizon: 5			horizon: 10		
						Y	**Q**	**P**	**Y**	**Q**	**P**	**Y**	**Q**	**P**
Copper	LR	1841-2010	London	CPI	4(AKI)	35	28	37	60	23	18	65	20	15
Lead	LR	1841-2010	London	CPI	2(AKI)	13	0	87	31	2	68	32	2	66
Tin	LR	1841-2010	London	CPI	3(AKI)	46	12	42	38	21	40	33	23	43
Zinc	LR	1841-2010	London	CPI	3(AKI)	21	1	79	30	4	66	32	4	64
Cr. Oil	LR	1862-2010	Internat.	CPI	2(AKI)	37	0	63	41	1	59	43	0	56

Notes: Y = World GDP, Q = Production, P = Price, LR = Long-run restrictions, CPI = Consumer Price Index, AKI = Akaike Information Criterion, Internat. = International.

Table 2.17: Forecast error variance decomposition for the baseline specification.

Comm.	**Model**	**Time**	**Market Place** P	**Deflator**	**Lag length**	**Forecast error variance decomp. (%)**								
						horizon: 1			horizon: 5			horizon: 10		
						Y	**Q**	**P**	**Y**	**Q**	**P**	**Y**	**Q**	**P**
Copper	SR	1841-2010	London	CPI	4(AKI)	20	4	76	46	2	52	51	2	47
Lead	SR	1841-2010	London	CPI	2(AKI)	15	3	82	26	11	63	26	13	61
Tin	SR	1841-2010	London	CPI	3(AKI)	14	0	85	11	3	86	8	4	88
Zinc	SR	1841-2010	London	CPI	3(AKI)	9	4	86	21	2	77	22	2	76
Cr. Oil	SR	1862-2010	Internat.	CPI	2(AKI)	2	10	89	2	15	83	1	15	83

Notes: Y = World GDP, Q = Production, P = Price, SR = Short-run restrictions, CPI = Consumer Price Index, AKI = Akaike Information Criterion, Internat. = International.

Table 2.18: Forecast error variance decomposition for the baseline specification using the alternative identification scheme.

Comm.	**Model**	**Time**	**Market Place**	**Deflator**	**Lag length**	**Forecast error variance decomp. (%)**								
						horizon: 1			horizon: 5			horizon: 10		
			P			**Y**	**Q**	**P**	**Y**	**Q**	**P**	**Y**	**Q**	**P**
Copper	LR	1841-2010	London	PPI	4(AKI)	23	17	60	46	18	36	54	16	30
Lead	LR	1841-2010	London	PPI	2(AKI)	13	3	84	13	7	80	12	8	81
Tin	LR	1841-2010	London	PPI	3	33	16	51	24	28	48	20	30	50
Zinc	LR	1841-2010	London	PPI	3(AKI)	18	4	77	17	4	79	18	4	77
Cr. Oil	LR	1862-2010	Internat.	PPI	2(AKI)	51	0	49	54	0	46	56	0	44

Notes: Y = World GDP, Q = Production, P = Price, LR = Long-run restrictions, PPI = Producer Price Index, AKI = Akaike Information Criterion, Internat. = International.

Table 2.19: Forecast error variance decomposition for the baseline specification using the producer price index instead of the consumer price index to disinflate prices.

Comm.	**Model**	**Time**	**Market Place** P	**Deflator**	**Lag length**	**Forecast error variance decomp. (%)**								
						horizon: 1			horizon: 5			horizon: 10		
						Y	**Q**	**P**	**Y**	**Q**	**P**	**Y**	**Q**	**P**
Copper	LR	1900-2010	London	CPI	4	48	24	27	70	17	13	76	14	10
Lead	LR	1900-2010	London	CPI	2	23	0	77	45	3	51	45	4	50
Tin	LR	1900-2010	London	CPI	3	49	29	22	36	41	22	30	43	27
Zinc	LR	1900-2010	London	CPI	3	39	9	52	49	12	39	50	12	38
Cr. Oil	LR	1900-2010	Int.	CPI	2	49	33	18	43	34	23	43	34	23
Copper	LR	1925-2010	London	CPI	4	38	5	57	71	5	24	77	4	19
Lead	LR	1925-2010	London	CPI	2	29	7	64	58	8	34	57	9	34
Tin	LR	1925-2010	London	CPI	3	67	22	11	52	33	15	33	34	22
Zinc	LR	1925-2010	London	CPI	3	35	4	61	53	12	36	57	11	32
Cr. Oil	LR	1925-2010	Internat.	CPI	2	45	40	14	38	42	20	40	20	20

Notes: Y = World GDP, Q = Production, P = Price, LR = Long-run restrictions, CPI = Consumer Price Index, Internat. = International.

Table 2.20: Forecast error variance decomposition for the baseline specification over the periods from 1900 to 2010 and from 1925 to 2010.

Comm.	**Model**	**Time**	**Market Place** P	**Deflator**	**Lag length**	**Forecast error variance decomp. (%)**								
						horizon: 1			horizon: 5			horizon: 10		
						Y	**Q**	**P**	**Y**	**Q**	**P**	**Y**	**Q**	**P**
Copper	LR	1850-2010	New York	CPI	4(AKI)	3	38	59	10	50	40	12	47	38
Lead	LR	1841-2010	New York	CPI	2	5	0	95	21	1	78	23	1	75
Tin	LR	1841-2010	New York	CPI	3	15	24	61	20	35	44	18	37	44
Zinc	LR	1872-2010	New York	CPI	3	1	5	94	4	13	83	6	13	81
Cr. Oil	LR	1862-2010	Internat.	CPI	2(AKI)	51	0	49	54	0	46	56	0	44

Notes: Y = World GDP, Q = Production, P = Price, LR = Long-run restrictions, CPI = Consumer Price Index, AKI = Akaike Information Criterion, Internat. = International.

Table 2.21: Forecast error variance decomposition for the baseline specification using New York instead of London prices.

Chapter 3

Industrialization and the demand for mineral commodities

3.1 Introduction

For business leaders and politicians facing rapid industrialization in China and elsewhere, understanding the nexus of industrialization - the process of moving production from primary to manufacturing sector (Black, Hashimzade, and Myles, 2009) - and the derived demand for mineral commodities is imperative. How does demand respond to changes in manufacturing output? What is the response to a change in price? What is the role of structural and technological change in shaping these relationships?

These questions have important implications both from a theoretical and a policy perspective. Demand shocks are a key driver of mineral commodity prices (see Kilian (2009) and Chapter 2), which have pronounced macroeconomic implications for both developing and developed countries (see Bernanke, 2006; IMF, 2012b). The response of demand to a change in manufacturing output determines the contribution of demand shocks to the fluctuations of prices (Slade, 1991). The price inelasticity of demand is a key parameter in models of commodity price speculation, as a low price elasticity enables speculation on these markets (see Hamilton, 2009a; Kilian and Murphy, 2012). Finally, Acemoglu et al. (2012) claim in their theoretical analyses of resource wars that the price elasticity of demand is critical in shaping war incentives.

There is a rich body of empirical studies on the long-run and short-run elasticities of demand of mineral commodities with respect to economic activity and price (see Hamilton, 2009b; Pei and Tilton, 1999; Kilian and Murphy, 2012, for surveys of the current literature). This literature mainly focusses on energy and only provides empirical evidence for relatively short periods. For the most part, the literature does not capture the effects of long-term structural changes.

Examining the long-run manufacturing output elasticity of demand reveals how the intensity of use of a mineral commodity develops over the course of industrialization. The intensity of use is defined as the use of a certain material per unit of manufacturing output (Malenbaum, 1978; Tilton, 1990). If the estimated long-run manufacturing output elasticity of demand is higher than one, the use of the mineral commodity increases faster than manufacturing output. An estimated long-run manufacturing output elasticity of demand equal to one implies no change in the intensity of use over time. An estimate below one means a decreasing intensity of use over time.

There are four underlying factors that drive the derived demand of the manufacturing sector. First, technological change causes changes in the production cost of mineral commodities. This might drive its relative price up or down and hence promote substitution. For example, the invention of the electrolytic method lowered the price of aluminum and it substituted tinplate in the production of beverage cans (Chandler, 1990). Second, technological change leads to a more efficient use of mineral commodities, e.g., the invention of new aluminum alloys has made aluminum beverage cans far thinner than they used to be (Pei and Tilton, 1999). These two types of technological change alter "the material composition of goods"(Pei and Tilton, 1999, p. 90).

The next two factors affect the product composition of manufacturing output (Pei and Tilton, 1999, p. 90). Technological change might lead to the invention of new products (Pei and Tilton, 1999), e.g., the invention of airplanes has increased the demand for aluminum. Finally, consumer preferences change over the course of economic development altering the mix of products the manufacturing sector produces. For example, at a low per capita manufacturing output the construction of infrastructure will lead to a product composition that is relatively steel intensive. At a higher per capita manufacturing output, consumers rather demand high tech and consumption goods that are relatively aluminum intensive.

This paper is the first to provide empirical evidence on the long-run elasticities of demand with respect to manufacturing output and prices for several mineral commodities based on a long panel. To cover the main periods of industrialization, I employ a newly constructed data set for twelve major economies, which for some parts spans back to 1840. I focus on the demand for aluminum, copper, lead, tin, and zinc, because they have been used broadly throughout history and have been traded on integrated world markets for much of that time making data available.[1]

In contrast to the aforementioned literature, I use manufacturing output and not GDP as the explanatory variable. This has two advantages. First, the demand for mineral commodities is a derived demand. It is only used as an input for the manufacturing sector. Using manufacturing output allows me to control for technological change and changing consumer preferences that cause sectorial shifts in the economy, e.g., the shift to the service sector. Second, if a country produces the mineral commodity domestically, regressing GDP on the quantity used in the economy leads to the problem of reverse causality as mining is also included in GDP.

My estimation strategy relies on an extension of the partial adjustment model, as it is the standard approach in empirical energy demand analysis. This is done in order to ensure the comparability of results with previous studies. I regress derived demand on manufacturing output, the relative price of the respective mineral commodity, and lagged values of demand. I follow Pesaran, Smith, and Akiyama (1998) and Pesaran, Shin, and Smith (1999) in accounting for differences in the economic structures across these countries by relaxing the assumption of equal short-run coefficients.

I attempt to control for the effects of the three types of technological change and the consumer preferences in a stepwise manner. The relative price of the respective mineral commodity basically accomodates technological change that drives substitution. I introduce a common linear time trend and finally time fixed effects following Pesaran, Smith, and Akiyama (1998) to account for technological changes that lead to new products and resource efficiency. Overall, it allows me to take advantage of the

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[1] Aluminum is only widely used since the end of the 19th century.

panel structure of the data, as it makes it possible to control for ommitted common technological trends and spillover effects (Pesaran, Smith, and Akiyama, 1998). This leaves those effects that are time independent and country specific and hence reflect changes in consumer preferences to be captured by per capita manufacturing output. I regard the comparison between the three specifications also as a misspecification test for the importance of omitted common trends and shocks in technological change (Pesaran, Smith, and Akiyama, 1998).

Several findings emerge. First, the estimated long-run manufacturing output elasticities of demand vary significantly between the five examined mineral commodities. A one percent increase in manufacturing output leads to an approximately 1.5 percent increase in the demand for aluminum. This means that its demand increases more than proportional to manufacturing output over time. The estimated manufacturing output elasticity of copper demand is close to one, which implies a stable intensity of use over time. The estimates are far below one for lead, tin, and zinc demand. This causes the intensity of use of these mineral commodities to decline over time.

The estimated long-run price elasticities of demand are rather low for the examined mineral commodities. Again, there are pronounced differences across the examined mineral commodities. While it is about -0.7 and -0.8 in the case of aluminum demand, it is about -0.4 for copper demand, and below or equal to about -0.2 for lead, tin, and zinc demand. This shows that with the exception of aluminum and copper, the aforementioned mineral commodities are rather essential to manufacturing output as the processing industry change its use slowly in response to price.

My estimation results show that the relationship between per capita manufacturing output, relative prices, and the per capita demand for mineral commodities is rather driven by technological change and consumer preferences that are country specific. Effects that are common to all countries over time play only a role in decreasing aluminum and lead demand over time. The model for tin seems to be misspecified.

I find strong evidence for the existence of long-run relationships in all regressions. The estimated speed of demand adjustment is rather slow for all commodities and it takes more than ten years in the cases of lead, tin, and zinc to revert back to equilibrium. This is reasonable, given that adjustments in manufacturing capital are rather slow and that inventories play an important role in these markets. Overall, my empirical results are plausible given narrative evidence on the use of the mineral commodities over time.

The estimated long-run manufacturing output elasticities of the demand for all examined mineral commodities except tin are higher or equal to the income elasticity of oil demand (which is 0.55 according to Gately and Huntington (2002) for twenty-five OECD countries over 1971 to 1997). The ones for copper and aluminum are also higher than estimates of the income elasticity of aggregate energy demand (0.8 according to Adeyemi and Hunt (2007) for fifteen OECD countries from 1962 to 2003).

The estimated manufacturing output elasticities of demand suggest that the industrialization in China will cause aluminum to increase relative to manufacturing output while copper will grow in proportion to manufacturing output. The demand for lead, tin, and zinc decreases relative to manufacturing output in the long-term. My results are important for developing long-term production strategies and allowing for smooth markets, as mining firms face high upfront costs and long lead times to open up new mines. Moreover, countries dependent on the exports of their mineral commodities may better judge the long-term perspective of the respective markets and adjust their macroeconomic and fiscal policies accordingly. Finally, my results suggest that demand is a larger contributor to the volatility of aluminum and copper prices than to that of lead, tin, zinc, and energy since manufacturing output fluctuations lead to larger fluctuations in the cases of aluminum and copper demand (see Slade, 1991).

The estimates of the price elasticity are in contrast to the literature on oil and energy, where long-run price elasticity is estimated to be significant (-1.25 for energy demand according to Heal and Chichilnisky (1991) and -0.64 for oil demand in OECD countries according to Gately and Huntington (2002)). These results are important, because according to models of commodity price speculation a low price elasticity of demand makes these markets prone to speculation (see Hamilton, 2009a; Kilian and Murphy, 2012). Moreover, the low price elasticity is a key parameter in shaping the incentives of war over resources as Acemoglu et al. (2012) claims.

The paper is structured as follows. Section 3.2 introduces the data set. Section

3.3 introduces the econometric model. Section 3.4 presents the estimation results. Section 3.5 describes robustness checks while Section 3.6 draws conclusions.

3.2 A new data set

Numerous authors have estimated the income and price elasticities of demand for crude oil, gasoline, aggregate energy, and other mineral commodities using data sets for the time after the Second World War (see Pesaran, Smith, and Akiyama, 1998; Hamilton, 2009b; Pei and Tilton, 1999, for surveys of the current literature). These studies do not include major periods of industrialization for currently industrialized countries, making comparison and inference with respect to emerging economies rather difficult. In this study, I extend the data set to a far longer time horizon.[2] The examined mineral commodities are aluminum, copper, lead, tin, and zinc. My data set consists of a sample of twelve industrialized countries, namely Belgium, Finland, France, Germany, Italy, Japan, South-Korea, the Netherlands, Spain, Sweden, the United Kingdom (U.K.), and the United States (U.S.), from 1840 to 2010. I assemble country-by-country annual data regarding demand, mineral commodity prices, and value added by manufacturing.

The demand for a mineral commodity, my dependent variable, is derived from the output of the manufacturing sector. The demand data captures those quantities of mineral commodities which are finished but unwrought (e.g., metal in primary shapes, such as cathodes and bars), and which manufacturers use at the first stage of production (e.g., brass mills, foundries). This is also the stage at which mineral commodities are usually traded, and it is the usual data employed for measuring the use of mineral commodities (Tilton, 1990; U.S. Geological Survey, 2011a).

To proxy demand, I collect data on the use of the respective mineral commodities. From the end of the First World War to today, I employ data from the BGR, 2012b. It is mainly based on direct surveys of the respective manufacturing industries. From 1840 to 1918, I compute the apparent usage of the respective mineral commodities from production, as well as from import and export data from several sources (see Table 3.7). The data is plotted in Figures 3.2 through 3.6 in the Appendix.

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[2] Please see also the chapter on data sources and description.

Three aspects of the construction of the demand data might cause potential measurement errors. As demand is also regressed on lagged values of itself, it also constitutes an independent variable in the regressions. First, the BGR, 2012b has rounded the data. This might lead to slightly larger standard deviations. Second, stocks are not included in the computation of usage before World War I, due to a lack of data. Third, there is no clear unanimous definition or accounting for the use of mineral commodities across the differing countries and periods. These latter two measurement errors are rather stochastic in their nature and the coefficients might be underestimated to a certain extent.

I employ per capita value added in the manufacturing sector as explanatory variable. In contrast to energy, mineral commodities are only used as an input for the processing of partially finished and finished goods in the manufacturing sector, which are then used in construction or mining equipment. Mineral commodities are not directly purchased by consumers. Manufacturing data provides hence the best proxy for the process of industrialization.

Variable	Mean	Std. Dev.	Min	Max	N
P.c. alu. demand^a	.0068	.0078	.0000	.0490	1094
P.c. copper demand^a	.0056	.0063	.0000	.0402	1401
P.c. lead demand^a	.0032	.0018	.0001	.0079	1189
P.c. tin demand^a	.0002	.0001	.0000	.0008	1292
P.c. use of zink^a	.0038	.0045	.0000	.0384	1391
P.c. manuf. prod.^{b}	1807	1273	83	6565	1414
Real price of alu.^{c}	1046	5333	.77	140411	1288
Real price of copper^c	602	1330	0.92	8358	1381
Real price of lead^c	180	392	.28	2633	1376
Real price of tin^c	1856	4155	2.53	29042	1368
Real price of zinc^c	238	518	.47	3798	1364

Notes: P.c. is the abbreviation for per capita, ^{a}mt/person, ^{b}GK-\$, ^{c}local currency. Please find summary statistics including between and within statistics in the Appendix.

Table 3.1: Summary statistics.

I collect national account data from several national and international sources. To obtain a comparable measure of the value added by the manufacturing sector across countries, I compute the share of manufacturing in GDP from the data. I then multiply these percentage shares with GDP data in constant international Geary-Khamis Dollar from the seminal Maddison (2010) data set. The international Geary-Khamis

Dollar is a hypothetical unit of currency that allows for international comparison of national accounts across countries and time periods. It relies on purchasing power parity converters and is deflated with the base year 1990.

All historical national account data is based on later reconstructions and measurement errors are a potential problem. To the extent that measurement errors are stochastic, estimates will be biased towards zero and underestimate the true value. There might also be systematic measurement errors, whose biases are hard to judge, as I have not created the individual country data sets by myself. However, I believe it is still constructive to investigate this data over the long-term horizon, given that it is the best available data, but it is necessary to interpret results carefully.

I use population data from Maddison (2010) to compute the per capita value added by manufacturing and per capita use of the respective mineral commodities.

I assemble historical price data for the U.S., U.K., and Germany from several sources. Unfortunately, there are no price data series available for the other countries. As the London Metal Exchange is the most important metal exchange in the world (Slade, 1991) and sets the world market price, I derive proxies for the national prices of the other countries by using historical exchange rates from standard sources such as Bordo (2001), Officer (2006, 2011), and Denzel (2010). This approach neglects some price differentials due to transport costs. These appear at the price level and decrease gradually over the time period. Finally, to compute real prices for each country, I have collected producer price indices from Mitchell (2003a,b, 1998), the IMF, and national sources.

3.3 Estimating manufacturing output and price elasticity of demand

My estimation strategy relies on an extension of the partial adjustment model, which is the standard approach in empirical energy demand analysis (Adeyemi and Hunt, 2007). Pesaran, Smith, and Akiyama (1998) derive a theory-consistent dynamic industrial energy demand function with the share of energy costs in all factor inputs as the dependent variable by solving a multivariate cost of adjustment optimization

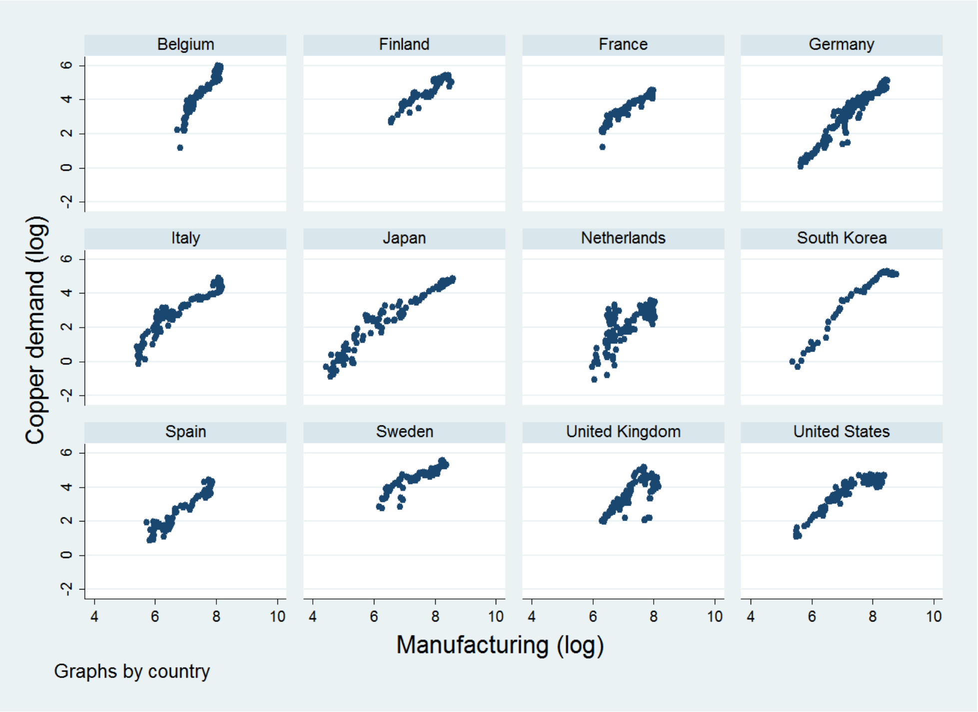

Figure 3.1: Scatter plot of per capita value added by manufacturing and per capita copper demand.

problem. However, they find that the resultant econometric model fails functional form tests. They weight theoretical consistency and statistical adequacy and decide to pursue estimations with the standard log linear partial adjustment model. I follow the approach by Pesaran, Smith, and Akiyama (1998) and Pesaran, Shin, and Smith (1999) in the rest of the my study.

I set up an autoregressive distributed lag model (ARDL)(p, q, r) of a log linear demand function, where p, q, and r notify the number of lags included of the three explanatory variables:

$$c_{i,t} = \sum_{j=1}^{p} \lambda_{i,j} c_{i,t-j} + \sum_{l=0}^{q} \delta_{i,l} y_{i,t-l} + \sum_{m=0}^{r} \gamma_{i,m} p_{i,t-m} + \mu_i + \epsilon_{it} \ . \qquad (3.1)$$

I explain the demand for mineral commodities $c_{i,t}$ (measured in metric tons per capita) of country i at time t by real per capita value added in the manufacturing sector $y_{i,t}$, by the real price of the respective mineral commodity $p_{i,t}$, and by its own lagged values. To capture proportional effects, I employ natural logs to all variables. $\lambda_{i,j}$, $\delta_{i,l}$, and $\gamma_{i,m}$ are the respective coefficients. μ_i represents country fixed effects, which capture omitted country-specific variables that are time independent. For example, a strong domestic copper mining industry might cause a generally higher level of copper demand in a country as downstream manufacturing specializes in processing copper.

Reparametrizing Equation 3.1, I obtain the error correction form

$$\begin{aligned}\Delta c_{i,t} &= \Phi_i(c_{i,t-1} - \theta_{0,i} - \theta_{1,i} y_{i,t} - \theta_{2,i} p_{i,t}) \\ &\quad + \sum_{j=1}^{p-1} \lambda^*_{i,j} \Delta c_{i,t-j} + \sum_{l=0}^{q-1} \delta^*_{i,l} \Delta y_{i,t-l} + \sum_{m=0}^{r-1} \gamma^*_{i,m} \Delta p_{i,t-m} + \epsilon_{it} \ ,\end{aligned} \tag{3.2}$$

where the vector θ_i captures the long-run relationship between the variables. $\theta_{1,i}$ is the long-run elasticity of demand with respect to value added by the manufacturing sector and $\theta_{2,i}$ represents the long-run elasticity of demand with respect to price. Φ_i denotes the speed of adjustment towards the long-run equilibrium.

I use the pooled mean group (PMG) estimator proposed by Pesaran, Smith, and Akiyama (1998) and Pesaran, Shin, and Smith (1999) to accommodate the heterogeneous dynamic of the demand functions across countries. Different economic structures across countries may affect the strength and speed at which manufacturing output and price affect the demand for mineral commodities in the short-run. To account for this heterogeneity, the PMG estimator allows the short-run effects to vary across countries. It only imposes homogeneity of the coefficients for the long-run effects.

My econometric model is potentially subject to the well-known identification problem in estimating energy demand elasticity. There is the problem of reverse causality running from the demand variable to the price variable. The demand curve will only be identified, if national prices track closely international prices and/or supply is highly elastic (Pesaran, Smith, and Akiyama, 1998). In my study, domestic prices follow - partly by construction - international prices as these markets have been fairly well integrated at the global level (see Chapter 2.3). At the same time, the respective shares of the U.S. and the U.K. in world consumption of the mineral commodities in this study were more than forty percent respectively during different sub-periods of my sample (Stürmer and von Hagen, 2012b). It is therefore likely that the change in demand in one of these two countries affected world prices. However, it is possible that it impacted prices only in the short-run as the supply of mineral commodities is highly elastic in the long-run according to Radetzki (2008) and others (see also the theoretical argument in Chapter 1). Chapter 2 also provides empirical evidence on this question, as it examines the effect of unexpected changes in world output on price. I find that such a shock affects the price of the different mineral commodities significantly between five and ten years of time. This suggest that supply is inelastic in the short- and medium-run. As I only examine long-run elasticities, I believe it is plausible to make the identifying assumption for the rest of the paper that the long-run supply is elastic and that a single country did not cause long-term price changes. However, I discuss alternative estimation strategies that do not depend on this assumption in the conclusion.

By choosing manufacturing output as an explanatory variable, I accomodate an identification problem often overlooked in studies of energy demand. Most of these studies use GDP or industrial output as explanatory variables. This can potentially cause reverse causality from demand to GPD or industrial output, if the domestic extractive sector produces the mineral commodity. The reason is that the extractive sector is part of GDP and industrial production, while it is not included in manufacturing output. Choosing manufacturing output reduces this potential identification problem.

Manufacturing output as an explanatory variable also allows controlling for the effects of structural change in the composition of total GDP on the demand for mineral commodities, e.g., the shift to the service sector, as described by Malenbaum (1978), Tilton (1990), Stürmer and von Hagen (2012b), and others. Furthermore, I control for the effect of population growth by using per capita manufacturing output as well as per capita demand of each mineral commodity. Overall, the scatter plots in Figure 3.1 for copper and in Figures 3.13 to 3.16 in the Appendix illustrate that the use of manufacturing data and controlling for population growth leads to an approximately linear log-log relationship, particularly in the cases of aluminum, copper, and zinc.

In my benchmark specification, the pooling of long-run coefficients shows that there is commonality across countries in the way manufacturing output and prices affect the demand for mineral commodities. In my benchmark specification the relative price of the respective mineral commodity partly controls to some extent for technological change that drives substitution over time. The other factors are implicitly included in the manufacturing output elasticity.

Following Pesaran, Smith, and Akiyama (1998), I add a common linear time trend and time fixed effects to my benchmark specification in a stepwise manner. I investigate whether there is a common linear trend or common shocks across countries, which reflect technological change in resource savings technology and in new products as well as changes in consumer preferences. This allows me to take advantage of the panel structure of the data, as it makes it possible to control for ommitted common technological trends and spillover effects (Pesaran, Smith, and Akiyama, 1998). However, time fixed effects also include other effects than technological change, e.g., the effect of the two World Wars on the demand for mineral commodities. I see the comparison between the three specifications also as a misspecification test, for the importance of ommitted common trends and shocks in technological change (Pesaran, Smith, and Akiyama, 1998).

I model the time fixed effects by expressing all variables as deviations from their respective cross-sectional means in each period in line with Pesaran, Shin, and Smith (1999). Such a procedure reduces the common time specific effects and also makes PMG estimates consistent. PMG estimation assumes that regression residuals are independent across countries. Non-zero error co-variances may arise due to the omission of these common effects (Pesaran, Shin, and Smith, 1999).

The disadvantage of including time fixed effects is that they also control for changes in the world market price, leaving only those price changes in the regression that are due to changes in inflation and exchange rates. If market participants assume that these nominal shocks exhibit no long-term impact on prices, the estimated price elasticities will be small and/or statistically insignificant. Moreover, besides technological change in resource efficiency and in the product composition of manufacturing output, they capture also technological change leading to substitution.

The ARDL specification makes no unit root pretesting of the variables necessary. Pesaran and Smith (1995) and Pesaran (1997) show that the method is valid whether or not the variables follow a unit root process or not. This is based on the assumptions that there is in fact a long-run relationship, that regressors are strictly exogenous, and that there is no serial correlation in the residuals. The existence of a long-run relationship requires the adjustment coefficient to fulfil $-2 < \Phi_i < 0$ (Loayza and Rancière, 2006).

Determining the lag order by information criteria on a country-by-country basis, reveals significant differences across countries. However, to make regression results for the short-run and long-run parameters comparable, I impose a common lag structure across countries. My benchmark model is an ARDL(4,4,2) model, which means that I include four lags of mineral commodity demand and of manufacturing output and two lags of mineral commodity prices respectively in Model 3.2. I choose to use a comparatively long lag structure to allow for rich dynamics and to account for possible serial correlation in the data.

I make use of unbalanced panel data for each of the five mineral commodities. The time dimension is relatively large, while the cross-sectional dimension is rather small with the number of countries $N = 12$, as Table 3.7 in the Appendix shows. The incidental parameter problem (Nickell, 1981), which affects dynamic panel data models with small T and large N, is therefore not an issue. The common long-run coefficients of θ_i from the PMG estimator are consistent as long as $T \to \infty$, even if N is small (Pesaran, Shin, and Smith, 1999).

I check the robustness of my results with respect to a different choice of lag lengths and the use of other estimators, which impose full heterogeneity and full homogeneity across the coefficients. I present estimation results for ARDL(1,1,1) and ARDL(3,3,3) of Model 3.2. Furthermore, I employ the mean group (MG) and the standard dynamic fixed effects (DFE) estimators as robustness checks. The PMG estimator stands between these two estimators with respect to the homogeneity that it imposes. On the one hand, the MG estimator proposed by Pesaran and Smith (1995) derives the full panel estimates of θ, Φ, δ, and γ by simply averaging the individual country coefficients θ_i, Φ_i, δ_i, and γ_i. It imposes no homogeneity restrictions on long-run or short-run restrictions. On the other hand, the DFE estimator restricts the long-run and short-run coefficients as well as the adjustment coefficient making them equal across the range of countries. I make use of a standard Hausman (1978) test, as proposed by Pesaran, Shin, and Smith (1999), to examine whether or not the long-run elasticity is in fact equal across the countries. If the null hypothesis of equality is not rejected, the PMG estimator is superior to the MG estimator as it is both consistent and efficient in this case, while the MG estimator is only consistent.

3.4 Estimation results

I present estimates of the three specifications for each of the examined mineral commodities: the first specification is the benchmark model in Equation 3.2 that I estimated with a pooled mean group estimator that imposes homogeneity on the long-run coefficients. In the second specification, I add a linear time trend to accomodate for common technological change. In the third specification, I make use of time fixed effects to control for common shocks from technological change and other factors such as the two World Wars.

I find pronounced differences in the estimated long-run manufacturing output elasticities of demand across the five examined mineral commodities. Aluminum has a high estimated long-run manufacturing output elasticity of demand, while lead has the lowest. The estimated long-run price elasticities of demand are inelastic for all examined mineral commodities. Changes in prices have either a small impact or no impact on demand.

My results for the estimated long-run manufacturing output elasticity of demand are relatively robust across the three specifications for aluminum, copper, lead, and zinc. The estimation results for the price elasticites of demand are only robust to the second specification. This is as expected as the time fixed effects in the third specification take out the price effects due to changes in the world market price. The common linear trend is statistically significant in the regressions for aluminum and lead. The empirical results are plausible given narrative evidence on the application of the different mineral commodities across time.

Finally, I find evidence for the existence of long-run relationships in all regressions. The estimated speed of demand adjustment is rather slow for all commodities and it takes more than 10 years to revert back to equilibrium. This is reasonable, given that adjustments in manufacturing capital are rather slow and that inventories play an important role in these markets.

3.4.1 Aluminum

I find a relatively high estimate for the long-run manufacturing output elasticity of aluminum demand. A one percent increase in manufacturing output leads to a more than 1.5 percent increase in aluminum demand. Including a linear time trend, increases the estimated elasticity to about 1.8. This means that the demand for aluminum increases more than proportional to manufacturing output and hence the material intensity of use in the manufacturing sector increases over the course of industrialization. Aluminum is mainly used for the production of high technology goods such as airplanes, electronics, or machinery, and for the packaging of consumer goods (Stürmer and von Hagen, 2012b; Krebs, 2006). It is plausible that changing consumer preferences increase the demand for aluminum in manufacturing production over the course of industrialization. The large estimates for the manufacturing output elasticity of demand imply that aluminum demand fluctuates far more strongly than manufacturing output. As a consequence, prices will be strongly driven by these large demand shocks.

	1	2	3
Time fixed effects	No	No	Yes
Manufacturing (log)	1.551***	1.759***	1.518***
	(0.092)	(0.173)	(0.073)
Aluminum price (log)	-0.706***	-0.883***	-0.836***
	(0.184)	(0.221)	(0.236)
Constant	-0.056	1.411***	0.054
	(0.059)	(0.421)	(0.083)
Linear trend		-0.012*	
		(0.007)	
Adjustment coefficient	-0.117***	-0.113***	-0.142***
	(0.023)	(0.023)	(0.031)
Observations	973	973	973
Log likelihood	404.4	405.2	432.4

Notes: The table shows results from the pooled mean group (PMG) estimations of the preferred ARDL(4,4,2) model. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 3.2: Estimates of the long-run manufacturing output and price elasticities of aluminum demand.

The estimated long-run price elasticity of aluminum demand is significant and ranges between -0.7 and about -0.8 across the three specifications. This is a low estimate of the long-run price elasticity in comparison to manufacturing goods. Compared to the other examined mineral commodities, the estimated long-run price elasticity of aluminum demand is by far the largest. This is in line with the fact that aluminum has substituted for many different materials such as composites, glass, paper, plastics, copper, and steel in a wide range of appliances in manufacturing production over the course of history (Radetzki, 2008; Krebs, 2006). Aluminum is in wide use since the end of the 19th century as production costs have decreased dramatically due to the invention of the electrolysis by Charles Martin Hall in 1886 (Chandler, 1990).

My regression results provide evidence for a negative linear time trend at a statistical significance of ten percent. This might reflect that there is a common technological trend across countries towards more resource efficiency in the use of aluminum over time. It is reassuring that imposing common time fixed effects do not change the results. I find evidence for the existence of long-term relationships as the coefficients of adjustment are statistically significant and negative in all specifications. The estimates suggest a speeds of convergence to equilibrium of about fourteen percent per year for aluminum.

3.4.2 Copper

Copper is very versatil in its uses in human history (Krebs, 2006). The manufacturing sector employs copper in the production of a broad variety of products in electronics, construction, transportation, and machinery (Krebs, 2006; Stürmer and von Hagen, 2012b).

The estimates for copper yield a point elasticity of demand to manufacturing output of about one across the three specifications. The demand for copper increases approximately in proportion to manufacturing output. This is plausible as copper is used in many different applications (Krebs, 2006). In the past, it was important in the production of hardware and cooking utensils in the form of alloys such as brass and bronze. It has been and is still essential in construction, roofing, and plumbing (Krebs, 2006). As an excellent conductor of electricity it has become more and more important in the use of technological goods and electronics (see Radetzki, 2009; Mardones, Silva, and Martinez, 1985). The estimated elasticity of demand with respect to manufacturing output is quite large for copper, compared to lead, tin, and zinc. This helps to explain why copper shows the strongest effect of "world output-driven demand shock" on the price compared to lead, tin, and zinc as I find in Chapter 2.

	1	2	3
Time fixed effects	No	No	Yes
Manufacturing (log)	0.914***	1.104***	1.128***
	(0.061)	(0.145)	(0.067)
Copper price (log)	-0.400***	-0.453***	-0.009
	(0.093)	(0.095)	(0.049)
Constant	-0.161***	0.474***	0.010
	(0.052)	(0.182)	(0.030)
Linear trend		-0.005	
		(0.004)	
Adjustment coefficient	-0.132***	-0.131***	-0.180***
	(0.028)	(0.028)	(0.057
Observations	1,206	1,206	1,206
Log likelihood	502.3	502.8	434.2

Notes: The table shows results from the pooled mean group (PMG) estimations of the preferred ARDL(4,4,2) model. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 3.3: Estimates of the long-run manufacturing output and price elasticities of copper demand.

The estimated long-run price elasticity of demand of copper is rather low with a point estimate of about -0.4 in the the first and second specification. This shows that copper is only moderately substitutable in its major applications. On the one hand, aluminum and plastics have been substituted for it, especially in building materials. On the other hand, its substitutabiliy is very low in applications as a conductor of electricity (see Krebs, 2006).

Including time fixed effects leads to a statistically insignificant estimated long-run price elasticity. As time fixed effects control for changes in the world prices, they only leave those price changes in the regression that are due to changes in inflation and exchange rates. If market participants assume that these nominal shocks exhibit no long-term impact on prices, the estimated price elasticity will be small and/or statistically insignificant. Hence, this result is not a big surprise. At the same time, it is reassuring that the estimate for the manufacturing output elasticity of demand does not change strongly.

The estimated coefficient for the linear trend is negative and not statistically significant different from zero. I find evidence for the existence of long-run relationships as the coefficients of adjustment are statistically significant and negative in all specifications. Overall, the estimated speed of demand adjustment is rather slow. The estimates suggest speeds of convergence to reach equilibrium at about fourteen percent per year for copper

3.4.3 Lead

The manufacturing sector employs lead for the production of a broad variety of manufactures such as TV screens, pipes, and batteries. It is an important alloy, especially in solder that is applied in electronics (Krebs, 2006). However, its use has been phased-out in many appliances such as in gasoline, paint pigments, and pipes due to health and environmental reasons (see Smith, 1999). At the same time, its use has strongly shifted to automobile batteries.

The estimated long-run manufacturing output elasticity of lead demand is estimated to be far below one. It ranges from about 0.4 and 0.7 across the three specifications. This shows that the demand for lead increases significantly less than the manufacturing output and hence its intensity of use tends to decline over the course of industrialization. This can be explained by changing preferences as consumers might tend to mitigate the health and environmental effects as per capita manufacturing output increases. However, comparing the results of the three specifications shows that the demand is also driven by shocks that are common to all countries over time. The estimated coefficicent for the linear time trend is negative and highly significant. This suggests that the decreasing use of lead due to negative health and environmental impacts is also strongly driven by time related common shocks as different governments started regulation at the same time in the 1960s and 1970s.

	1	2	3
Time fixed effects	No	No	Yes
Manufacturing (log)	0.435***	0.675***	0.745***
	(0.057)	(0.110)	(0.112)
Lead price (log)	-0.220**	-0.215***	-0.014
	(0.093)	(0.080)	(0.204)
Constant	0.048**	0.393***	0.028
	(0.022)	(0.095)	(0.022)
Linear trend		-0.005***	
		(0.002)	
Adjustment coefficient	-0.094***	-0.121***	-0.148***
	(0.021)	(0.026)	(0.033)
Observations	1,059	1,059	1,059
Log likelihood	474.7	476.9	435.3

Notes: The table shows results from the pooled mean group (PMG) estimation of the preferred ARDL(4,4,2) model. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 3.4: Estimates of the long-run manufacturing output and price elasticities of lead demand.

My estimates for the price elasticity of lead demand are far lower than those for copper and aluminum. They are about -0.2 for Specifications 1 and 2. This hints at the low substitutability of lead. As in the case of copper, the estimate of the price elasticity in the specification with time fixed effects is not statistically significant.

I find evidence for the existence of long-run relationships as the coefficients of adjustment are statistically significant and negative in all specifications. Overall, the estimated speed of demand adjustment is even lower than for copper and aluminum. It takes up to 10 years before demand reaches equilibrium after a shock. This is reasonable, given that adjustments in manufacturing capital are rather slow and that inventories play an important role.

3.4.4 Tin

Tin is mainly used in the packaging industry as tinplate, which is thin steel coated by tin. It is also employed as an aloy with lead as solder in electronics. Furthermore, it is applied in different alloys, of which bronze is the most important (Krebs, 2006; Stürmer and von Hagen, 2012b).

The estimated manufacturing output elasticity and the estimated price elasticity of tin demand varie strongly across the the three specifications. In Specifications 1 and 2 the output elasticity of demand is about 0.6 to 0.7. However, in the third specification with time fixed effects, it is far lower, about 0.3. For the price elasticity, the estimated elasticity is positive at about 0.1 in Specifications 1 and 2, while it is negative and about 0.4 in Specification 3.

	1	2	3
Time fixed effects	No	No	Yes
Manufacturing (log)	0.616***	0.712***	0.295**
	(0.035)	(0.080)	(0.141)
Tin price (log)	0.169**	0.110	-0.384***
	(0.085)	(0.084)	(0.046)
Constant	-0.522**	-0.149	0.006
	(0.209)	(0.118)	(0.026)
Linear trend		-0.004	
		(0.003)	
Adjustment coefficient	-0.132***	-0.131***	-0.180***
	(0.028)	(0.028)	(0.057
Observations	1,142	1,142	1,142
Log likelihood	399.5	400.1	408.9

Notes: The table shows results from the pooled mean group (PMG) estimations of the preferred ARDL(4,4,2) model. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 3.5: Estimates of the long-run manufacturing output and price elasticities of tin demand.

These results might point to a misspecification of the model. As the scatter plot in Figure 3.15 in the Appendix shows, there is a broad variety of different patterns in the relationship between per capita manufacturing output and tin demand. In addition, they do not show a linear log-log relationship. Several reasons might explain this result. First, in comparison to the other mineral commodities examined, it is the one with the most narrow range of applications in manufacturing production. Second, it has strongly lost its importance due to aluminum substitution (see Thoburn, 1994; Krebs, 2006; Stürmer and von Hagen, 2012b). Finally, the strong turbulences in its price due the collapse of the "International Tin Agreement" in 1985 (see Rudolf Wolff & Co Lt., 1987) might cause further problems in the estimation.

I find evidence for the existence of long-run relationships as the coefficients of adjustment are statistically significant and negative in all three specifications. Overall, the estimated speed of demand adjustment is, as in the case for lead and zinc, very slow. It takes up to 10 years before demand reaches equilibrium after a shock.

3.4.5 Zinc

Zinc is mainly used in the galvanization of steel, as an alloy with copper in brass, zinc rich paint, casting, batteries, and zinc sheet for roofing (see Gupta, 1982; Jolly, 1997).

The long-run manufacturing output elasticity of zinc demand is estimated to be between about 0.7 and 0.8 in the three specifications. Demand increases hence less than manufacturing output over the course of industrialization pointing to a slight decrease in the intensity of use. This is plausible as zinc demand is on the one hand close to general industrial and economic conditions (see Gupta, 1982; Jolly, 1997). On the other hand, as its main appliance is in galvanization, its use is strongly linked to products of the steel industry that rather loose importance over the course of industrialization.

	1	2	3
Time fixed effects	No	No	Yes
Manufacturing (log)	0.734***	0.852***	0.834***
	(0.033)	(0.101)	(0.132)
Zinc price (log)	-0.064	-0.066	0.207**
	(0.088)	(0.084)	(0.083)
Constant	-0.204***	-0.090	-0.017
	(0.209)	(0.118)	(0.026)
Linear trend		-0.004	
		(0.003)	
Adjustment coefficient	-0.132***	-0.131***	-0.180***
	(0.055)	(0.062)	(0.022)
Observations	1,216	1,216	1,216
Log likelihood	579.2	579.8	518.9

Notes: The table shows results from the pooled mean group (PMG) estimations of the preferred ARDL(4,4,2) model. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 3.6: Estimates of the long-run manufacturing output and price elasticities of zinc demand.

The estimates for the price elasticity of zinc demand are different between the specifications with and without the time fixed effects. In Specifications 1 and 2 the estimates are not statistically significantly different from zero. Inclusion of time fixed effects in Specification 3 leads to a positive value of about 0.2, which is statistically significant, but without a plausible explanation, and hard to interpret as price only includes changes due to inflation and exchange rates when applying time-fixed effects. The time trend is not statistically significant.

I find evidence for the existence of long-run relationships, as the coefficients of adjustment are statistically significant and negative in all three specifications. It takes up to ten years before demand reaches equilibrium after a shock.

3.5 Sensitivity analysis

I check the robustness of my results with respect to a different choice of lag lengths and the use of other estimators.

I reestimate the model using an ARDL(1,1,1) and an ARDL(3,3,3) configuration (see Tables 3.13 to 3.22 in the Appendix). Smaller lag lengths yield qualitatively similar results for all mineral commodities except tin, where the price elasticity becomes insignificant in the case of ARDL(3,3,3). The null hypothesis of the Hausman test is not rejected in any of the specifications with the mean substracted data. The adjustment coefficients are statistically significant in all estimations showing strong evidence for long-run relationships between the variables.

Tables 3.8 to 3.12 in the Appendix present the results from the alternative pooled estimators. The two alternative pooled estimators are the mean group estimator (MG), which does not impose any homogeneity, and the dynamic fixed effects (DFE) estimator, which imposes homogeneity across all slopes and error variances.

The estimated long-run price and manufacturing output elasticities of demand are relatively robust across the different estimators. As expected, the standard error of the MG estimates are larger and coefficients are not often statistically significant. Pooling sharpens the estimates considerably as they are more robust to outliers. In the case of aluminum, the effect of the outlier Belgium is obvious and distorts the estimates. The estimated coefficients for the speed of adjustment are in all cases fairly low but significant.

The joint Hausman tests in Tables 3.8 to 3.12 do not reject the hypothesis of homogeneity of all long-run coefficients at conventional levels of significance, when the PMG estimates are compared to the MG estimates for results with country fixed effects. As PMG estimates are more efficient than MG estimates, they ought to be preferred. Overall, the joint Hausman tests provide evidence that I am not violating the data by relying on PMG estimates rather than MG estimates for all mineral commodities in the regressions with time fixed effects (Pesaran, Shin, and Smith, 1999).

3.6 Conclusion

This paper is the first to provide empirical evidence from a panel data set that covers the nexus of industrialization and the derived demand for mineral commodities for a time period spanning partly back to 1840. I focus on the demand for aluminum, copper, lead, tin, and zinc, because they have been used in many applications throughout history. I employ the pooled mean group estimator to the standard partial adjustment model to estimate the manufacturing output elasticity of demand and the price elasticity of demand of each of the commodities examined. The pooled mean group estimator allows me to account for the heterogeneity in the short-run effects. I control for possible ommitted technology development that is common across countries and time dependent by implementing a linear time trend and time-fixed effects in a stepwise manner.

I find strong differences in the estimated long-run manufacturing output elasticities of demand across the five examined mineral commodities. Aluminum has an estimated long-run manufacturing output elasticity of demand of about 1.5. This means that its demand increases more than proportional to manufacturing output over time. I find an estimate for the long-run manufacturing output elasticitiy of copper demand of about one, while it is below one for lead, tin, and zinc demand. This causes the intensity of use of these mineral commodities to decline over time in the manufacturing sector.

My results suggest that the structural change in the relationship between per capita manufacturing output and the demand for mineral commodities over the course of industrialization is rather driven by changes in technology and consumer preferences specific to the stage of industrialization. Controlling for ommitted common technology and spillover effects across countries by employing specifications with a time trend and country fixed effects show that common effects only play a role in decreasing aluminum and lead demand over time. The model for tin seems to be misspecified.

The estimated long-run demand of the examined mineral commodities is rather inelastic with respect to price. This points to the low effect of technological change in substitution. It illustrates that the examined mineral commodities are rather essential to manufacturing output, as the processing industry does not change its use in response to price.

The empirical results are plausible given narrative evidence on the application of the different mineral commodities over time. I find evidence for the existence of long-run relationships in all regressions. The estimated speed of demand adjustment is rather slow for all commodities and it takes more than ten years in the cases of lead, tin, and zinc to revert back to equilibrium. This is reasonable, given that adjustments in manufacturing capital are rather slow and that inventories play an important role in these markets.

My estimates of the long-run manufacturing output elasticity of demand suggest that the industrialization in China will cause aluminum and copper demand to increase while the demand for lead, tin, and zinc decreases relative to manufacturing output in the long-term. As mining firms face high upfront costs and long lead times to open up new mines, my results are important for developing long-term production strategies and allowing for smooth markets. Moreover, countries dependent on the exports of their mineral commodities may better judge the long-term perspective of the respective markets and adjust their macroeconomic and fiscal policies accordingly. My results suggest that demand is a larger contributor to the volatility of aluminum and copper prices than to that of lead, tin, zinc, and energy prices (see Slade, 1991). Moreover, the manufacturing output elasticities of demand for all examined mineral commodities except tin are higher than the income elasticities of oil demand (which is 0.55 according to Gately and Huntington (2002) for twenty-five OECD countries from 1971 to 1997) .

Acemoglu et al. (2012) claim that the low price elasticity leads to an increase in the value of the outstanding stock over time. Therefore the incentives of war increase, making war even inevitable in the long run. It is questionable whether this is really the case as a low price inelasticity of derived demand might also be driven by the fact that the costs of these inputs as a share of total costs of manufacturing are relatively small, as the law of derived demand by Hicks (1932) and Marshall (1890) suggests. Furthermore, the model by Acemoglu et al. (2012) depends on the assumption of a finite stock, which my coauthor and I question in Chapter 1. Following models of commodity price speculation the low price elasticity of demand makes these markets prone to speculation (see Hamilton, 2009a; Kilian and Murphy, 2012).

Measurement errors might lead to an underestimation of coefficients and larger standard errors. One possible way to correct for these errors would be to use instrumental variables. I could employ historical labor dispute data from Mitchell (2007) as an instrument for manufacturing output. Labor disputes are correlated to manufacturing output, but not directly correlated to the demand of the respective mineral commodities. I could use historical price data for gold (data is available from Schmitz (1979)), wheat (data is available from Uebele (2011)), or other mineral commodities, as an instrument for the five mineral commodity prices examined here. The seminal article by Pindyck and Rotemberg (1990) shows that there is “excess co-movement” between prices of commodities whose markets are otherwise unrelated. The correlation due to the “excess co-movement” of commodity markets could be used to mitigate the effect of measurement errors in prices. This approach would also check the robustness of my identifying assumption that supply is highly elastic in the long run. Another way to correct for the latter problem would be to explicitly model the possible endogeneity of prices with respect to demand in a structural panel vector error correction model. I leave these robustness checks to further research.

My results show that it is relatively difficult to separate and interpret the different effects of technological change and consumer preferences on the dynamic relationship between manufacturing output and the demand for mineral commodities. This offers directions for further research. First, I could explicitely use variables that control for specific uses of the different mineral commodities, e.g., the number of telephones (data available from Mitchell (2003a) and others) in the case of copper use. This would help to separate the effect of technological change on the production composition of manufacturing output from the technological change in resource efficiency. Secondly, as substitution effects play an important role, I might include prices of close substitutes in the regressions, e.g., the aluminum price as a control variable in the regression on copper demand. Third, I could try to find more direct proxies for technological change in resource efficiency, e.g., Considine (1991) uses automotive fuel economy as a proxy to technological change in resource efficiency in mineral commodity demand. Finally, applying time-varying parameter regression could help to better account for the dynamic structure of the relationship between manufacturing output and the derived demand for mineral commodities.

A3 Appendix

A3.1 Tables

Variable		Mean	Std. Dev.	Min	Max	Observations
Per capita GDP (Geary-Khamis $)	overall	8341	6698	860	31618	N = 1454
	between		1562	6098	11200	n = 12
	within		6523	-1053	28759	T-bar = 121.1
Per capita value added by manufacturing (GK-$)	overall	1807	1273	83	6565	N = 1414
	between		320	1209	2266	n = 12
	within		1241	-276	6109	T-bar = 117.8
Per capita use of aluminum (mt/person)	overall	.0068	.0078	.0000	.0490	N = 1094
	between		.0037	.0036	.0171	n = 12
	within		.0071	-.0102	.0388	T-bar = 91.1
Per capita use of copper (mt/person)	overall	.0056	.0063	.0000	.0402	N = 1401
	between		.0038	.0013	.0139	n = 12
	within		.0053	-.0080	.0319	T-bar = 116.8
Per capita use of lead (mt/person)	overall	.0032	.0018	.0001	.0079	N = 1189
	between		.0012	.0015	.0051	n = 12
	within		.0014	-.0009	.0076	T-bar = 99.1
Per capita use of tin (mt/person)	overall	.0002	.0001	.0000	.0008	N = 1292
	between		.0001	.0001	.0004	n = 11
	within		.0001	-.0001	.0007	T-bar = 117.4
Per capita use of zink (mt/person)	overall	.0038	.0045	.0000	.0384	N = 1391
	between		.0034	.0017	.0146	n = 12
	within		.0031	-.0102	.0276	T-bar = 115.9
Real price of aluminum (local currencies per mt)	overall	1046	5333	.77	140411.3	N = 1288
	between		1995	8.50	6491	n = 12
	within		4976	-4545	134966	T-bar = 107.3
Real price of copper (local currencies per mt)	overall	602	1330	0.92	8358	N = 1381
	between		1234	2.73	3804	n = 12
	within		566	-2577	5156	T-bar = 115.1
Real price of lead (local currencies per mt)	overall	180	392	.28	2633	N = 1376
	between		366	.73	1116	n = 12
	within		161	-656	1698	T-bar = 114.7
Real price of tin (local currencies per mt)	overall	1856	4155	2.53	29042	N = 1368
	between		3750	6.55	11799	n = 12
	within		1925	-6920	19099	T-bar = 114
Real price of zinc (local currencies per mt)	overall	238	518	.47	3798	N = 1364
	between		480	.81	1477	n = 12
	within		218	-949	2837	T-bar = 113.7

Table 3.7: Detailed summary statistics.

A3.2 Additional figures

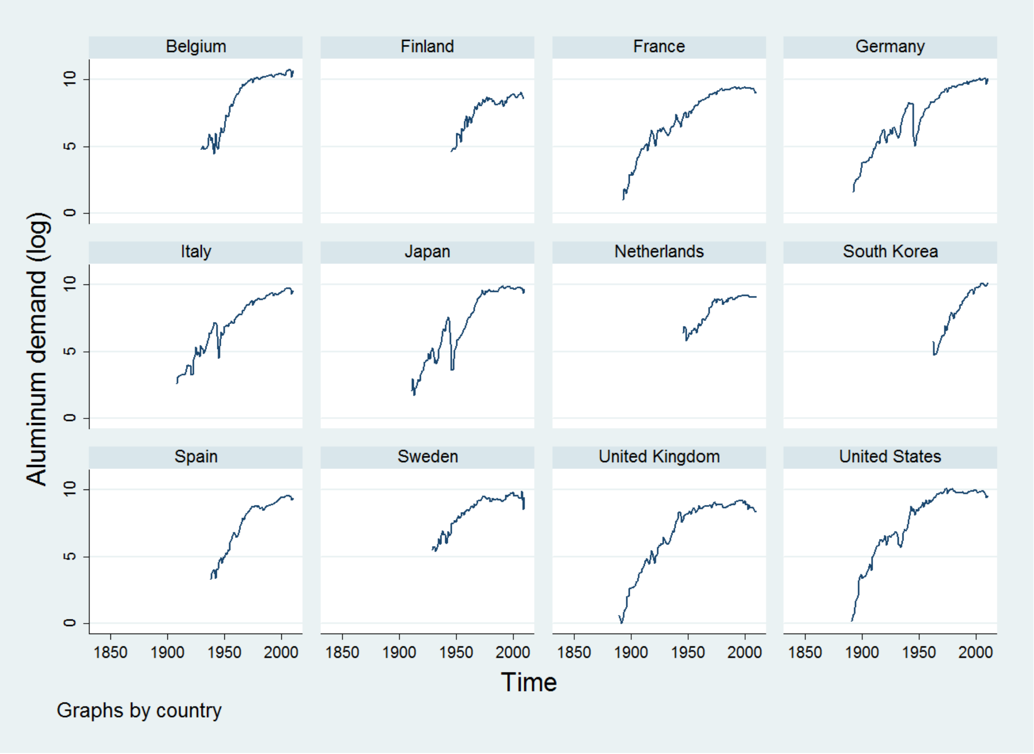

Figure 3.2: Per capita use of aluminum (log).

Figure 3.3: Per capita use of copper (log).

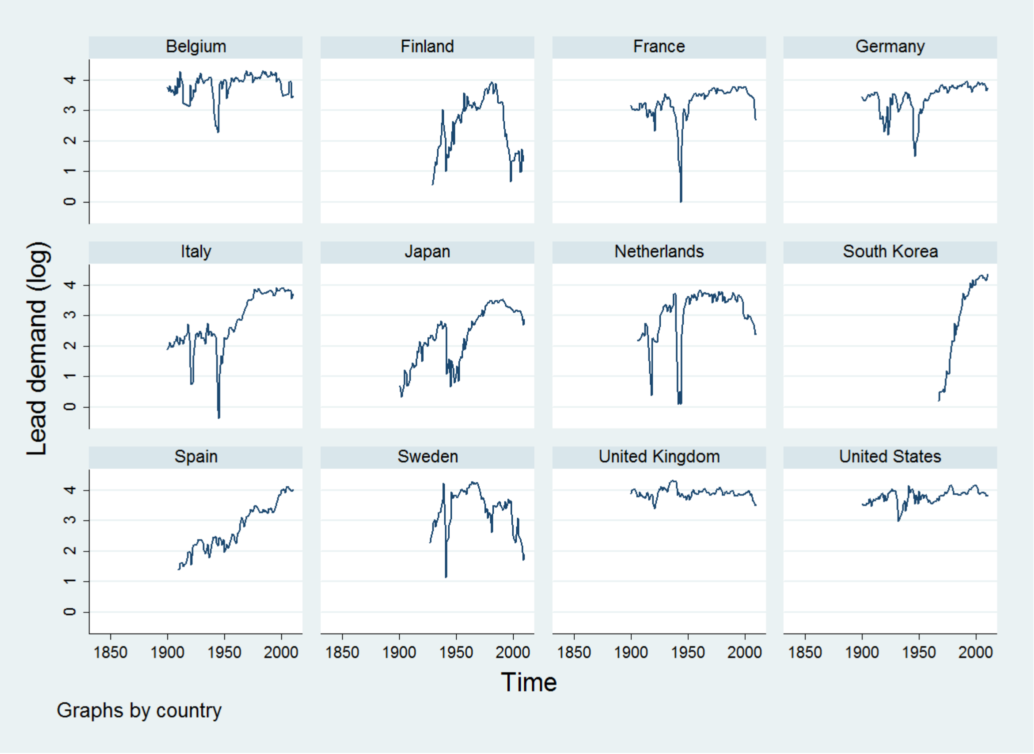

Figure 3.4: Per capita use of lead (log).

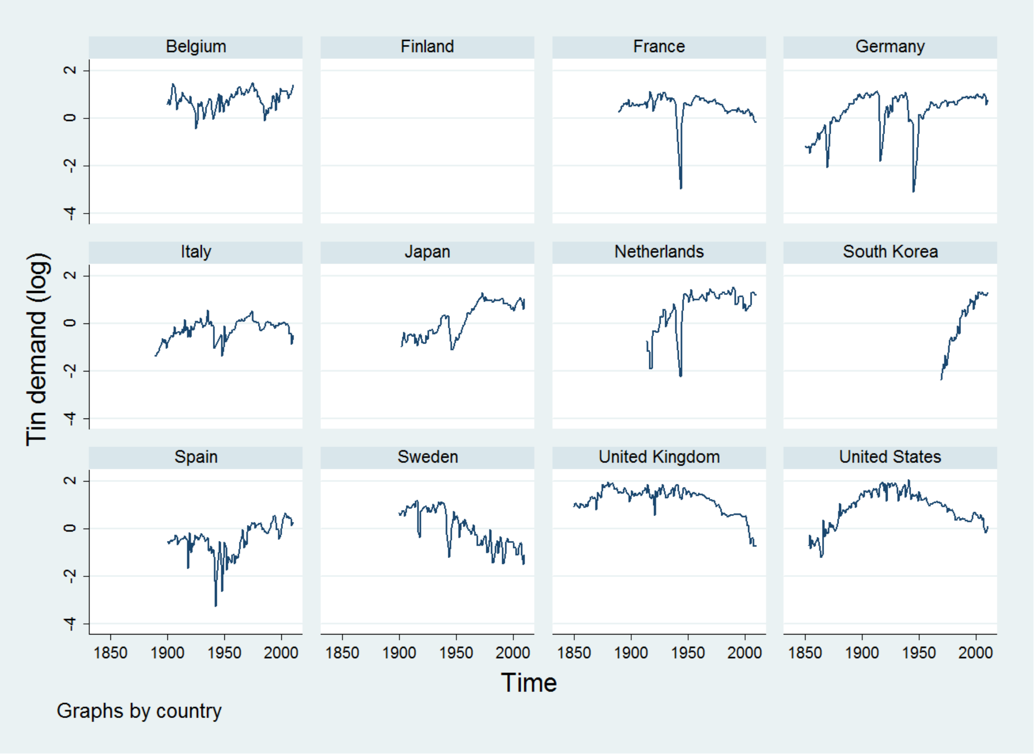

Figure 3.5: Per capita use of tin (log).

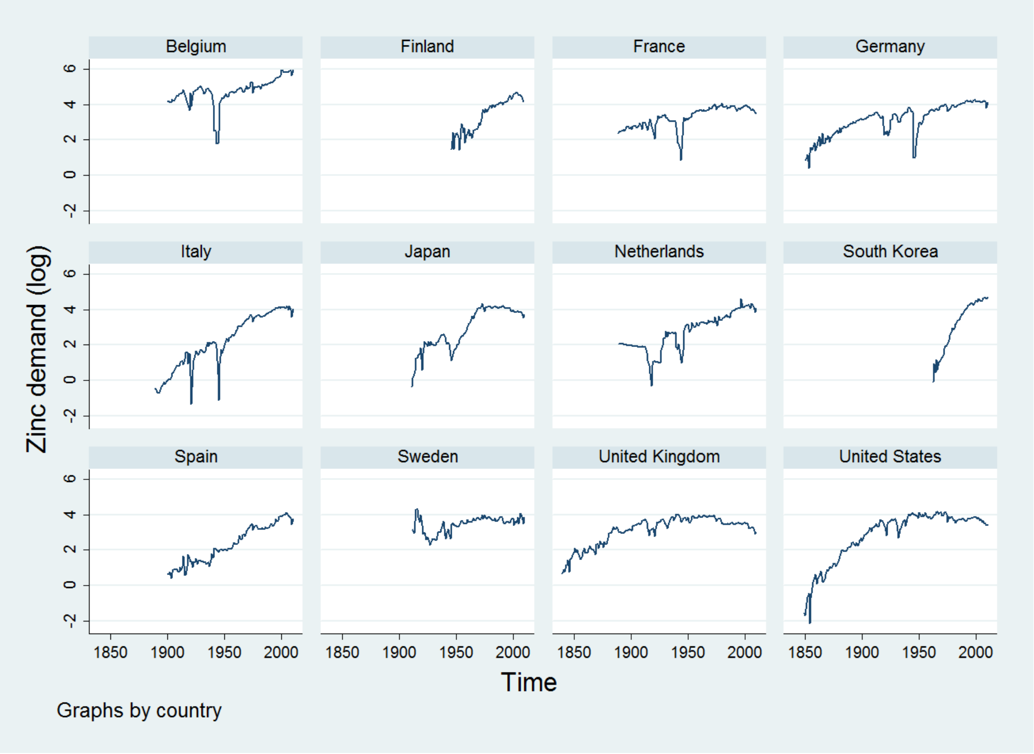

Figure 3.6: Per capita use of zinc (log).

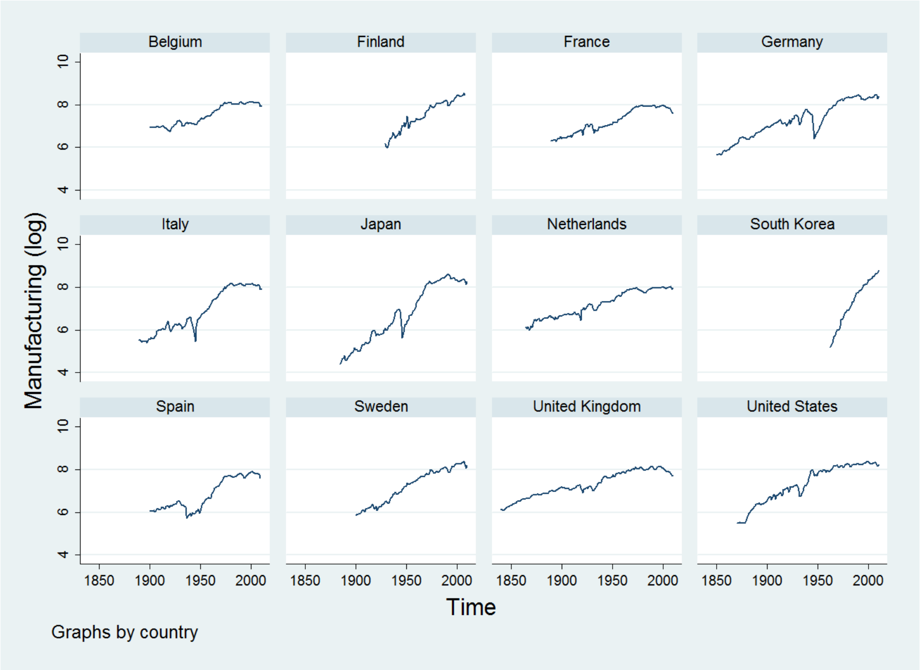

Figure 3.7: Per capita value added by the manufacturing sector (log).

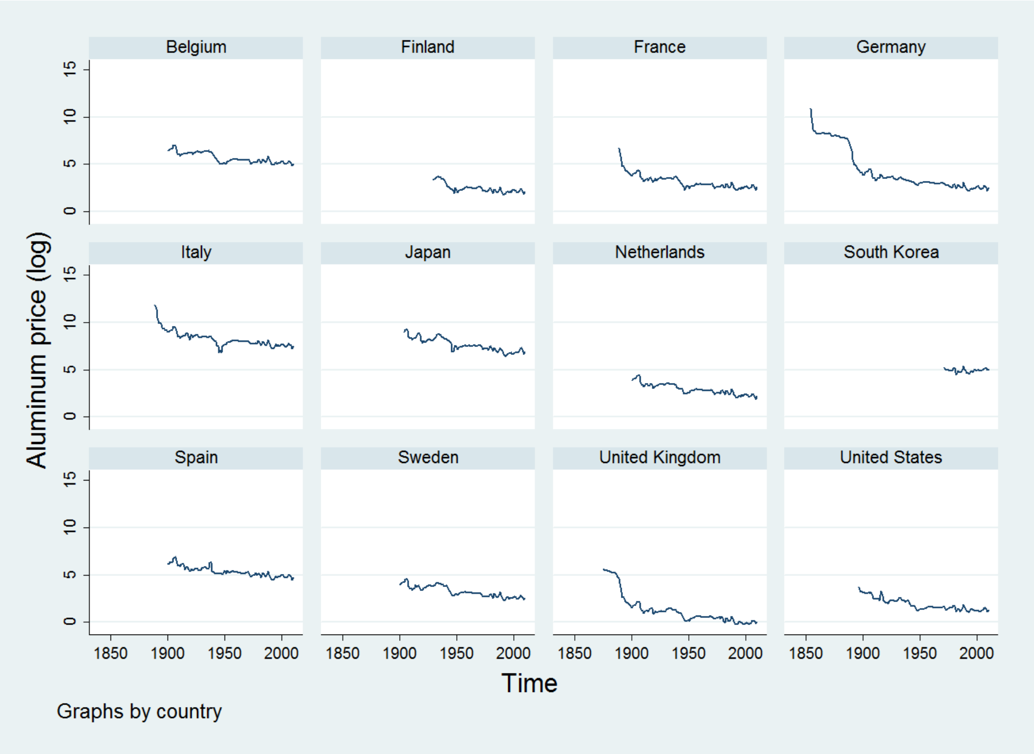

Figure 3.8: Real price of aluminum (log).

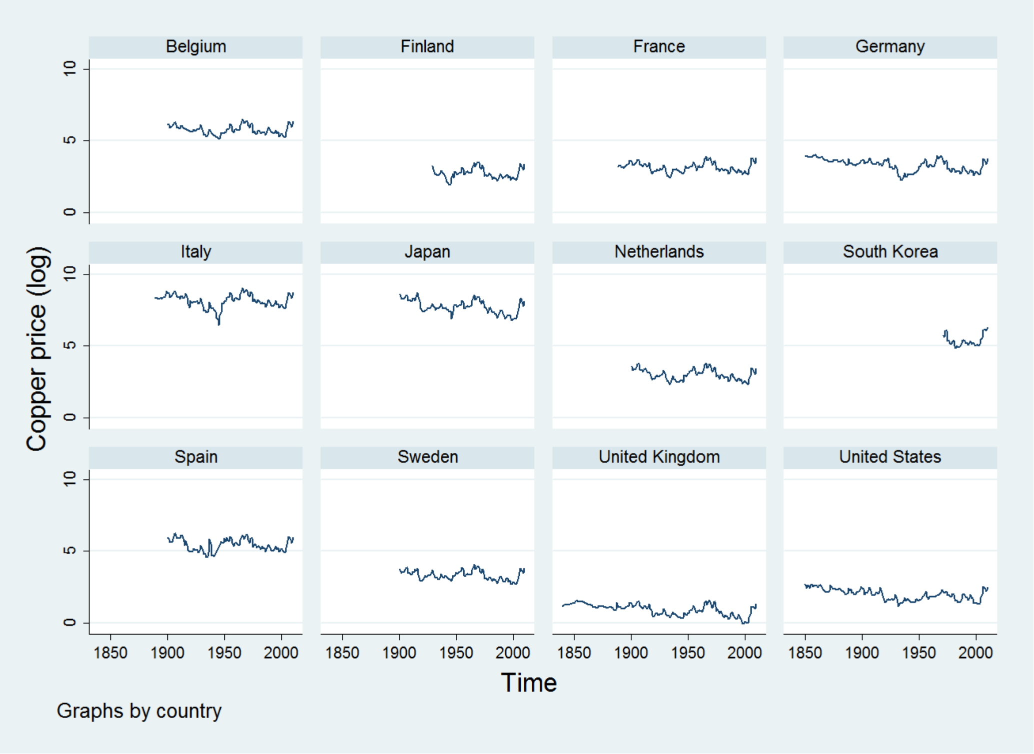

Figure 3.9: Real price of copper (log).

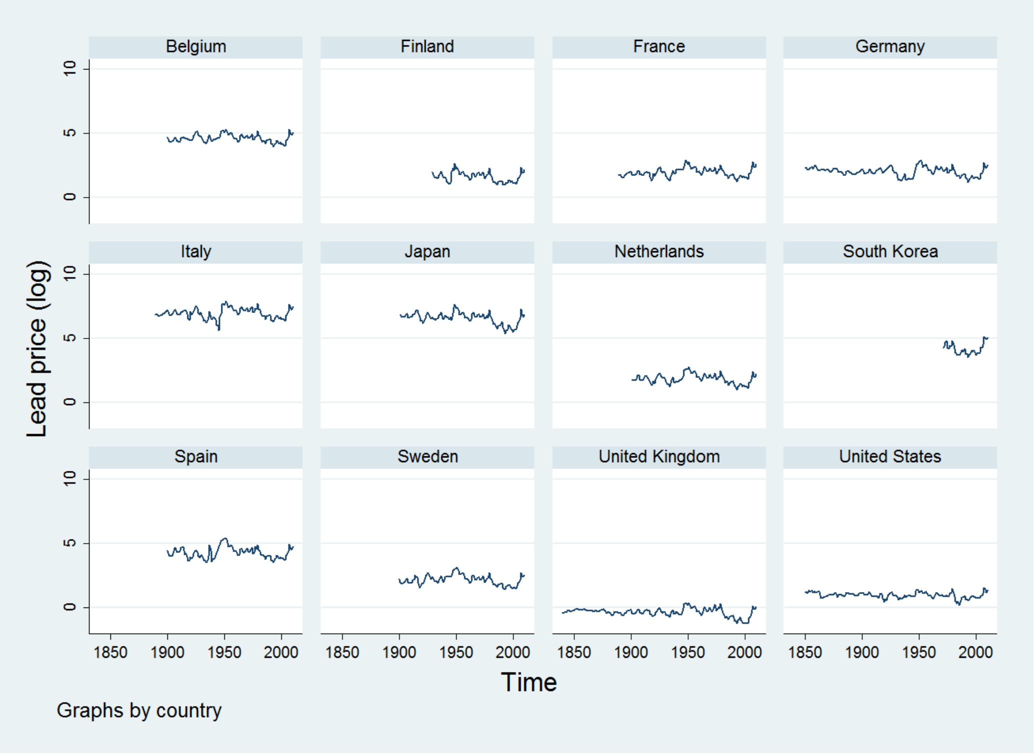

Figure 3.10: Real price of lead (log).

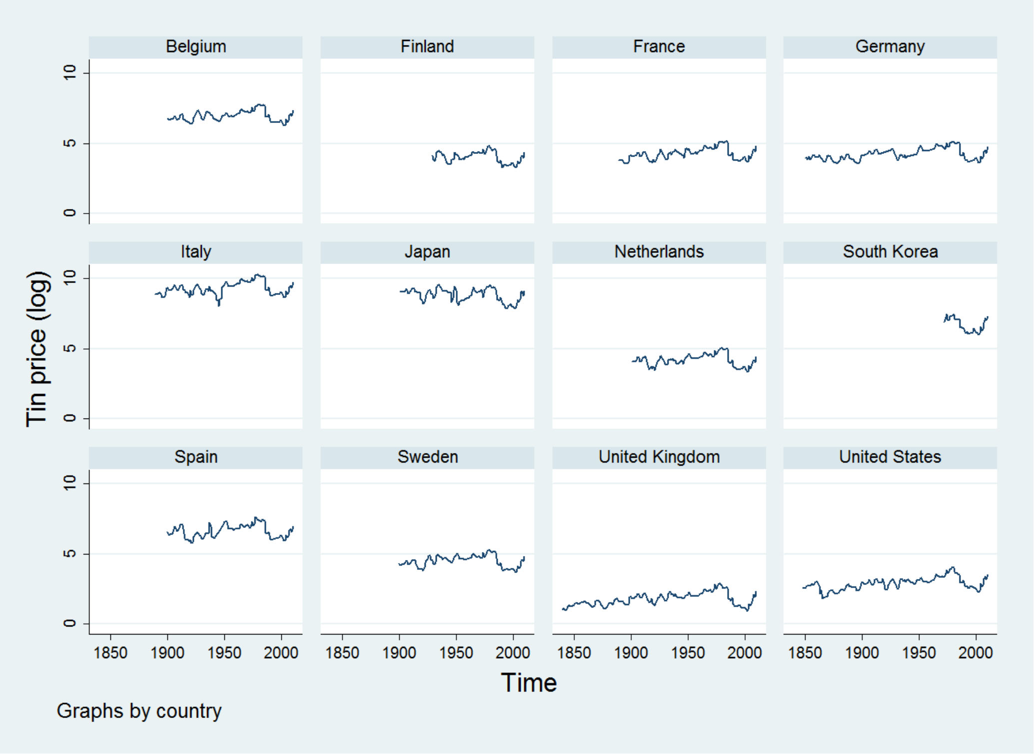

Figure 3.11: Real price of tin (log).

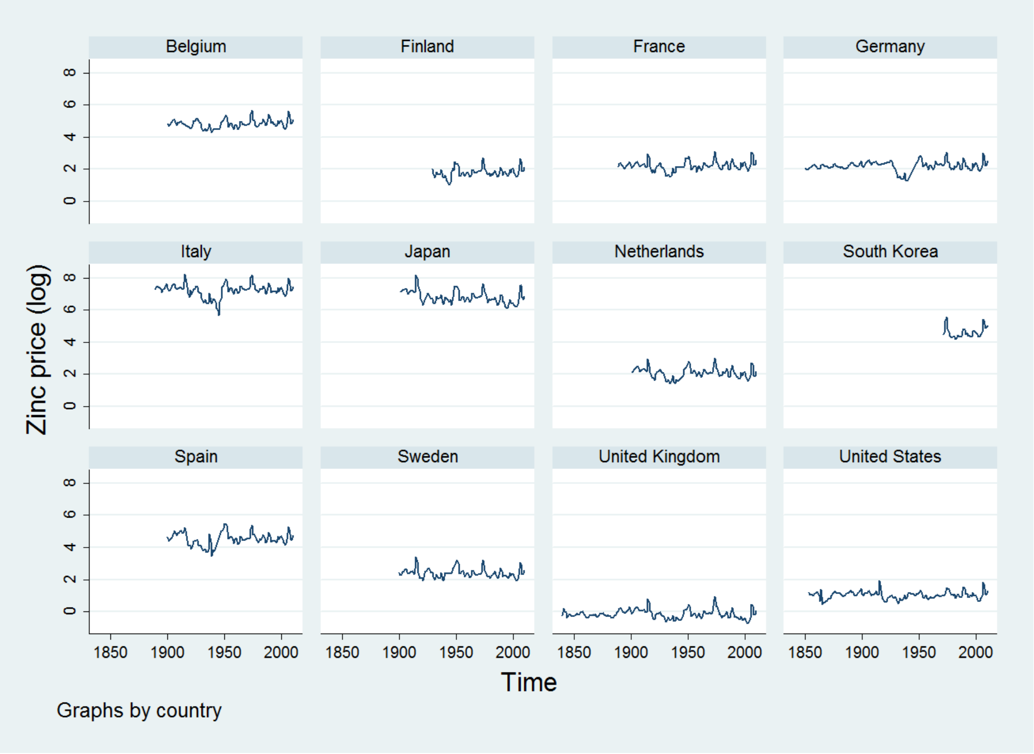

Figure 3.12: Real price of zinc (log).

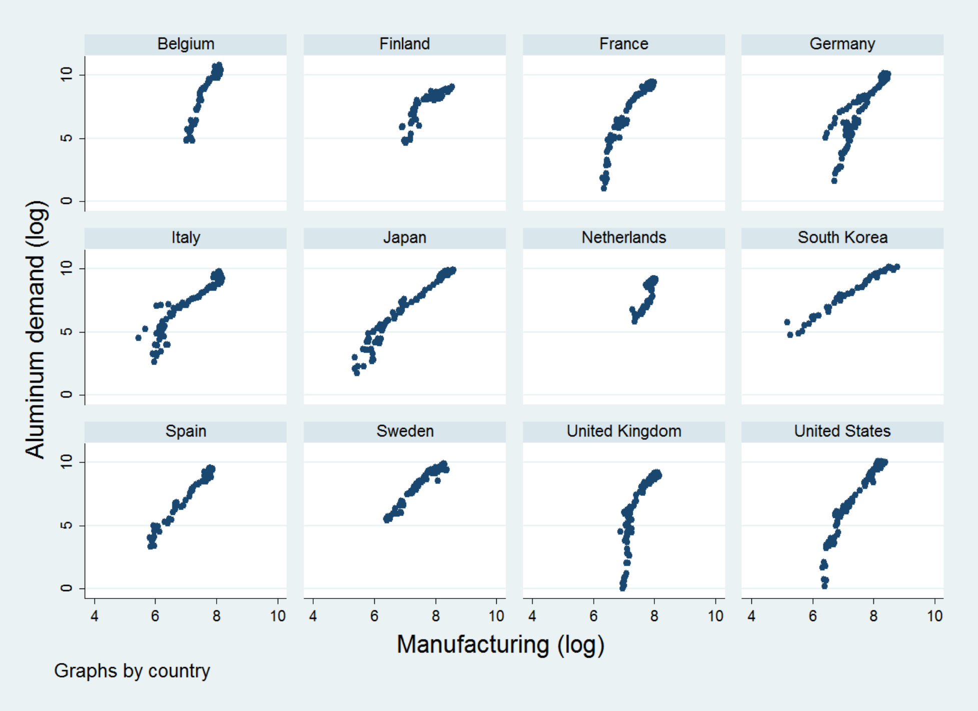

Figure 3.13: Scatter plot of per capita value added by manufacturing (horizontal axis) and per capita aluminum use (vertical axis).

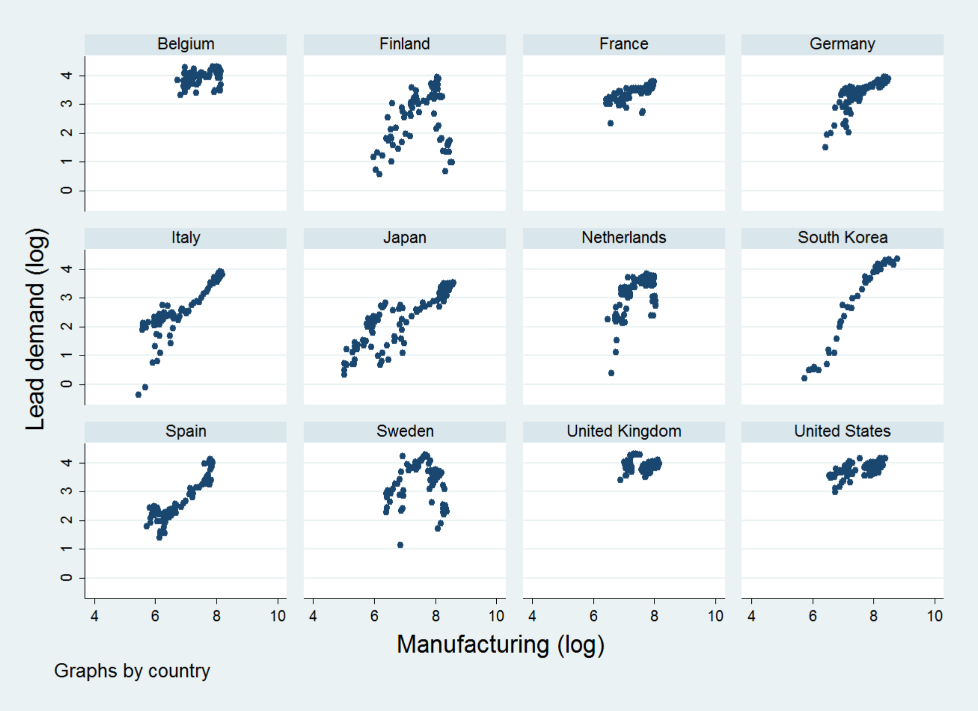

Figure 3.14: Scatter plot of per capita value added by manufacturing (horizontal axis) and per capita lead use (vertical axis).

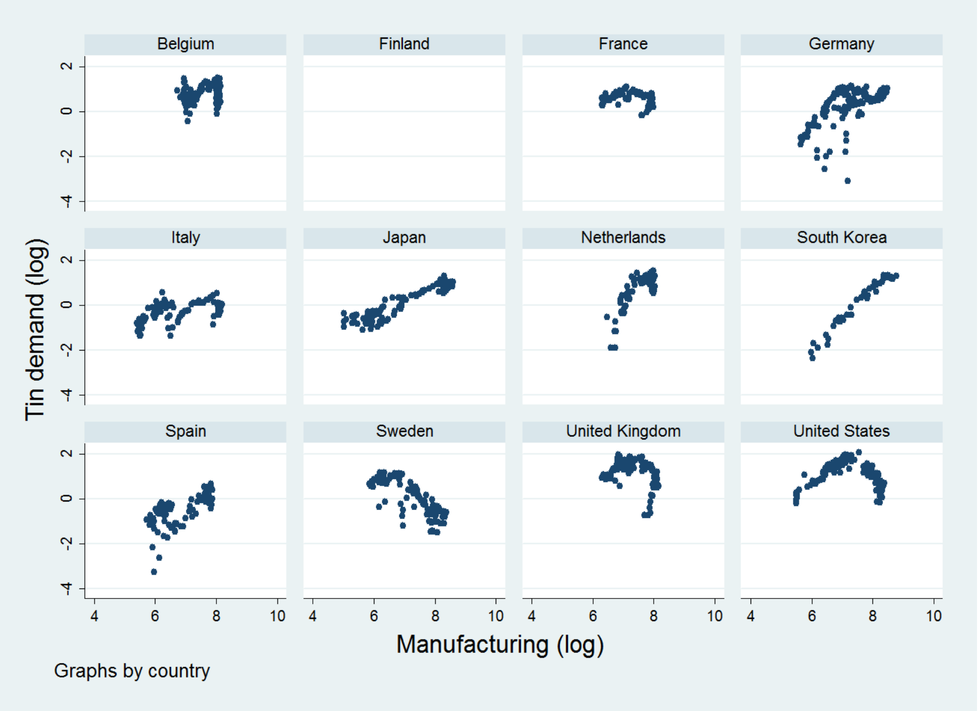

Figure 3.15: Scatter plot of per capita value added by manufacturing (horizontal axis) and per capita tin use (vertical axis).

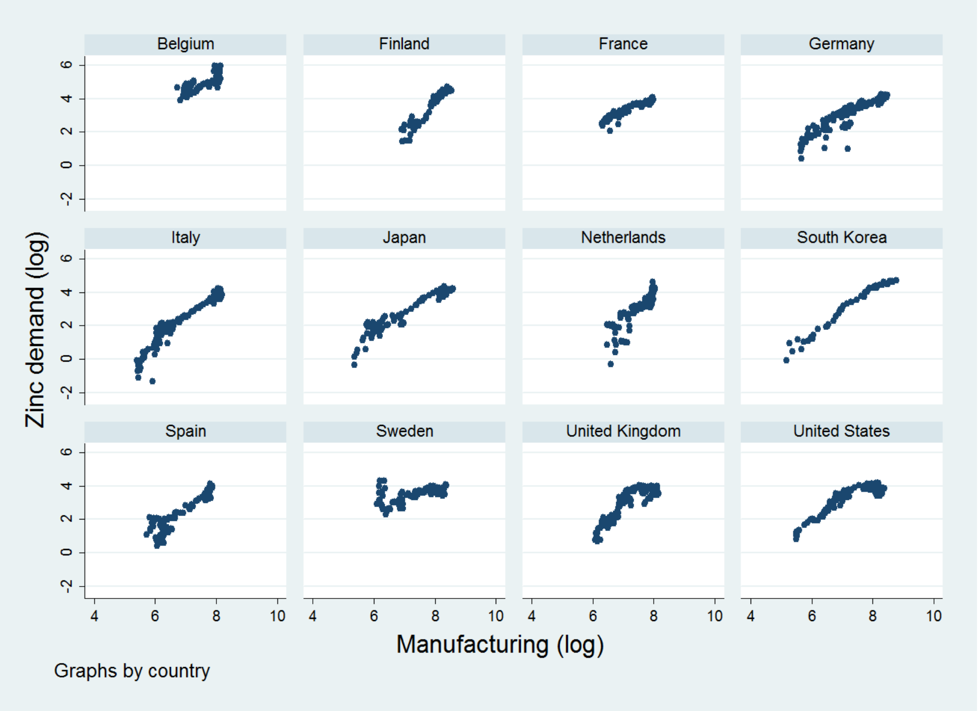

Figure 3.16: Scatter plot of per capita value added by manufacturing (horizontal axis) and per capita zinc use (vertical axis).

A3.3 Regression results

VARIABLES Time fixed effects	MG No	PMG No	DFE No	MG No	PMG No	DFE No	MG Yes	PMG Yes	DFE Yes
Manufacturing (log)	0.287	1.551***	1.542***	0.565	1.759***	1.439***	0.792	1.518***	1.353***
	(1.315)	(0.092)	(0.194)	(1.411)	(0.173)	(0.248)	(0.521)	(0.073)	(0.200)
Aluminum price (log)	-0.363	-0.706***	-0.919***	-1.076	-0.883***	-0.801**	-1.474***	-0.836***	-1.258***
	(1.621)	(0.184)	(0.267)	(0.809)	(0.221)	(0.322)	(0.526)	(0.236)	(0.355)
Linear trend				0.006	-0.012*	0.005			
				(0.017)	(0.007)	(0.008)			
Adjustment coefficient	-0.124***	-0.117***	-0.080***	-0.150***	-0.113***	-0.083***	-0.189***	-0.142***	-0.107***
	(0.027)	(0.023)	(0.010)	(0.032)	(0.023)	(0.011)	(0.035)	(0.031)	(0.016)
Constant	0.028	-0.056	0.014	2.291	1.411***	-0.413	0.169	0.054	-0.005
	(0.743)	(0.059)	(0.177)	(2.907)	(0.421)	(0.717)	(0.149)	(0.083)	(0.007)
Observations	973	973	973	973	973	973	973	973	973
Joint Hausman Test-stat.		2.161			3.115			3.024	
p-value		0.339			0.374			0.220	
Log likelihood		404.4			405.2			432.4	

Notes: The table shows results from the mean group (MG), pooled mean group (PMG), and dynamic fixed effects (DFE) estimations of the preferred ARDL(4,4,2) model. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 3.8: Preferred estimates of the long-run manufacturing output and price elasticities of aluminum demand.

VARIABLES	MG	PMG	DFE	MG	PMG	DFE	MG	PMG	DFE
Time fixed effects	No	No	No	No	No	No	Yes	Yes	Yes
Manufacturing (log)	1.053***	0.914***	1.080***	1.020***	1.104***	1.091***	0.932***	1.128***	1.164***
	(0.175)	(0.061)	(0.087)	(0.188)	(0.145)	(0.178)	(0.341)	(0.067)	(0.173)
Copper price (log)	-0.097	-0.400***	-0.142	-0.177	-0.453***	-0.145	-0.523	-0.009	0.222**
	(0.176)	(0.093)	(0.176)	(0.125)	(0.095)	(0.182)	(0.440)	(0.049)	(0.101)
Linear trend				0.006	-0.005	-0.000			
				(0.005)	(0.004)	(0.004)			
Adjustment coefficient	-0.200***	-0.132***	-0.102***	-0.236***	-0.131***	-0.102***	-0.240***	-0.180***	-0.114***
	(0.039)	(0.028)	(0.015)	(0.036)	(0.028)	(0.015)	(0.064)	(0.057)	(0.016)
Constant	-0.754***	-0.161***	-0.387***	-3.733*	0.474***	-0.366	0.094	0.010	0.003
	(0.229)	(0.052)	(0.134)	(2.021)	(0.182)	(0.334)	(0.137)	(0.030)	(0.006)
Observations	1,206	1,206	1,206	1,206	1,206	1,206	1,206	1,206	1,206
Joint Hausman Test-stat.		3.799			98.01			1.693	
p-value		0.150			0			0.429	
Log likelihood		502.3			502.8			434.2	

Notes: The table shows results from the mean group (MG), pooled mean group (PMG), and dynamic fixed effects (DFE) estimations of the preferred ARDL(4,4,2) model. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 3.9: Preferred estimates of the long-run and short-run manufacturing output and price elasticities of copper demand.

VARIABLES	MG	PMG	DFE	MG	PMG	DFE	MG	PMG	DFE
Time fixed effects	No	No	No	No	No	No	Yes	Yes	Yes
Manufacturing (log)	0.208	0.435***	0.436***	1.949***	0.675***	0.795***	1.971	0.745***	0.761***
	(0.202)	(0.057)	(0.144)	(0.664)	(0.110)	(0.256)	(1.657)	(0.112)	(0.259)
Lead price (log)	0.061	-0.220**	0.212	-0.174	-0.215***	0.186	1.893	-0.014	0.113
	(0.606)	(0.093)	(0.277)	(0.111)	(0.080)	(0.249)	(1.727)	(0.204)	(0.510)
Linear trend				-0.046**	-0.005***	-0.009			
				(0.023)	(0.002)	(0.006)			
Adjustment coefficient	-0.158***	-0.094***	-0.074***	-0.214***	-0.121***	-0.083***	-0.211***	-0.148***	-0.086***
	(0.028)	(0.021)	(0.015)	(0.029)	(0.026)	(0.017)	(0.047)	(0.033)	(0.017)
Constant	0.128	0.048**	-0.061	9.787	0.393***	0.507	0.210	0.028	0.002
	(0.173)	(0.022)	(0.111)	(7.065)	(0.095)	(0.408)	(0.157)	(0.022)	(0.007)
Observations	1,059	1,059	1,059	1,059	1,059	1,059	1,059	1,059	1,059
Joint Hausman Test-stat.		1.332			3.423			1.524	
p-value		0.514			0.331			0.467	
Log likelihood		474.7			476.9			435.3	

Notes: The table shows results from the mean group (MG), pooled mean group (PMG), and dynamic fixed effects (DFE) estimations of the preferred ARDL(4,4,2) model. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 3.10: Preferred estimates of the long-run manufacturing output and price elasticities of lead demand.

VARIABLES	MG	PMG	DFE	MG	PMG	DFE	MG	PMG	DFE
Time fixed effects	No	No	No	No	No	No	Yes	Yes	Yes
Manufacturing (log)	-0.302	0.616***	-0.091	0.760***	0.712***	0.517*	0.397	0.295**	0.709***
	(0.475)	(0.035)	(0.151)	(0.226)	(0.080)	(0.268)	(0.445)	(0.141)	(0.273)
Tin price (log)	-0.109	0.169**	-0.569**	-0.138	0.110	-0.454*	-0.166	-0.384***	-0.216
	(0.248)	(0.085)	(0.284)	(0.166)	(0.084)	(0.237)	(0.303)	(0.046)	(0.157)
Linear trend				–0.017***	-0.004	-0.013**			
				(0.005)	(0.003)	(0.005)			
Adjustment coefficient	-0.268***	-0.095**	-0.061***	-0.341***	-0.105**	-0.072***	-0.196***	-0.096***	-0.071***
	(0.082)	(0.040)	(0.012)	(0.126)	(0.043)	(0.013)	(0.038)	(0.030)	(0.013)
Constant	-0.820	-0.522**	0.241***	8.264	-0.149	0.944***	0.222*	0.006	0.008
	(0.756)	(0.209)	(0.093)	(7.147)	(0.118)	(0.338)	(0.123)	(0.026)	(0.006)
Observations	1,142	1,142	1,142	1,142	1,142	1,142	1,142	1,142	1,142
Joint Hausman Test-stat.		7.675			11.37			0.672	
p-value		0.0215			0.00987			0.715	
Log likelihood		399.5			400.1			408.9	

Notes: The table shows results from the mean group (MG), pooled mean group (PMG), and dynamic fixed effects (DFE) estimations of the preferred ARDL(4,4,2) model. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 3.11: Preferred estimates of the long-run manufacturing output and price elasticities of tin demand.

VARIABLES Time fixed effects	MG No	PMG No	DFE No	MG No	PMG No	DFE No	MG Yes	PMG Yes	DFE Yes
Manufacturing (log)	0.765***	0.734***	0.862***	1.059***	0.852***	0.898***	1.151	0.834***	0.905***
	(0.229)	(0.033)	(0.095)	(0.341)	(0.101)	(0.206)	(0.928)	(0.132)	(0.226)
Zinc price (log)	0.708	-0.064	0.042	0.186	-0.066	0.041	1.005	0.207**	0.123
	(1.223)	(0.088)	(0.253)	(0.397)	(0.084)	(0.253)	(1.540)	(0.083)	(0.116)
Linear trend				-0.007	-0.002	-0.001			
				(0.009)	(0.002)	(0.004)			
Adjustment coefficient	-0.216***	-0.113***	-0.085***	-0.286***	-0.119***	-0.085***	-0.137***	-0.085***	-0.083***
	(0.062)	(0.030)	(0.013)	(0.062)	(0.031)	(0.013)	(0.029)	(0.019)	(0.013)
Constant	-1.247*	-0.204***	-0.269***	1.779	-0.090	-0.218	0.140	-0.017	0.002
	(0.719)	(0.055)	(0.103)	(4.597)	(0.062)	(0.275)	(0.135)	(0.022)	(0.005)
Observations	1,216	1,216	1,216	1,216	1,216	1,216	1,216	1,216	1,216
Joint Hausman Test-stat.		0.759			14.68			0.248	
p-value		0.684			0.00211			0.883	
Log likelihood		579.2			579.8			518.9	

Notes: The table shows results from the mean group (MG), pooled mean group (PMG), and dynamic fixed effects (DFE) estimations of the preferred ARDL(4,4,2) model. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 3.12: Preferred estimates of the long-run manufacturing output and price elasticities of zinc demand.

VARIABLES	MG	PMG	DFE	MG	PMG	DFE	MG	PMG	DFE
Time fixed effects	No	No	No	No	No	No	Yes	Yes	Yes
Manufacturing (log)	2.216***	1.601***	1.737***	2.283***	1.750***	1.602***	1.123***	1.518***	1.371***
	(0.344)	(0.069)	(0.205)	(0.275)	(0.142)	(0.144)	(0.352)	(0.051)	(0.145)
Aluminum price (log)	-0.515**	-0.823***	-1.019***	-0.462	-0.913***	-0.879**	-0.881***	-0.771***	-0.786***
	(0.258)	(0.132)	(0.267)	(0.287)	(0.165)	(0.370)	(0.324)	(0.169)	(0.253)
Linear time trend				-0.004	-0.007	0.006			
				(0.006)	(0.006)	(0.007)			
Adjustment coeff.	-0.192***	-0.135***	-0.082***	-0.224***	-0.131***	-0.085***	-0.284***	-0.200***	-0.128***
	(0.038)	(0.035)	(0.012)	(0.052)	(0.035)	(0.015)	(0.054)	(0.050)	(0.032)
Constant	-1.335***	-0.051	-0.078	2.709	0.986***	-0.591	0.038	0.066	-0.007***
	(0.508)	(0.064)	(0.219)	(3.520)	(0.364)	(0.786)	(0.135)	(0.107)	(0.003)
Observations	1,018	1,018	1,018	1,018	1,018	1,018	1,018	1,018	1,018
Joint Hausman Test-stat.		3.583			3.668			1.153	
p-value		0.167			0.300			0.562	
log likelihood		206.1			206.5			280.0	

Notes: The table shows results from the mean group (MG), pooled mean group (PMG), and dynamic fixed effects (DFE) estimations of the preferred ARDL(1,1,1) model. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 3.13: Estimated long-run manufacturing output and price elasticities of aluminum demand in the ARDL(1,1,1) model.

VARIABLES Time fixed effects	MG No	PMG No	DFE No	MG No	PMG No	DFE No	MG Yes	PMG Yes	DFE Yes
Manufacturing (log)	1.098***	1.055***	1.097***	1.392***	0.983***	1.113***	0.859***	1.165***	1.248***
	(0.193)	(0.039)	(0.097)	(0.249)	(0.095)	(0.206)	(0.306)	(0.072)	(0.210)
Copper price (log)	-0.182	-0.219***	-0.201*	-0.205*	-0.208***	-0.205*	0.188	0.053	0.232
	(0.121)	(0.072)	(0.107)	(0.115)	(0.071)	(0.107)	(0.201)	(0.051)	(0.157)
Linear trend				-0.004	0.002	-0.000			
				(0.006)	(0.002)	(0.006)			
Adjustment coefficient	-0.238***	-0.168***	-0.132***	-0.274***	-0.168***	-0.132***	-0.253***	-0.199***	-0.145***
	(0.032)	(0.030)	(0.026)	(0.033)	(0.032)	(0.027)	(0.047)	(0.051)	(0.029)
Constant	-1.097***	-0.524***	-0.483***	-0.097	-0.742***	-0.443	0.075	0.010	0.007***
	(0.284)	(0.107)	(0.169)	(1.719)	(0.146)	(0.725)	(0.077)	(0.029)	(0.002)
Observations	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253	1,253
Joint Hausman Test-stat.		0.161			15.28			2.332	
p-value		0.923			0.00159			0.312	
log likelihood		352.8			353.1			305.1	

Notes: The table shows results from the mean group (MG), pooled mean group (PMG), and dynamic fixed effects (DFE) estimations of the preferred ARDL(1,1,1) model. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 3.14: Estimated long-run manufacturing output and price elasticities of copper demand in the ARDL(1,1,1) model.

VARIABLES Time fixed effects	MG No	PMG No	DFE No	MG No	PMG No	DFE No	MG Yes	PMG Yes	DFE Yes
Manufacturing (log)	0.454***	0.349***	0.525***	1.553***	0.664***	0.975***	3.540	0.888***	0.966***
	(0.128)	(0.048)	(0.157)	(0.450)	(0.094)	(0.203)	(3.444)	(0.102)	(0.237)
Lead price (log)	0.140	-0.094	0.268	-0.081	-0.092	0.217	5.719	0.067	0.345
	(0.253)	(0.075)	(0.347)	(0.080)	(0.065)	(0.293)	(5.498)	(0.194)	(0.358)
Linear trend				-0.035**	-0.005***	-0.012***			
				(0.016)	(0.002)	(0.004)			
Adjustment coefficient	-0.204***	-0.128***	-0.098***	-0.255***	-0.148***	-0.111***	-0.205***	-0.152***	-0.117***
	(0.029)	(0.024)	(0.016)	(0.030)	(0.027)	(0.020)	(0.041)	(0.026)	(0.024)
Constant	-0.048	0.130***	-0.150	8.441	0.475***	0.829***	0.126	0.017	0.002
	(0.243)	(0.035)	(0.156)	(6.360)	(0.131)	(0.283)	(0.144)	(0.024)	(0.002)
Observations	1,110	1,110	1,110	1,110	1,110	1,110	1,110	1,110	1,110
Joint Hausman Test-stat.		2.541			6.082			2.514	
p-value		0.281			0.108			0.285	
log likelihood		405.6			410.0			358.8	

Notes: The table shows results from the mean group (MG), pooled mean group (PMG), and dynamic fixed effects (DFE) estimations of the preferred ARDL(1,1,1) model. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 3.15: Estimated long-run manufacturing output and price elasticities of lead demand in the ARDL(1,1,1) model.

VARIABLES	MG	PMG	DFE	MG	PMG	DFE	MG	PMG	DFE
Time fixed effects	No	No	No	No	No	No	Yes	Yes	Yes
Manufacturing (log)	0.200	0.257***	0.083	0.683***	0.778***	0.560*	0.248	0.469***	0.814***
	(0.214)	(0.060)	(0.194)	(0.237)	(0.124)	(0.335)	(0.481)	(0.108)	(0.306)
Tin price (log)	-0.031	-0.061	-0.163	-0.014	-0.194**	-0.128	0.221	-0.364***	-0.124
	(0.100)	(0.115)	(0.168)	(0.107)	(0.099)	(0.130)	(0.534)	(0.040)	(0.155)
Linear trend				-0.013*	-0.015***	-0.011*			
				(0.007)	(0.003)	(0.006)			
Adjustment coefficient	-0.254***	-0.118***	-0.089***	-0.292***	-0.127***	-0.102***	-0.267***	-0.137***	-0.100***
	(0.045)	(0.035)	(0.019)	(0.058)	(0.028)	(0.023)	(0.043)	(0.034)	(0.024)
Constant	-0.757	-0.160***	0.057	5.927	1.505**	0.862	0.370**	0.015	0.005**
	(0.535)	(0.050)	(0.131)	(5.246)	(0.599)	(0.592)	(0.168)	(0.032)	(0.002)
Observations	1,194	1,194	1,194	1,194	1,194	1,194	1,204	1,204	1,204
Joint Hausman Test-stat.		-0.541			21.70			1.480	
p-value		1			7.53e-05			0.477	
log likelihood		233.4			236.7			299.4	

Notes: The table shows results from the mean group (MG), pooled mean group (PMG), and dynamic fixed effects (DFE) estimations of the preferred ARDL(1,1,1) model. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 3.16: Estimated long-run manufacturing output and price elasticities of tin demand in the ARDL(1,1,1) model.

VARIABLES	MG	PMG	DFE	MG	PMG	DFE	MG	PMG	DFE
Time fixed effects	No	No	No	No	No	No	Yes	Yes	Yes
Manufacturing (log)	1.064***	0.818***	0.965***	0.951***	0.959***	0.945***	0.619	0.951***	1.012***
	(0.146)	(0.030)	(0.143)	(0.212)	(0.076)	(0.257)	(0.526)	(0.090)	(0.282)
Zinc price (log)	-0.288**	-0.148**	-0.178	-0.199*	-0.153**	-0.176	-0.199	0.174***	0.106**
	(0.118)	(0.073)	(0.173)	(0.102)	(0.070)	(0.165)	(0.720)	(0.050)	(0.045)
Linear Trend				-0.000	-0.003*	0.000			
				(0.005)	(0.001)	(0.004)			
Adjustment coefficient	-0.265***	-0.144***	-0.121***	-0.317***	-0.152***	-0.121***	-0.208***	-0.135***	-0.110***
	(0.069)	(0.030)	(0.022)	(0.069)	(0.032)	(0.022)	(0.037)	(0.024)	(0.019)
Constant	-1.495*	-0.319***	-0.399*	-1.528	-0.131	-0.440	0.204*	-0.008	0.002
	(0.827)	(0.069)	(0.208)	(2.594)	(0.086)	(0.299)	(0.122)	(0.023)	(0.001)
Observations	1,266	1,266	.	1,266	1,266	.	1,266	1,266	.
Joint Hausman Test-stat.		2.703			0.478			0.580	
p-value		0.259			0.924			0.748	
log likelihood		456.6			458.1			426.2	

Notes: The table shows results from the mean group (MG), pooled mean group (PMG), and dynamic fixed effects (DFE) estimations of the preferred ARDL(1,1,1) model. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 3.17: Estimated long-run manufacturing output and price elasticities of zinc demand in the ARDL(1,1,1) model.

VARIABLES Time fixed effects	MG No	PMG No	DFE No	MG No	PMG No	DFE No	MG Yes	PMG Yes	DFE Yes
Manufacturing (log)	0.985*	1.528***	1.618***	1.017	1.740***	1.562***	1.089**	1.584***	1.493***
	(0.548)	(0.042)	(0.203)	(0.929)	(0.131)	(0.271)	(0.499)	(0.072)	(0.208)
Aluminum price (log)	-1.224**	-0.824***	-0.967***	-1.280**	-0.931***	-0.902***	-1.347**	-1.038***	-1.438***
	(0.482)	(0.138)	(0.277)	(0.624)	(0.175)	(0.348)	(0.549)	(0.242)	(0.376)
Linear trend				0.006	-0.012*	0.003			
				(0.018)	(0.007)	(0.009)			
Adjustment coeff.	-0.151***	-0.134***	-0.076***	-0.175***	-0.125***	-0.077***	-0.192***	-0.142***	-0.104***
(0.054)	(0.051)	(0.010)	(0.054)	(0.044)	(0.011)	(0.037)	(0.032)	(0.015)	
Constant	0.073	0.057	-0.019	0.956	1.738**	-0.228	0.110	0.077	-0.009
	(0.515)	(0.081)	(0.177)	(2.087)	(0.776)	(0.715)	(0.143)	(0.107)	(0.007)
Observations	980	980	980	980	980	980	980	980	980
Joint Hausman Test-stat.		0.934			11.31			0.985	
p-value		0.627			0.0102			0.611	
log likelihood		378.2			379.4			422.1	

Notes: The table shows results from the mean group (MG), pooled mean group (PMG), and dynamic fixed effects (DFE) estimations of the preferred ARDL(3,3,3) model. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 3.18: Estimated long-run manufacturing output and price elasticities of aluminum demand in the ARDL (3,3,3) model.

VARIABLES Time fixed effects	MG No	PMG No	DFE No	MG No	PMG No	DFE No	MG Yes	PMG Yes	DFE Yes
Manufacturing (log)	1.117***	0.963***	1.063***	1.142***	1.399***	1.053***	0.957***	1.047***	1.131***
	(0.160)	(0.055)	(0.085)	(0.139)	(0.097)	(0.175)	(0.321)	(0.063)	(0.177)
Copper price (log)	-0.096	-0.285***	-0.116	-0.130	-0.468***	-0.113	-0.139	-0.041	0.263**
	(0.142)	(0.087)	(0.174)	(0.130)	(0.065)	(0.181)	(0.290)	(0.053)	(0.102)
Linear trend				0.002	-0.012***	0.000			
				(0.004)	(0.003)	(0.004)			
Adjustment coefficient	-0.217***	-0.141***	-0.105***	-0.241***	-0.147***	-0.105***	-0.259***	-0.179***	-0.112***
	(0.048)	(0.028)	(0.015)	(0.047)	(0.041)	(0.015)	(0.067)	(0.049)	(0.016)
Constant	-0.924***	-0.291***	-0.395***	-3.604*	1.514***	-0.416	0.170	0.017	0.005
	(0.218)	(0.059)	(0.134)	(2.176)	(0.586)	(0.341)	(0.170)	(0.028)	(0.006)
Observations	1,213	1,213	1,213	1,213	1,213	1,213	1,213	1,213	1,213
Joint Hausman Test-stat.		2.827			20.72			0.125	
p-value		0.243			0.000120			0.939	
log likelihood		481.2			485.1			427.5	

Notes: The table shows results from the mean group (MG), pooled mean group (PMG), and dynamic fixed effects (DFE) estimations of the preferred ARDL(3,3,3) model. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 3.19: Estimated long-run manufacturing output and price elasticities of copper demand in the ARDL (3,3,3) model.

VARIABLES Time fixed effects	MG No	PMG No	DFE No	MG No	PMG No	DFE No	MG Yes	PMG Yes	DFE Yes
Manufacturing (log)	0.382***	0.023	0.499***	1.609***	0.779***	0.833***	3.456	0.829***	0.813***
	(0.085)	(0.067)	(0.124)	(0.496)	(0.127)	(0.227)	(3.033)	(0.119)	(0.228)
Lead price (log)	0.070	-0.053	0.289	-0.062	-0.257***	0.244	6.764	-0.014	0.253
	(0.480)	(0.082)	(0.251)	(0.138)	(0.091)	(0.229)	(5.547)	(0.224)	(0.459)
Linear trend				-0.037**	-0.008***	-0.008			
				(0.018)	(0.002)	(0.005)			
Adjustment coefficient	-0.151***	-0.085***	-0.083***	-0.201***	-0.117***	-0.092***	-0.207***	-0.143***	-0.095***
	(0.019)	(0.026)	(0.015)	(0.017)	(0.023)	(0.016)	(0.043)	(0.026)	(0.016)
Constant	0.150	0.287***	-0.126	6.902	0.692***	0.471	0.281	0.025	0.001
	(0.164)	(0.103)	(0.112)	(4.594)	(0.167)	(0.402)	(0.171)	(0.022)	(0.007)
Observations	1,068	1,068	1,068	1,068	1,068	1,068	1,068	1,068	1,068
Joint Hausman Test-stat.		40.09			2.956			2.321	
p-value		1.97e-09			0.398			0.313	
log likelihood		490.8			491.7			444.8	

Notes: The table shows results from the mean group (MG), pooled mean group (PMG), and dynamic fixed effects (DFE) estimations of the preferred ARDL(3,3,3) model. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 3.20: Estimated long-run manufacturing output and price elasticities of lead demand in the ARDL (3,3,3) model.

VARIABLES Time fixed effects	MG No	PMG No	DFE No	MG No	PMG No	DFE No	MG Yes	PMG Yes	DFE Yes
Manufacturing (log)	-0.203	0.611***	-0.010	0.988***	-0.490	0.815***	0.406	1.158***	0.834***
	(0.422)	(0.041)	(0.163)	(0.296)	(0.358)	(0.279)	(0.500)	(0.081)	(0.276)
Tin price (log)	-0.273	0.019	-0.736**	-0.224*	-0.229	-0.561**	-0.094	-0.124	-0.131
	(0.190)	(0.114)	(0.340)	(0.135)	(0.187)	(0.262)	(0.317)	(0.093)	(0.157)
Linear trend				-0.019***	-0.008	-0.018***			
				(0.007)	(0.009)	(0.006)			
Adjustment coefficient	-0.228***	-0.086**	-0.054***	-0.283***	-0.063*	-0.068***	-0.195***	-0.106***	-0.068***
	(0.060)	(0.035)	(0.011)	(0.081)	(0.032)	(0.012)	(0.035)	(0.026)	(0.013)
Constant	-0.591	-0.388**	0.227**	6.782	1.001*	1.137***	0.213*	0.009	0.004
	(0.607)	(0.153)	(0.092)	(5.190)	(0.594)	(0.332)	(0.121)	(0.018)	(0.006)
Observations	1,152	1,152	1,152	1,152	1,152	1,152	1,152	1,152	1,152
Joint Hausman Test-stat.		6.140			41.56			2.210	
p-value		0.0464			4.97e-09			0.331	
log likelihood		392.7			395.0			399.0	

Notes: The table shows results from the mean group (MG), pooled mean group (PMG), and dynamic fixed effects (DFE) estimations of the preferred ARDL(3,3,3) model. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 3.21: Estimated long-run manufacturing output and price elasticities of tin demand in the ARDL (3,3,3) model.

VARIABLES	MG	PMG	DFE	MG	PMG	DFE	MG	PMG	DFE
Time fixed effects	No	No	No	No	No	No	Yes	Yes	Yes
Manufacturing (log)	0.885***	0.749***	0.866***	1.107***	0.894***	0.895***	-1.686	0.709***	0.934***
	(0.184)	(0.031)	(0.096)	(0.316)	(0.090)	(0.210)	(2.547)	(0.117)	(0.224)
Zinc price (log)	0.629	-0.085	0.025	0.188	-0.098	0.023	1.359	0.146*	0.102
	(1.017)	(0.085)	(0.269)	(0.400)	(0.080)	(0.270)	(1.393)	(0.082)	(0.114)
Linear trend				-0.007	-0.003	-0.001			
				(0.008)	(0.002)	(0.004)			
Adjustment coefficient	-0.190***	-0.114***	-0.084***	-0.260***	-0.121***	-0.084***	-0.136***	-0.090***	-0.084***
	(0.049)	(0.033)	(0.013)	(0.053)	(0.035)	(0.013)	(0.032)	(0.019)	(0.013)
Constant	-1.094*	-0.207***	-0.266**	0.572	-0.056	-0.226	0.112	-0.007	0.001
	(0.566)	(0.062)	(0.106)	(3.655)	(0.063)	(0.279)	(0.110)	(0.015)	(0.005)
Observations	1,224	1,224	1,224	1,224	1,224	1,224	1,224	1,224	1,224
Joint Hausman Test-stat.		1.664			12.12			1.377	
p-value		0.435			0.00697			0.502	
log likelihood		563.4			564.6			512.5	

Notes: The table shows results from the mean group (MG), pooled mean group (PMG), and dynamic fixed effects (DFE) estimations of the preferred ARDL(3,3,3) model. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 3.22: Estimated long-run manufacturing output and price elasticities of zinc demand in the ARDL (3,3,3) model.

Data sources and description

Table 3.23: Data sources for the mineral commodity prices.

Mineral Comm.	**Country**	**Time**	**Units**	**Sources**	**Notes**
Aluminum	U.K.	1904-75	£/mt	Schmitz 1979, pp. 263-5	1913-45: Ingots, 99-99.5% metal cont., London market; 1946-75: Ingots, min. 99.5% metal cont., London market.
	U.K.	1976-2010	US-$/mt	BGR, 2011a	1976-Nov 78: Primary aluminum, cash, in London Metal Exchange (LME) warehouse, min. 99.5% metal content; Dec 1978-Jul 87: Primary aluminum, cash, in LME warehouse, min. 99.5% metal cont.; Aug 1987-2010: High grade primary aluminum, cash, in LME warehouse, min. 99.7% metal cont.
Aluminum	U.S.	1895-1976	US-$/mt	Schmitz 1979, pp. 263-5	1895-1945: Ingots, min. 99% metal cont., New York market; 1946-76: Ingots, min. 99.5% metal cont., New York market.
	U.S.	1977-98	US-$/mt	Sachs 1999, p. 3	1977-82: New York market, 1983-98: New York market, 99.7% pure aluminum ingot.
	U.S.	1999-2000	US-$/mt	U.S. Geological Survey 2001	New York market, 99.7% pure aluminum ingot.
	U.S.	2001-5	US-$/mt	U.S. Geological Survey 2007	New York market, 99.7% pure aluminum ingot.
	U.S.	2006-10	US-$/mt	U.S. Geological Survey 2011c	New York market, 99.7% pure aluminum ingot.

Aluminum	Germany	1854-1975	Marks/mt	Schmitz 1979, pp. 263-5	1854-89: Continental European price, selling price of refined aluminum, Deville Co. France; 1858, 1860-3, 1865-73, 1875-7, 1879-83, 1887: linear trend; 1890-Mar 1958: Ingots, min. 99% metal cont., av. selling price of German primary aluminum; Apr 1958-75: Ingots, min. 99.5% metal cont., av. selling price of German primary aluminum; 1914: Jan-Jul only; 1915-8, 1942-7: Official max. price.
	Germany	1976-2010	US-$/mt	BGR, 2011a	1976-Nov 78: Primary aluminum, cash, in LME warehouse Hamburg, min. 99.5% metal cont.; Dec 1978-Jul 87: Primary aluminum, cash, in LME warehouse Hamburg, min. 99.5% metal cont.; Aug 1987-2010: High grade primary aluminum, cash, in LME warehouse Hamburg, min. 99.7% metal cont.

Copper	U.K.	1790-1976	£/mt	Schmitz 1979, pp. 268-72	1790-1879: Tough copper, fire-refined, av. 99.25% metal cont., London market; 1880-1914: Best selected copper, fire-refined, av. 99.75% metal cont., London market; 1915-76: Electrolytic wirebars, min. 99.9% metal cont., London market; 1939: Price av. Jan-Aug only as LME dealings were suspended; Sep 1940-Aug 53: controlled selling price of the Ministry of Supply.
	U.K.	1977-2010	US-$/mt	BGR, 2011a	Grade A, cash, in LME warehouse, min. 99.99% metal cont.
Copper	U.S.	1850-1976	US-$/mt	Schmitz 1979, pp. 268-72	1850-99: Lake copper, fire-refined, New York market, min. 99.9% metal cont.; 1900-1934: Electrolytic wirebars, min. 99.9% metal cont., New York market; 1935-1976: Electrolytic wirebars (domestic), net Atlantic seaboard refinery, min. 99.9% metal cont.; Sep 1967-Apr 68: U.S. producer strike, so 1967 is the average of Jan-June and 1968 is the average of May-Dec.
	U.S.	1977-90	U.S.-$/mt	U.S. Bureau of Mines 1981, 1987, 1993	Cathode, min. 99.99% metal cont., U.S. producer price.
	U.S.	1991-2010	U.S.-$/mt	U.S. Geological Survey 1996, 2001, 2007, 2011c	Cathode, min. 99.99% metal cont., U.S. producer price.

Copper	Germany	1845-57	Marks/mt	Schmitz 1979, pp. 270-2	Price of Mansfeld copper, Berlin market; 1847-50: linear trend.
	Germany	1858	Marks/mt	Ministerium für Handel, Gewerbe und öffentliche Arbeiten 1859, p. 14	Price of Mansfeld copper, Berlin market.
	Germany	1859-1975	Marks/mt	Schmitz 1979, pp. 270-2	1859: lin. trend; 1860-1913: Mansfeld fire-refined copper ex-works; 1914-23: Source unknown; 1924-75: Electrolytic wirebars, FOB, av. selling price of German refineries; Oct 1939 - Jun 50 official max. price.
	Germany	1976-2010	US-$/mt	BGR, 2011a	Grade A, cash, in LME warehouse Hamburg, min. 99.99% metal cont.
Lead	U.K.	1790-1976	£/mt	Schmitz 1979, pp. 226-37	1790-1886: English pig lead, mostly prices in provincial markets pre-1850, then mainly London prices; 1887-1945: Good soft pig lead, London market; 1946-76: Refined pig lead, min. 99.97% metal cont., London market; 1914: Average Jan-July and Nov-Dec only; 1940-Sept 52: Fixed selling price, Ministry of Supply.
	U.K.	1977-2010	U.S.-$/mt	BGR, 2011a	Lead, min. 99.97% metal cont., cash, in LME warehouse.

Lead	U.S.	1820-1976	U.S.-$/mt	Schmitz 1979, pp. 274-8	1820-79: Pig lead, New York; 1880-1976: Common grade lead, min. 99.73% metal cont., New York.
	U.S.	1977-90	U.S.-$/mt	U.S. Bureau of Mines 1981, 1987, 1993	Min. 99.97% metal cont., North American producer price, delivered.
	U.S.	1991-2010	U.S.-$/mt	U.S. Geological Survey 1996, 2001, 2007, 2011c	Min. 99.97% metal cont., North American producer price, delivered.
Lead	Germany	1840-1976	Marks/mt	Schmitz 1979, pp. 274-8	1840-98: Silesian lead, ex-works at Tarnowitz; 1899-1918: Rhenish refined lead ex-smelter, min 99.9% metal cont.; 1924-39: Good soft pig lead, min. 99.9% metal cont., Berlin Metal Exchange; Oct 1939-Aug 50: Officially regulated price; 1950-76: Soft pig lead, min. 99.9% metal cont.
	Germany	1977-2010	U.S.-$/mt	BGR, 2011a	Min. 99.97% metal cont., cash, in LME warehouse Hamburg.
Tin	U.K.	1790-1976	£/mt	Schmitz 1979, pp. 240-1	1790-1837: Common refined tin, Cornwall; 1838-72: Standard tin, London market; 1873-1976: Standard tin, min. 99.75% metal cont., London market; 1914: Average price of Jan-July and Oct-Dec only; 1942-9: controlled price, Ministry of Supply.

	U.K.	1977-8	U.S.-$/mt	U.S. Bureau of Mines 1980, p. 915	Standard tin, min. 99.75% metal cont., London market.
	U.K.	1979-2010	U.S.-$/mt	BGR, 2011a	Min. 99.85% metal cont., in LME warehouse, cash.
Tin	U.S.	1841-55	U.S.-$/mt	House of Commons 1853,	Computed from quantities and values of U.S. imports of tin in blocks and pigs; 1851-5: lin. trend.
	U.S.	1856-1962	U.S.-$/mt	Secretary of the Treasury 1864, pp. 46-8	Computed from quantities and values of U.S. imports of tin in blocks and pigs.
	U.S.	1863	U.S.-$/mt	House of Commons 1866, p. 358	Computed from quantities and values of U.S. imports of tin in blocks and pigs.
	U.S.	1864-9	U.S.-$/mt	House of Commons 1868, p. 378	Computed from quantities and values of U.S. imports of tin in blocks and pigs; 1866-9: lin. trend.
	U.S.	1870-1976	U.S.-$/mt	Schmitz 1979, pp. 293-8	1869-80: Block tin, New York; 1881-1919: Ordinary brands, min. 99% metal cont., New York; 1920-76: Straits tin, Grade A, min. 99.85% metal cont., New York; 1918: median price; 1976: av. Jan, Jul, & Dec.
	U.S.	1977-90	U.S.-$/mt	U.S. Bureau of Mines 1981, 1987, 1993	Contained tin, New York market.
	U.S.	1991-2010	U.S.-$/mt	U.S. Geological Survey 1996, 2001, 2007, 2011c	Contained tin, New York market.

Tin	Germany	1840-1975	Marks/mt	Schmitz 1979, pp. 293-8	1840-1902: Saxon tin at Freiberg; 1903-14: Banca tin (from Dutch East Indies) in Frankfurt am Main; 1925-75: Banca and Straits tin, Hamburg, min. 99.9% metal cont.; Oct 1939-47: Official max. price; 1973: Jan-June average only; 1974: Mar-Dec average only.
	Germany	1976-8	U.S.-$/mt	U.S. Bureau of Mines 1980, p. 915	Standard tin, min. 99.75% metal cont., in LME warehouse Hamburg.
	Germany	1979-2010	U.S.-$/mt	BGR, 2011a	Min. 99.85% metal cont., in LME warehouse Hamburg, cash.
Tin	Japan	1950-86	Yen/mt	Ministry of Internal Affairs and Communication of Japan 2012	Computed from data on the quantity and value of tin ore.
Zinc	U.K.	1823-1976	£/mt	Schmitz 1979, pp. 299-303	1823-1951: Ordinary brands zinc, London market; 1940-4: controlled price, U.K. Ministry of Supply; 1952-76: virgin zinc, min. 98% metal cont., London market.
	U.K.	1977-8	U.S.-$/mt	U.S. Bureau of Mines 1980, p. 981	Prime Western grade, min. 98% metal cont., London market.
	U.K.	1979-2010	U.S.-$/mt	BGR, 2011a	Special high grade, min. 99.995% metal cont., cash, LME warehouse.
Zinc	U.S.	1872-4	U.S.-$/mt	U.S. Bureau of Mines 1883	U.S. import price of zinc in blocks or pigs.

	U.S.	1875-1976	U.S.-$/mt	Schmitz 1979, pp. 300-3	1875-99: Prime Western spelter, min. 98% metal cont., New York; 1900-76: Prime Western spelter, Saint Louis, min. 98% metal cont.
	U.S.	1977-90	U.S.-$/mt	U.S. Bureau of Mines 1981, 1987, 1993	1977-9: Prime Western spelter, delivered, min. 98% metal cont.; 1980-90: High grade, min. 99.9% metal cont., delivered.
	U.S.	1991-2010	U.S.-$/mt	U.S. Geological Survey 1996, 2001, 2007, 2011c	Special high grade, delivered, min. 99.99% metal cont.
Zinc	Germany	1840-1975	Marks/mt	Schmitz 1979, pp. 299-303	1840-1914: Upper Silesian zinc ex-works at Breslau; 1924-34: Berlin Metal Exchange quotation for primary zinc, min. 97% metal cont.
	Germany	1977-8	U.S.-$/mt	U.S. Bureau of Mines 1980, p. 981	Prime Western grade, min. 98% metal cont., LME warehouse, Hamburg.
	Germany	1979-2010	U.S.-$/mt	BGR, 2011a	Special high grade, min. 99.995% metal cont., cash, LME warehouse, Hamburg.
Crude Oil	U.S./U.K.	1861-2010	U.S.-$/barrel	British Petroleum 2011	1861-1944: U.S. average; 1945-83: Arabian Light posted at Ras-Tanura; 1984-2010: Brent dated.

Note: Parts of the data described in the table above are based on a revised and extended version of data used in figures in Stürmer and von Hagen (2012b).

Table 3.24: Data sources for the producer price indices.

Country	**Time**	**Source**	**Notes**
Belgium	1840-1980	Mitchell 2003a, pp. 857-8	Wholesale price index
	1981-2011	IMF, 2012a	Wholesale price index/ producer price index
Finland	1913-48	Mitchell 2003a, pp. 858-60	Wholesale price index
	1949-2011	IMF, 2012a	Wholesale price index/ producer price index
France	1850-1980	Mitchell 2003a, pp. 857-8	1850-1974: Wholesale price index; 1974-80: No general index published, producer price index for metals products.
	1981-96	IMF, 2012a	Producer price index for intermediate goods
	1997-2010	IMF, 2012a	Wholesale price index/ producer price index
Germany	1850-1991	Mitchell 2003a, pp. 857-8	Wholesale price index
	1992-2011	IMF, 2012a	Wholesale price index/ producer price index
Italy	1861-1981	Mitchell 2003a, pp. 857-60	Wholesale price index
	1982-2011	IMF, 2012a	Wholesale price index/ producer price index
Japan	1901-60	Mitchell 1998, pp. 945-8	Wholesale price index
	1961-2011	IMF, 2012a	Wholesale price index/ producer price index
Netherlands	1901-53	Mitchell 2003a, pp. 857-60	Wholesale price index
	1954-2011	IMF, 2012a	Wholesale price index/ producer price index
South Korea	1930-53	Mitchell 1998, pp. 945-8	Wholesale price index; value for 1952: crude estimate by author
	1954-2011	IMF, 2012a	Wholesale price index/ producer price index
Spain	1850-1948	Mitchell 2003a, pp. 857-60	Wholesale price index

	1949-2011	IMF, 2012a	Wholesale price index/ producer price index
Sweden	1860-1968	Mitchell 2003a, pp. 857-60	Wholesale price index
	1969-2011	IMF, 2012a	Wholesale price index/ producer price index
U.K.	1820-1913	Mitchell 1988, pp. 722-4	Rousseaux price index constructed from wholesale prices and unit-value of imports of vegetable, animal, agricultural, and industrial products.
	1914-59	Mitchell 1988, pp. 725-7	Sauerbeck-Statist price index constructed from wholesale prices and unit-value of food (vegetable and animnal) and raw materials (minerals, textile fibres, sundry).
	1960-2010	World Bank 2012	Wholesale price index
U.S.	1850-9	Mitchell 2003b, p. 702	Wholesale price index
	1860-1912	Hanes 1998	Wholesale price index
	1913-2010	U.S. Bureau of Labor Statistics 2011	Producer price index: all commodities.

Table 3.25: Data sources for the consumer price indices.

Country	**Time**	**Source**	**Notes**
U.K.	1820-2010	U.K. Office of Statistics 2011	
U.S.	1774-2008	Officer and Williamson 2011	

Table 3.26: Data sources for the exchange rates between the British-£ and other currencies.

Country	**Currencies**	**Time**	**Source**	**Notes**
Belgium	British-£ per 1000 Guilders	1840-3	Denzel 2010, p. 21	
	British-£ per 1000 France	1844-1914	Denzel 2010, pp. 21-3	
France	British-£ per 1000 Old Francs	1840-1914	Denzel 2010, pp. 21-3	
Italy	British-£ per 1000 Piedmontese Lire Nuovo	1840-60	Denzel 2010, pp. 41-2	
	British-£ per 1000 Italian Lire	1861-1914	Denzel 2010, pp. 42-3	
Japan	British-£ per 100 Yen	1862-1914	Denzel 2010, pp. 533-4	No data available for 1872.
Netherlands	British-£ per 1000 Guilders	1840-1914	Denzel 2010, pp. 21-3	
Spain	British-£ per 100 Pesos de Plata Antigua	1840-7	Denzel 2010, p. 34	
	British-£ per 100 Pesos Duros	1848-98	Denzel 2010, pp. 34-5	
	British-£ per 1000 Pesetas	1899-1914	Denzel 2010, pp. 35-6	
Sweden	British-£ per 1000 Rixdollars Species	1840-57	Denzel 2010, pp. 346-7	
	British-£ per 1000 Rixdollars Rixmynt	1858-74	Denzel 2010, p. 347	
	British-£ per 1000 Crowns	1875-1914	Denzel 2010, pp. 347-8	

Table 3.27: Data sources for the exchange rates between the U.S.-$ and other currencies.

Country	**Currencies**	**Time**	**Source**	**Notes**
Belgium	Francs per U.S.-$	1915-9	Bordo 2001	
	Francs per U.S.-$	1920-99	Officer 2006	From 1927-40 the exchange rate is expressed in belgas.
	Euro per U.S.-$	2000-11	Officer 2011	
Finland	New Markaa per U.S.-$	1911-70	Bordo 2001	Bordo et al (2001) transformed the original Old Markaa data into New Markaa.
	New Markaa per U.S.-$	1971-99	Officer 2006	
	Euro per U.S.-$	2000-11	Officer 2011	
France	Old Francs per U.S.-$	1915-40	Officer 2006	
	Old Francs per U.S.-$	1941-4	Officer 2011	
	Old Francs per U.S.-$	1945-59	Officer 2006	
	Francs per U.S.-$	1960-99	Officer 2006	
	Euro per U.S.-$	2000-2011	Officer 2011	
Germany	Mark per U.S.-$	1976-1999	Officer 2006	
	Euro per U.S.-$	2000-2011	Officer 2011	
Italy	Lire per U.S.-$	1915-1940	Officer 2006	
	Lire per U.S.-$	1941-7	Bordo 2001	
	Lire per U.S.-$	1948-99	Officer 2006	
	Euro per U.S.-$	2000-11	Officer 2011	

Japan	Yen per U.S.-$	1915-55	Bordo 2001
	Yen per U.S.-$	1956-2011	Officer 2011
Netherlands	Guilder per U.S.-$	1915-40	Officer 2006
	Guilder per U.S.-$	1941	Bordo 2001
	Guilder per U.S.-$	1945-99	Officer 2006
	Euro per U.S.-$	2000-11	Officer 2011
South Korea	Won per U.S.-$	1971-81	Bordo 2001
	Won per U.S.-$	1982-2009	Officer 2011
	Won per U.S.-$	2010	IMF, 2012a
	Won per U.S.-$	2011	Officer 2011
Spain	Loyalist Peseta per U.S.-$	1915-38	Officer 2006
	National Peseta per U.S.-$	1939-41	Officer 2006
	National Peseta per U.S.-$	1947-78	Bordo 2001
	National Peseta per U.S.-$	1979-99	Officer 2006
	Euro per U.S.-$	2000-11	Officer 2011
Sweden	Kronor per U.S.-$	1915-41	Officer 2006
	Kronor per U.S.-$	1942-5	Bordo 2001
	Kronor per U.S.-$	1946-99	Officer 2006
	Kronor per U.S.-$	2000-11	Officer 2011
U.K.	British-£per U.S.-$	1791-2011	Officer 2013

Table 3.28: Data sources for the manufacturing data.

Country	**Time**	**Source**	**Notes**
Belgium	1850-1988	Smits, Woltjer, and Ma 2009	GDP in current prices, total industry (incl. mining, manufacturing, energy, and construction).
	1989-94	OECD, 2012	GDP in current prices, total industry (incl. mining, manufacturing, energy, and construction).
	1995-2011	OECD, 2012	GDP in current prices, manufacturing.
Finland	1860-2001	Smits, Woltjer, and Ma 2009	GDP in current prices, manufacturing.
	2002-10	OECD, 2012	GDP in current prices, manufacturing.
France	1850-1913	Smits, Woltjer, and Ma 2009	GDP in current prices, total industry (incl. mining, manufacturing, energy, and construction).
	1920-38	Smits, Woltjer, and Ma 2009	GDP in current prices, total industry (incl. mining, manufacturing, energy, and construction).
	1950-60	United Nations, Statistical Office 1963, p. 270	GDP in current prices, manufacturing (incl. also fishing and the quarring of building materials).
	1961-9	United Nations, Statistical Office 1972	GDP in current prices, manufacturing.
	1970-98	Groningen Growth and Development Centre 2008	GDP in current prices, manufacturing.
	1999-2009	OECD, 2012	GDP in current prices, manufacturing.

	2010	OECD, 2012	GDP in current prices, manufacturing.
Germany	1850-1949	Hoffmann 1965	NDP at factor costs in constant 1913 prices, Industry and handcraft (incl. no mining, but possibly energy and construction); 1914-24 and 1939-49: linear trends.
	1950-90	Groningen Growth and Development Centre 2008	GDP at constant prices (base year = 1991); manufacturing; West Germany.
	1991-2011	Statistisches Bundesamt der Bundesrepublik Deutschland 2012	GDP in current prices, manufacturing.
Italy	1861-69	Baffigi 2011	GDP in current prices, manufacturing.
	1970-2010	OECD, 2012	GDP in current prices, manufacturing.
Japan	1885-1940	Timmer and de Vries 2007, p. 283	NDP in current prices, mining and manufacturing.
	1941-54	Ohkawa and Rosovsky 1973	NDP in current prices, manufacturing.
	1955-98	Ministry of Internal Affairs and Communication of Japan 2012	GDP in current prices, manufacturing.
	1999-2008	Japan Cabinet Office 2010	GDP in current prices, manufacturing.
	2009-2010	OECD, 2012	GDP in current prices, manufacturing.
Netherlands	1850-1912	Groningen Growth and Development Centre 2008	GDP in current prices, manufacturing.
	1913-39	Smits and Van der Bie 2001, pp. 90-3	GDP in current prices, manufacturing, data for the ceramic, glass, and diamonds sectors has been computed based on data from Smits, Horlings, and van Zanden (2000).

	1948-55	United Nations, Statistical Office 1963	GDP in current prices, manufacturing, 1949: linear trend.
	1956-62	United Nations, Statistical Office 1966	GDP in current prices, manufacturing.
	1963-68	United Nations, Statistical Office 1977	GDP in current prices, manufacturing. 1964 and 1966: linear trend.
	1969-2010	OECD, 2012	GDP in current prices, manufacturing.
South Korea	1911-40	Smits, Woltjer, and Ma 2009	GDP in current prices, manufacturing.
	1953-2011	Bank of Korea 2012	Manufacturing as a percentage share of GDP.
Spain	1850-1954	Smits, Woltjer, and Ma 2009	GDP in current prices, manufacturing.
	1955-9	United Nations, Statistical Office 1966	GDP in current prices, manufacturing.
	1960-9	United Nations, Statistical Office 1972	GDP in current prices, manufacturing.
	1970-94	Groningen Growth and Development Centre 2008	GDP in current prices, manufacturing.
	1995-2009	OECD, 2012	GDP in current prices, manufacturing.
Sweden	1850-1969	Smits, Woltjer, and Ma 2009	GDP in current prices, manufacturing.
	1970-92	Groningen Growth and Development Centre 2008	GDP in current prices, manufacturing.
	1993-2010	OECD, 2012	GDP in current prices, manufacturing.

U.K.	1840-1919	Mitchell 2003a	GDP in current prices, total industry.
	1920-59	Mitchell 1988	GDP in current prices, total industry.
	1960-2010	OECD, 2012	GDP in current prices, total industry.
U.S.	1869-89	Smits, Woltjer, and Ma 2009	GNP in current prices, manufacturing, 1870-8 and 1880-8: linear trend.
	1890-8		Linear trend.
	1899-1937	Martin 1939	GNP in current prices, manufacturing.
	1938-46		Linear trend.
	1947-97	Groningen Growth and Development Centre 2008	GNP in current prices, manufacturing.
	1998-2010	OECD, 2012	GDP in current prices, manufacturing.

Table 3.29: Data sources for world GDP.

Time Period	**Unit**	**Source**	**Notes**
1820-2008	Million 1990 International Geary-Khamis dollars	Maddison 2010	Description of data in Maddison, 2010.
2009-10	Million 1990 International Geary-Khamis dollars	The Conference Board 2012	Computed from growth rates of real GDP (PPP adjusted).

Table 3.30: Data sources for the usage of aluminum.

Country	**Time**	**Source**	**Notes**
Belgium	1930-2010	BGR, 2012a	Refined aluminum; including Luxembourg.
Finland	1946-2010	BGR, 2012a	Refined aluminum.
France	1893-9	Metallgesellschaft 1905, p. 30	Computed from import, export, and production data for aluminum.
	1900-2010	BGR, 2012a	Refined aluminum.
Germany	1892-5	Metallgesellschaft 1905, p. 30	Usage equals refined aluminum production; no imports and exports according to Metallgesellschaft; production includes Austria-Hungary and Switzerland as it is based on data of the Aluminium Industrie AG with production facilities in Neuhausen (Switzerland), Rheinfelden (Germany), and Lend-Gastein (Austria).
	1895-9	Metallgesellschaft 1905, p. 30	Computed from German exports and imports of refined aluminum and refined aluminum production for Austria-Hungary, Switzerland, and Germany, as it is based on data of the Aluminium Industrie AG with production facilities in Neuhausen (Switzerland), Rheinfelden (Germany), and Lend-Gastein (Austria).
	1900-9	Metallgesellschaft 1910, p. 16	Aluminum; estimates by Metallgesellschaft.
	1910-2	Metallgesellschaft 1913, p. 16	Aluminum.
	1913	Metallgesellschaft 1927, p. 4	Aluminum.
	1914-9	Metallgesellschaft 1922, p. 4	Aluminum.
	1920-2010	BGR, 2012a	Refined aluminum. 1949-90: West Germany.

Italy	1908-2010	BGR, 2012a	Refined aluminum.
Japan	1911-2010	BGR, 2012a	Refined aluminum.
Netherlands	1946-2010	BGR, 2012a	Refined aluminum.
South Korea	1962-2010	BGR, 2012a	Refined aluminum. 1964: linear trend.
Spain	1938-2010	BGR, 2012a	Refined aluminum.
Sweden	1929-2010	BGR, 2012a	Refined aluminum.
U.K.	1890-1	Metallgesellschaft 1899, p. 32	Usage equal to production of aluminum. No data on imports and exports available. I assume no considerable amounts of imports and exports.
	1892-9	Metallgesellschaft 1905, p. 30	Usage equal to production of aluminum. No data on imports and exports available. I assume no considerable amounts of imports and exports. 1895: lin. trend.
	1900-2010	BGR, 2012a	Refined aluminum.
U.S.	1890-1	Metallgesellschaft 1899, p. 32	Computed from imports and domestic production of aluminum. No export data available.
	1892-9	Metallgesellschaft 1905, p. 30	Computed from imports and domestic production of aluminum. Export data only in U.S.-$ terms. According to this data, quantities seem to be not considerable.
	1900-2010	BGR, 2012a	Refined aluminum.

Note: Parts of the data described in the Table above and in Tables 3.31, 3.33, 3.34 are based on a revised and extended version of data used in figures in Stürmer and von Hagen (2012b).

Table 3.31: Data sources for the usage of copper.

Country	**Time**	**Source**	**Notes**
Belgium	1900-2010	BGR, 2012a	Refined copper.
Finland	1941-2010	BGR, 2012a	Refined copper.
France	1881-4	Metallgesellschaft 1899, p. 53	Unwrought copper including changes in apparent stocks.
	1885-1902	Metallgesellschaft 1905, p. 51	Unwrought copper including changes in apparent stocks.
	1903-12	Metallgesellschaft 1913, p. 50	Unwrought copper including changes in apparent stocks.
	1913-2010	BGR, 2012a	Refined copper.
Germany	1850-64	Bienengräber 1868, pp. 303-4, Schmitz 1979, p. 63	Computed from imports and exports of unwrought copper and brass (Bienengräber, 1868), and the production of primary copper (Schmitz, 1979).
	1865-6	Schmitz 1979, p. 63	Exports and imports: linear trends; computed from imports and exports and the production of primary copper (Schmitz, 1979).
	1867	Hirth 1869, p. 122, Schmitz 1979, p. 63	Computed from imports and exports of primary and secondary copper (Hirth, 1869), and the production of primary copper (Schmitz, 1979).
	1868-71	Hirth 1871, p. 560 and 670, Schmitz 1979, p. 63	Computed from imports and exports of primary and secondary copper (Hirth, 1871), and the production of primary copper (Schmitz, 1979); imports in 1871: linear trend; exports in 1870-1: linear trend.
	1872-5	Kaiserliches Statistisches Amt 1890, p. 144	Computed from imports and exports of primary and secondary copper, and the production of primary copper of the German Reich, excluding Hamburg.
	1876-80	Kaiserliches Statistisches Amt 1890, p. 131	Computed from imports and exports of primary and secondary copper, and the production of primary copper of the German Reich, excluding Hamburg. Hamburg joined the German customs area in 1881, but maintained a free trade zone. Copper production in Hamburg started in 1878 with a relatively small amount of 40t p.a.
	1881-4	Metallgesellschaft 1899, p. 49	Computed from imports, exports, and the production of unwrought copper of the German Reich, excluding Hamburg.

	1885-94	Metallgesellschaft 1913, p. 30	Computed from imports, exports, and the production of unwrought copper of the German Reich, excluding Hamburg.
	1895-9	Metallgesellschaft 1913, p. 45	Computed from imports, exports, and the production of unwrought copper of the German Reich, excluding Hamburg.
	1900-2010	BGR, 2012a	Refined copper.
Italy	1881-4	Metallgesellschaft 1899, p. 55	Unwrought copper and copper alloys.
	1885-1902	Metallgesellschaft 1905, p. 53	Unwrought copper and copper alloys.
	1903-11	Metallgesellschaft 1913, p. 54	Unwrought copper.
	1912-2010	BGR, 2012a	Refined copper.
Japan	1885-8	House of Commons 1892b, pp. 128-9, Mitchell 1998, p. 387	Computed from imports, exports (House of Commons, 1901), and the mine production of copper (Mitchell, 1998). 1886: linear trend.
	1889-91	House of Commons 1901, pp. 156-7, Mitchell 1998, p. 387	Computed from imports, exports (House of Commons, 1901), and the mine production of copper (Mitchell, 1998).
	1892-1900	House of Commons 1901, pp. 156-7, House of Commons 1914, p. 485	Computed from imports, exports (House of Commons, 1901), and the production of copper (House of Commons, 1914); Exports 1900: linear trend.
	1901-10	House of Commons 1914, pp. 238-9, BGR, 2012b	Computed from imports and exports of unwrought copper and the domestic production of refined copper.
	1911-2010	BGR, 2012a	Refined copper.
Netherlands	1864-9	House of Commons 1874, pp. 40-5	Computed from imports and exports of unwrought copper; no domestic production.
	1870-80	House of Commons 1881, pp. 62-4	Computed from imports and exports of unwrought copper; no domestic production; no reasonable data in 1872.
	1881-90	House of Commons 1892b, pp. 82-5	Computed from imports and exports of unwrought copper; no domestic production; no reasonable data in 1882.
	1891-9	House of Commons 1901, pp. 92-5	Computed from imports and exports of unwrought copper; no domestic production.

	1900		Linear trend.
	1901-12	House of Commons 1914, pp. 136-9	Computed from imports and exports of unwrought copper; no domestic production.
	1913	House of Commons 1915, pp. 32-4	Computed from imports and exports of unwrought copper; no domestic production; quantities during the eleven months ended in November.
	1914-6	House of Commons 1917, pp. 26-8	Computed from imports and exports of unwrought copper; no domestic production.
	1918-20	House of Commons 1921, p. 38	Computed from imports and exports of unwrought copper; no domestic production.
	1921	House of Commons 1922, p. 34	Computed from imports and exports of unwrought copper; no domestic production.
	1924-2010	BGR, 2012a	Refined copper.
South Korea	1964-2010	BGR, 2012a	Refined copper.
Spain	1922-2010	BGR, 2012a	Refined copper.
Sweden	1922-2010	BGR, 2012a	Refined copper.
U.K.	1850	House of Commons 1852, pp. 87-9, Schmitz 1979, p. 209	Computed from imports of unwrought and partly wrought copper, exports of unwrought copper, and the domestic smelter production.
	1851	House of Commons 1853, pp. 99-100, Schmitz 1979, p. 209	Computed from imports of unwrought and partly wrought copper, exports of unwrought copper, and the domestic smelter production.
	1852	House of Commons 1854c, pp. 101-2, Schmitz 1979, p. 209	Computed from imports of unwrought and partly wrought copper, exports of unwrought copper, and the domestic smelter production.
	1853	House of Commons 1855, pp. 2-3, Schmitz 1979, p. 209	Computed from imports of unwrought and partly wrought copper, exports of unwrought copper, and the domestic smelter production.

1854-80	House of Commons 1882, pp. 110-21, Schmitz 1979, p. 209	Computed from imports of unwrought and partly wrought copper, exports of unwrought copper, and the domestic smelter production. Production data from 1877-80: House of Commons (1884a, p. 44), copper produced (computed by source from copper ores and precipitat from mines in the UK, colonial and foreign ores imported, copper precipitate and regulus imported and burnt ores from imported cupreous pyrites, deducting British copper ores exported to foreign countries).
1881	House of Commons 1885a, p. 23, House of Commons 1884a, p. 44	Computed from imports of unwrought and partly wrought copper, exports of unwrought copper, and the domestic copper production (computed by House of Commons (1884a) from copper ores and precipitat from mines in the UK, colonial and foreign ores imported, copper precipitate and regulus imported and burnt ores from imported cupreous pyrites, deducting British copper ores exported to foreign countries).
1882	House of Commons 1884a, pp. 41-4	Computed from imports of unwrought and partly wrought copper, exports of unwrought copper, and domestic copper production (computed by source from copper ores and precipitat from mines in the UK, colonial and foreign ores imported, copper precipitate and regulus imported and burnt ores from imported cupreous pyrites, deducting British copper ores exported to foreign countries).
1883	House of Commons 1884b, pp. 43-5, House of Commons 1885b, p. 42	do.
1884	House of Commons 1885b, pp. 39-41	do.
1885	House of Commons 1886, pp. 39-41	do.
1885	House of Commons 1886, pp. 39-41	do.
1886	House of Commons 1887, pp. 45-7, House of Commons 1888, p. 33	do.
1887	House of Commons 1888, pp. 28-33	do.

	1888-9	House of Commons 1891a, pp. 30-2	do.
	1890	House of Commons 1891b, pp. 32-5	do.
	1891	House of Commons 1892a, pp. 34-7	do.
	1892-3	House of Commons 1894, pp. 42-6	do.
	1894-5	House of Commons 1896, pp. 43-7	do.
	1896-7	House of Commons 1898, pp. 187-90	do.
	1898-9	House of Commons 1900, pp. 189-92	do.
	1900-2010	BGR, 2012a	Refined copper.
U.S.	1847-9	House of Commons 1854b, p. 2, Carter et al. 2006	Computed from imports of unwrought copper from the U.K., and smelter production from domestic ores. No imports or exports from other countries declared.
	1850-5	House of Commons 1856, p. 351, Carter et al. 2006	do.
	1856-62	Secretary of the Treasury 1864, pp. 44-8, Carter et al. 2006	Computed from imports of copper from the U.K., exports of copper to different countries and smelter production from domestic ores. No imports from other countries declared.
	1863	House of Commons 1866, p. 357, Carter et al. 2006	Computed from imports of pig copper and smelter production from domestic ores. No exports declared.
	1864-8	Weed 1916, p. 1315, House of Commons 1868, p. 377, Carter et al. 2006	Computed from imports of pig copper, exports of refined copper, and smelter production from domestic ores. Imports 1866-8: linear trend.
	1869-78	U.S. Bureau of Statistics 1879, p. 73 & 92, Carter et al. 2006	Computed from imports of copper pigs, bars, ingots, old, and other unmanufactured, exports of pigs, bars, sheets and old, and smelter production from domestic ores. Export and import data: years ended June 30th.

	1879-81	U.S. Bureau of Statistics 1889, p. 87 & 102, Carter et al. 2006	Computed from imports of copper pigs, bars, ingots, old, and other unmanufactured, exports of ingots, bars, sheets and old, and smelter production from domestic ores. Export and import data: years ended June 30th.
	1882-8	U.S. Bureau of Statistics 1889, p. 87 & 102 Schmitz 1979, p. 210	Computed from imports of copper pigs, bars, ingots, old, and other unmanufactured, exports of ingots, bars, and old, and domestic smelter production. Export and import data: years ended June 30th.
	1889-98	U.S. Bureau of Statistics 1899, p. 196 & 168, Schmitz 1979, p. 212	Computed from imports of copper pigs, bars, ingots, old, and other unmanufactured, exports of pigs, ingots, bars, and old, and domestic smelter production. Export and import data: years ended June 30th.
	1899	U.S. Bureau of Statistics 1909, p. 437 & 406, Schmitz 1979, p. 212	Computed from imports of copper pigs, bars, ingots, plats, and old, exports of pigs, ingots, plats, and old, and domestic smelter production. Export and import data: years ended June 30th.
	1900-2010	BGR, 2012a	Refined copper.

Table 3.32: Data sources for the usage of refined lead.

Country	**Time**	**Source**	**Notes**
Belgium	1900-2010	BGR, 2012a	Including Luxembourg.
Finland	1929-2010	BGR, 2012a	
France	1900-2010	BGR, 2012a	
Germany	1900-2010	BGR, 2012a	
Italy	1900-2010	BGR, 2012a	

Japan	1900-2010	BGR, 2012a
Netherlands	1906-2010	BGR, 2012a
South Korea	1967-2010	BGR, 2012a
Spain	1909-2010	BGR, 2012a
Sweden	1927-2010	BGR, 2012a
U.K.	1900-2010	BGR, 2012a
U.S.	1900-2010	BGR, 2012a

Table 3.33: Data sources for the usage of tin.

Country	**Time**	**Source**	**Notes**
Belgium	1900-2010	BGR, 2012a	Refined tin, including Luxembourg.
Finland			No data available.
France	1889-96	Metallgesellschaft 1899, p. 68	Unwrought tin.
	1897-1902	Metallgesellschaft 1907, p. 83	Unwrought tin.
	1903-2010	BGR, 2012a	Refined tin.
Germany	1850-64	Bienengräber 1868, pp. 337-8, Neumann 1904, pp. 251-3	Computed from imports and exports of tin in bars, blocks, and old tin, and the production of tin.
	1865-6	Königlich Preussisches Statistisches Bureau 1868, p. 211, Neumann 1904, pp. 251-3	Computed from imports and exports of tin in bars, blocks, and old tin, and the production of tin.
	1867	Hirth 1869, p. 130, Neumann 1904, pp. 251-3	Computed from imports and exports of tin in bars and blocks, and the production of tin. Exports: linear trend.
	1868-9	Hirth 1871, p. 567, Neumann 1904, pp. 251-3	Computed from imports and exports of tin in blocks etc, and the production of tin.
	1870-1	Neumann 1904, pp. 251-3	Computed from imports and exports of tin in blocks etc, and the production of tin. Exports and Imports: linear trends.
	1872-83	Kaiserliches Statistisches Amt 1885, p. 144	Tin.
	1884-5	Metallgesellschaft 1899, p. 66	Unwrought tin.
	1886-1902	Metallgesellschaft 1905, p. 64	Unwrought tin.
	1903-5	Metallgesellschaft 1913, p. 81	Unwrought tin.

	1906-2010	BGR, 2012a	Refined tin, 1949-90: West-Germany.
Italy	1889-96	Metallgesellschaft 1899, p. 27	Unwrought tin.
	1897-1902	Metallgesellschaft 1907, p. 84	Unwrought tin.
	1900-2010	BGR, 2012a	Refined tin.
Japan	1902-2010	BGR, 2012a	Refined tin.
Netherlands	1904-2010	BGR, 2012a	Refined tin.
South Korea	1969-2010	BGR, 2012a	Refined tin.
Spain	1900-2010	BGR, 2012a	Refined tin.
Sweden	1900-2010	BGR, 2012a	Refined tin.
U.K.	1850-96	Mitchell 1988, pp. 313-21, Schmitz 1979, pp. 164-8, House of Commons 1884a, p. 120	Computed from imports and exports (including re-exports) of unmanufactured tin and the production of metallic tin (equiv. to mine production).
	1897-9	Metallgesellschaft 1907, p. 81	Use of unwrougth tin including changes in apparent stocks.
	1900-2010	BGR, 2012a	Refined tin.
U.S.	1853-8	House of Commons 1859, p. 29	Tin in pigs and bars; consumption equal to imports as there seems to be no production and exports at the time. Imports: Crude estimates based on the value of imports; year ended 30th June.
	1859-60		Linear trend.
	1861-2	House of Commons 1864, p. 341	Tin in pigs, blocks and bars; consumption equal to imports as there seems to be no production and exports at the time; year ended 30th June.
	1863	House of Commons 1866, p. 358	Tin in blocks and pigs; consumption equal to imports as there seems to be no production and exports at the time, supposed error in data source corrected; year ended 30th June.

1864-5	House of Commons 1868, p. 378	Tin in blocks and pigs; consumption equal to imports as there seems to be no production and exports at the time, 1864: obvious error in data source corrected; year ended 30th June.
1866-7	House of Commons 1870, p. 368	Tin in bars, blocks, or pigs; consumption equal to imports as there seems to be no production and exports at the time; year ended 30th June.
1868	National Bureau of Economic Research 2013	Tin; consumption equal to imports as there seems to be no production and exports at the time; year ended 30th June.
1869-78	U.S. Bureau of Statistics 1879, pp. 71 and 77	Tin in bars, blocks, pigs, grain, or granulated; consumption equal to imports as there seems to be no production and exports at the time; year ended June 30th.
1879-88	U.S. Bureau of Statistics 1889, p. 85	Tin in bars, blocks, pigs, grain, or granulated; consumption equal to imports as there seems to be no production and exports at the time; year ended June 30th.
1889-96	Metallgesellschaft 1899, p. 69	Use of unwrougth tin including changes in apparent stocks.
1897-9	Metallgesellschaft 1907, p. 81	Use of unwrougth tin including changes in apparent stocks.
1900-2010	BGR, 2012a	Refined tin.

Table 3.34: Data sources for the usage of zinc.

Country	**Time**	**Source**	**Notes**
Belgium	1900-2010	BGR, 2012a	Refined zinc; including Luxembourg.
Finland	1946-2010	BGR, 2012a	Refined zinc.
France	1903-2010	BGR, 2012a	Refined zinc.
Germany	1850-9	Bienengräber 1868, p. 310, Neumann 1904, p. 314	Computed from imports and exports of unwrought zin and the production of zinc.
	1860-78	Kaiserliches Statistisches Amt 1880, p. 136	Unwrought zinc.
	1879-83	Kaiserliches Statistisches Amt 1885, p. 144	Unwrought zinc.
	1884-8	Kaiserliches Statistisches Amt 1890, p. 131	Unwrought zinc.
	1889-96	Metallgesellschaft 1905, p. 56	Unwrought zinc.
	1897-9	Metallgesellschaft 1913, p. 65	Unwrought zinc, no scrap.
	1900-2010	BGR, 2012a	Refined zinc; 1945-90: West Germany.
Italy	1889-94	Metallgesellschaft 1898, p. 57	Unwrought zinc.
	1895-1902	Metallgesellschaft 1905, p. 61	Unwrought zinc.
	1903-2010	BGR, 2012a	Refined zinc.
Japan	1911-2010	BGR, 2012a	Refined zinc.
Netherlands	1889-90	Metallgesellschaft 1897, p. 31	Unwrought zinc; estimate by Metallgesellschaft.
	1891-9	Metallgesellschaft 1901, p. 27	Unwrought zinc; estimate by Metallgesellschaft.
	1900-2010	BGR, 2012a	Refined zinc.
South Korea	1962-2010	BGR, 2012a	Refined zinc.
Spain	1900-2010	BGR, 2012a	Refined zinc.

Sweden	1911-2010	BGR, 2012a	Refined zinc.
U.K.	1840-9	Mitchell 1988, pp. 312-23	Computed from imports and exports of unmanufactured zinc. No domestic zinc production according to Neumann (1904) and Schmitz (1979) before 1855.
	1850-1	House of Commons 1853, p. 108, Mitchell 1988, pp. 320-3, Neumann 1904, p. 314	Computed from imports of zinc and spelter, and exports of unmanufactured zinc. No domestic zinc production according to Neumann (1904) and Schmitz (1979) before 1855.
	1852-4	Mitchell 1988, pp. 312-7	Computed from imports and exports of unmanufactured zinc. No domestic zinc production according to Neumann (1904) and Schmitz (1979) before 1855.
	1855-9	House of Commons 1882, pp. 17-21, Mitchell 1988, pp. 320-3, Neumann 1904, p. 314	Computed from imports of zinc or spelter, crude, and in cakes, exports of unmanufactured zinc, and the domestic mine production.
	1860-1	House of Commons 1882, pp. 17-21, Mitchell 1988, pp. 320-3, Schmitz 1979, p. 184	Computed from imports of zinc or spelter, crude, and in cakes, exports of unmanufactured zinc, and the domestic mine production.
	1862-9	House of Commons 1882, pp. 17-21, Schmitz 1979, p. 184	Computed from imports and exports of zinc or spelter, crude, and in cakes, and the domestic mine production.
	1870-6	House of Commons 1882, pp. 17-21, BGR, 2012b	Computed from imports and exports of zinc or spelter, crude, and in cakes, and the domestic smelter production; 1871: linear trend.
	1877-9	House of Commons 1882, pp. 17-21, Schmitz 1979, p. 184	Computed from imports and exports of zinc or spelter, crude, and in cakes, and the domestic mine production.
	1880	House of Commons 1882, pp. 17-21, Metallgesellschaft 1898, p. 16	Computed from imports and exports of zinc or spelter, crude, and in cakes, and the domestic unwrought zinc production.
	1881-3	House of Commons 1885a, p. 6 and p. 14, Metallgesellschaft 1898, p. 16	Computed from imports and exports of zinc or spelter, crude, and in cakes, and the domestic unwrought zinc production.

	1884-8	Mitchell 1988, pp. 312-23, Metallgesellschaft 1898, p. 16	Computed from imports and exports of unmanufactured zinc, and the domestic unwrought zinc production.
	1889-94	Metallgesellschaft 1899, p. 60	Unwrought zinc; no changes in apparent stocks included.
	1895-1901	Metallgesellschaft 1905, p. 58	Unwrought zinc; no changes in apparent stocks included.
	1902-2010	BGR, 2012a	Refined zinc.
U.S.	1849-51	House of Commons 1853, p. 109	Usage equal to imports of British zinc or spelter. No production according to Mitchell (1988, p. 366) and Schmitz (1979, p. 184). No export data available. I suppose there have not been considerable amounts of exports.
	1852-3	House of Commons 1854a, p. 9	Usage equal to imports of British zinc or spelter. No production according to Mitchell (1988, p. 366) and Schmitz (1979, p. 184). No export data available. I suppose there have not been considerable amounts of exports. Imports 1852: linear trend.
	1854-8	House of Commons 1855, p. 9	Usage equal to imports of British zinc or spelter. No production according to Mitchell (1988, p. 366) and Schmitz (1979, p. 184). No export data available. I suppose there have not been considerable amounts of exports. Imports 1855-8: linear trend.
	1859	House of Commons 1862, p. 277, Jolly 1992, p. 20	Computed from imports of zinc and spelter and the domestic production of zinc. No export data available. I suppose there have not been considerable amounts of exports.
	1860-2	House of Commons 1862, p. 277, BGR, 2012b	Computed from imports of zinc and spelter and the domestic refined production of zinc. No export data available. I suppose there have not been considerable amounts of exports. Imports 1861-2: linear trend.
	1863	House of Commons 1866, p. 358, BGR, 2012b	Computed from imports of zinc in blocks and sheets and the domestic refined production of zinc. No export data available. I suppose there have not been considerable amounts of exports.
	1864-6	House of Commons 1868, p. 378, Carter et al. 2006, BGR, 2012b	Computed from imports of zinc in blocks and sheets, exports of refined zinc in blocks, pigs, and slabs, and the domestic refined production of zinc. Imports 1866: linear trend.

	1867-79	Carter et al. 2006, BGR, 2012b	Computed from imports and exports of refined zinc in blocks, pigs, and slabs, and the domestic refined production of zinc.
	1880-8	Carter et al. 2006, Metallgesellschaft 1898, p. 16	Computed from imports and exports of refined zinc in blocks, pigs, and slabs, and the domestic production of unwrought zinc.
	1889-94	Metallgesellschaft 1899, p. 60	Unwrought zinc.
	1895-1904	Metallgesellschaft 1905, p. 63	Unwrought zinc.
	1905-2010	BGR, 2012a	Refined zinc.

Table 3.35: Data sources for the world primary production of the mineral commodities.

Mineral commodity	**Time**	**Unit**	**Sources**	**Notes**
Aluminum	1854-62	mt	Neumann 1904, p. 395	Primary aluminum production; 1856-8 and 1860-1: linear trend.
	1863-1976	mt	Schmitz 1979, pp. 197-208	Primary refined production; before 1890 most aluminum has been produced by the Deville process.
	1977-2009	mt	BGR, 2012b	Primary refined production
Copper	1820-78	mt	Schmitz 1979, pp. 64-9	Metal content of mined ores.
	1879-82	mt	Schmitz 1979, pp. 209-13	Smelter production from primary materials.
	1883-1902	mt	Metallgesellschaft 1904	Unwrought copper.
	1903-12	mt	Metallgesellschaft 1913	Unwrought copper.
	1913-28	mt	Schmitz 1979, pp. 209-13	Smelter production from primary materials.
	1929-59	mt	Schmitz 1979, pp. 213-25	Primary refined production.

	1960-2005	mt	International Copper Study Group 2010b	Refined production from primary and secondary materials.
	2006-10	mt	International Copper Study Group 2012b	Refined production from primary and secondary materials.
Lead	1800-2009	mt	BGR, 2012b	Metal content of mine production; missing data for Russia (1841-4, 1846-9, 1851-4, 1856-9), for Spain (1846-50, 1853-7), and for the United Kingdom (1839-40, 1842-4) has been filled by using geometric trends.
Tin	1791-1883	mt	Schmitz 1979, pp. 162-8	Metal content of mine production; 1800: break in time series due to missing Malayan data.
	1884-1976	mt	Schmitz 1979, p. 247	Primary refined tin production.
	1977-2010	mt	U.S. Geological Survey 2012b	Metal content of mine and mill production.
Zinc	1820-2	mt	Neumann 1904, p. 313	Unwrought zinc production.
	1823-79	mt	Schmitz 1979, pp. 160-6	Mine production.
	1880-94	mt	Metallgesellschaft 1889, pp. 15-6	Unwrought zinc.
	1895-9	mt	Metallgesellschaft 1901, p. 25,	Unwrought zinc.
	1900-2007	mt	U.S. Geological Survey 2012c	1900-12, 1914-17, and 1929-42: Metal cont. of smelter production; 1913, 1918-28, and 1943-2007: Metal cont. of mine production.

Table 3.36: Data sources for the world refined production of the mineral commodities.

Mineral commodity	**Time**	**Unit**	**Sources**	**Notes**

Copper	1820-78	mt	Schmitz 1979, pp. 64-9	Metal content of mined ores.
	1879-1928	mt	Schmitz 1979, pp. 209-13	Smelter production (primary but may also include secondary materials according to a personal communication with Doris Homberg-Heumann of the Federal Institute for Geosciences and Natural Resources).
	1929-59	mt	Schmitz 1979, pp. 213-25	Refined production; according to a personal communication with Doris Homberg-Heumann from the Federal Institute for Geosciences and Natural Resource the data includes both primary and secondary sources. This is also the case when the data is compared with data from the International Copper Study Group (2010b) from 1960s onwards.
	1960-2005	mt	International Copper Study Group 2010b	Refined production from primary and secondary materials.
	2006-10	mt	International Copper Study Group 2012b	Refined production from primary and secondary materials.
Lead	1840-60	mt	Neumann 1904, pp. 149-51	Metal content of mine production; missing data for Russia (1841-4, 1846-9, 1851-4, 1856-9), for Spain (1846-50, 1853-7), and for the United Kingdom (1839-40, 1842-4) has been filled by using geometric trends.
	1861-2010	mt	BGR, 2012b	Metal content of refined production from primary and secondary materials; total production by smelters or refineries of refined lead, including the lead content of antimonial lead, ores, concentrates, lead bullion, lead alloys, mattes, residues, slag, or scrap. Pig lead and lead alloys recovered from secondary materials by remelting alone without undergoing further treatment before reuse are excluded. (See International Lead and Zinc Study Group (2011))
Tin	1821-83	mt	Neumann 1904, pp. 251-3	Tin production.

	1884-2010	mt	BGR, 2012b	Primary smelter production.
Zinc	1850-79	mt	Schmitz 1979, pp. 160-6	Mine production.
	1880-94	mt	Metallgesellschaft 1889, pp. 15-6	Unwrought zinc.
	1895-9	mt	Metallgesellschaft 1901, p. 25,	Unwrought zinc.
	1900-2010	mt	BGR, 2012b	Total production by smelters or refineries of zinc in marketable form or used directly for alloying regardless of the type of source material. Remelted zinc and zinc dust are excluded. (See International Lead and Zinc Study Group (2011))
Oil	1861-1964	mt	Mitchell 2007, Russia: Alekperov 2011	Crude petroleum (not from oil shales); Russia 1893-4: geometric trend.
	1965-2010	mt	British Petroleum 2011	Includes crude oil, shale oil, oil sands and NGLs (the liquid content of natural gas where this is recovered separately). Excludes liquid fuels from other sources such as biomass and coal derivatives.

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