How Much Does Natural Resource Extraction Really Diminish National Wealth?

The Implications of Discovery

Alan Gelb, Kai Kaiser, and Lorena Viñuela

Abstract

The paper considers the process of discovery for subsoil resources, including both hard minerals and hydrocarbons and estimates its magnitude in recent years, as derived from the sum of extraction and changes in proven reserves. Spurred on by technology change and strong market conditions, discovery has been substantial for most minerals. The value of discovered reserves is high relative to the costs of exploration, particularly when low social discount rates are used to value potential production in the future. Discovery is therefore valuable and should be considered as adding to national wealth through increases in proven reserves. Many countries can continue to generate resource rents far longer than indicated by current reserve estimates and this has implications for decisions on how to plan to spend or save rents. With the high response of discovery to prices and technology, environmental constraints (climate change, water) are more likely than the actual exhaustion of resource deposits to limit resource-based development.

The divergence between private and social valuation of discoveries may also justify measures taken by countries to encourage exploration, including through the provision of geo-scientific data to increase interest in discovery as well as competition among mining companies. More information is needed on the payoff to such investments, some of which are supported by donors. However, exploration is, of course, only a slice of the resource value chain. Many countries will need to improve management along the entire chain if resource wealth is to benefit their development.

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Contents

Why Discovery?

There are known knowns; there are things we know we know.
We also know that there are known unknowns; that is to say we know there are some things we do not know.
But there are also unknown unknowns—the ones we don't know we don't know.

—Donald Rumsfeld,
February 12, 2002.

Development is often seen as a structural transition from a resource-based economy towards manufacturing, and later into services. But some 30 developing countries are heavily dependent on hydrocarbons for fiscal revenue and exports and a further dozen depend on hard mineral resources. For many of these countries, a structural transition is far in the future. Indeed, with prices driven by demand from Asia, the number of mineral-dependent countries is increasing rather than falling. New and aspiring oil exporters include Ghana and Uganda, while Zimbabwe also may be transitioning from an agricultural exporter to a minerals-dependent economy. This trend is likely to continue because there is still so much natural wealth to be discovered in poor countries. Estimates from the Wealth of Nations database (World Bank 2006, 2010) indicate that the value of known subsoil assets per square kilometer of Sub Saharan Africa is barely one quarter of that for high-income countries. Proven and prospective reserves will be the "lifeline to development" for many countries over next 20-40 years, and even beyond, as well as a major component of national wealth.

This paper addresses resource discovery, with special reference to sub-soil assets—hard minerals and hydrocarbons. Each type of natural resource has distinctive characteristics. Some, such as softwood forests, are clearly measurable, and they are reproducible in the sense that natural processes, as well as planned replanting, can regenerate them in a reasonable timeframe if depletion is slow enough. Tropical hardwoods are similar, except that the regeneration process is far slower. Other resources, such as guano deposits, are also easily quantifiable but are essentially non-reproducible. As discovered by tiny Nauru—the only country to actually run out of its natural resources in recent times—when they are gone, they are gone forever.[1] Subsoil mineral assets are different. The absolute quantity of reserves—the total amount of copper, tin, or gold below the surface of a country, in its rivers and oceans and beneath its coastal sea-bed—is not observable, and even if it can be accurately estimated it is not a useful concept from the perspective of estimating national wealth. For example, the global seawater gold reserve has been estimated at about 25 billion ounces, about seven times the total of all gold ever extracted (Burk 1989). But there is no point in including seawater gold in the assets of countries with a coastline, since no viable extraction technology exists.

[1] It is of course theoretically possible to regenerate guano deposits but this would take a very long time. Resource exhaustion may have contributed to the downfall of cultures and civilizations in the past: deforestation on Easter Island has been cited as an example, but the details are still debated.

More relevant from the standpoint of development and natural wealth is the value of "proven" reserves able to be extracted given geology, technology and market conditions. The discovery of proven reserves takes exploration effort, and increases in estimates of proven reserves are often also related to knowledge gained in the process of extraction. Reserve depletion is therefore not simply a one-for-one mirror of extraction. On the contrary, in recent years proven reserves have risen for most minerals, even as extraction rates have soared.

The topic of discovery is especially relevant in light of the "super-cycle" that resource sectors have been experiencing since the early 2000's. Prices of metals, as well as hydrocarbons, have been high in historical terms—except for the short interlude of the global economic crisis—and have moved in a more synchronized way than in previous booms. This has focused attention on the question of sustainability and also on the division of resource rents between producing countries and mining companies. Resource industries have also seen some major changes in industrial organization in the last decade, with the emergence of a growing number of smaller firms that specialize in hydrocarbons and are willing to take on exploration risks, as well as the trend of national companies controlling an increasing share of reserves.

Section 2 of this paper reviews the concept and the process of discovery, and the generation of estimates of proven reserves—the "known knowns" of the resource world. Reserve increases only partially reflect new discoveries created by investments in exploration. They are also driven by advances in technology (exploration, operating, refining and processing) and by learning about the characteristics of fields local to the point of extraction. In this sense, extraction can itself be seen partly as an act of investment in reserve information. We introduce the concept of "imputed discovery" as the sum of net proven reserve changes and resource extraction.

Section 3 summarizes data on proven reserve trends for major minerals. These are not exact; countries and companies face incentives to exaggerate or downplay reserve levels, and discoveries may also not always be reflected in data changes in a timely way. Nevertheless, on the whole, data provide a reasonable picture of extraction potential as seen at the time. Imputed discovery rates are shown to be high for many minerals; indeed the dominant pattern has been for imputed discovery to exceed extraction, resulting in sizeable additions to proven reserves. Only in a few cases is the pattern different, and some of these appear to reflect policy decisions to declassify reserves because of concern over climate change (coal), or responses to particular market conditions, rather than actual reserve exhaustion.

The section also considers the "known unknowns" of subsoil assets, estimates of probable but still unproven reserves which are largely estimated on the basis of geological extrapolation. Their size relative to cumulative extraction tends to be higher for "frontier" regions such as Sub-Saharan Africa than for mature regions but some well explored regions still have enormous known potential. These estimates do not, of course, take into account the "unknown unknowns" —the likely increases in reserves that will be realized as technology advances, such as the recent increases in oil and gas reserves opened up by horizontal drilling and "fracking", or by more detailed geological investigation in less-surveyed areas remote from known geological structures.

How much does it cost to find new reserves relative to the value of discoveries? Section 4 brings together estimates of the value of imputed discovery and of the cost of exploration. This raises the question of how natural resource wealth, discoveries and depletion should be valued. World Bank 2006 values resources extracted as the current rent embedded in the extracted quantity (Bolt, Matate and Clemens 2002). We term this the Current Rent (CR) approach. When discovery is valued in a similar way, as the current rent embodied in the newly-proven reserves, its valuation can be extremely high. To take one example, with rent value at $80 per barrel, global imputed oil discovery over 2000-2008 represents $38 trillion, or about 70 percent of global GDP. Comprehensive estimates of exploration costs only exist for hard minerals; for hydrocarbons it is not possible to separate out overall operating costs from exploration investment. However, we consider the data for five leading oil multinationals and the recent case of discovery in Uganda. In all cases, the result is similar to the picture for hard minerals. Relative to the value of discoveries as estimated above, the cost of exploration is modest, on the order of 2-5 percent. It is not clear whether the percentage has increased or fallen. While new fields are more often found in more demanding environments, technology continues to drive down discovery and extraction costs.

This large wedge between the costs and benefits of discovery is at odds with the proposition that discovery should proceed to the point where its marginal costs equal the marginal value of resources discovered. We offer several reasons that can at least partially account for the discrepancy. One reason is that both depletion and discovery are over-valued by the CR method. Depending on the level of reserves, these activities will impact on production and on the net present value of future flows of natural rent only years into the future, and their effects may be subject to discounting. Hamilton and Ruta (2009) note this overvaluation (assuming that resource prices do not rise at or above the discount rate), and introduce two alternative methods based on changes in resource wealth, defined as the discounted sum of future expected rents. These measures combine assumptions on future prices and unit rents and the future level of extraction. Depending on the degree of discounting and reserve life, they reduce the valuation of both extraction and discoveries and shrink the margin of discovery value over exploration cost. However, this ratio will still be high for modest social discount rates unless the reserve horizon is very long. We suggest that rent taxation, differences between private and social discount rates, and the option value of waiting for better technology sustain the high value of discovery relative to cost.

Reserve discovery therefore cannot be considered in the same way as normal capital accumulation, where the increase in the stock of capital is derived from cumulative investments, which in turn require savings. Indeed, if the rent value of discovered reserves (defined as the future value of resource production less the costs and normal returns to factors used in the production process) included only a normal return on exploration expenses, there would be no true natural rent at all and no need to account for discovery over and above the investments in exploration. But discovery is far more valuable; it increases known wealth over and above the normal return to exploration. Of course, it can be argued that simply finding and confirming reserves that already exist does not represent an increment to natural wealth, but this approach runs up against the problem noted above, that wealth cannot reasonably be estimated on the basis of the actual quantity of minerals in the ground.

Why then does discovery matter? Section 5 considers three questions. First, what are the implications for Green Accounting? As is well known, conventional measures of Gross National Savings (GNS) are misleading in several respects when considered as indicators of trends in national wealth or sustainability. They do not take into account the depreciation of capital or environmental damage or the rent value of natural resources extracted and used up by the economy. Neither do they allow for the impact of education spending in creating human capital. Estimates of Adjusted National Savings (ANS) include these effects and offer a better perspective on the sustainability of the development path of a country. Many resource exporters have low ANS because of the negative impact of resource extraction on national wealth. Some even have negative adjusted national savings. If, however, the value of discovery is included (either gross or net of likely exploration costs) to provide an estimate that we term Discovery-Adjusted National Savings (DANS), the resource and savings trends can look very different. A country like Vietnam or Venezuela, where reserves have been rising and further major reserve increases are likely for many years as fields are developed, may not find the sustainability implications of ANS analysis convincing.

Second, how should discovery be integrated into fiscal policy? How much should resource-rich countries consume or save and invest for the future? Most analyses place a high weight on saving and re-investing resource rents to preserve total national wealth. High savings are certainly appropriate if reserves are expected to be exhausted in a few years. In that case, the stream of permanent consumption that a country can sustain out of resource wealth is small relative to the flow of resource rents into the budget. The picture is different if the reserve horizon is long. In such a case, it is quite reasonable to consume a high share of the rents since the investments made out of even modest savings can cumulate over many years to leave post-resource generations richer than the present one.

This prescription is not intended to encourage profligacy. There can be many reasons for resource rich countries to save, including funding a buffer against adverse price trends; history suggests that mineral markets may not always be as strong in the future. But fiscal recommendations based on existing reserve levels may be overly conservative and not sufficiently credible to drive policy.

The third question, given the relationship between exploration costs and discovery value, is the case for public action to reduce the costs and risks of exploration and increase national wealth by boosting proven reserves. One way to do this, as in Australia, Canada and some other advanced economies, is to invest in making geological information available as a public good. The aim is to reduce the risks for individual mining companies, to open up the sector to more competition and also to reduce information asymmetry between the government and mining companies. Countries face a difficult tradeoff between encouraging exploration and stimulating competition. Some public provision might be the most effective way of resolving this.

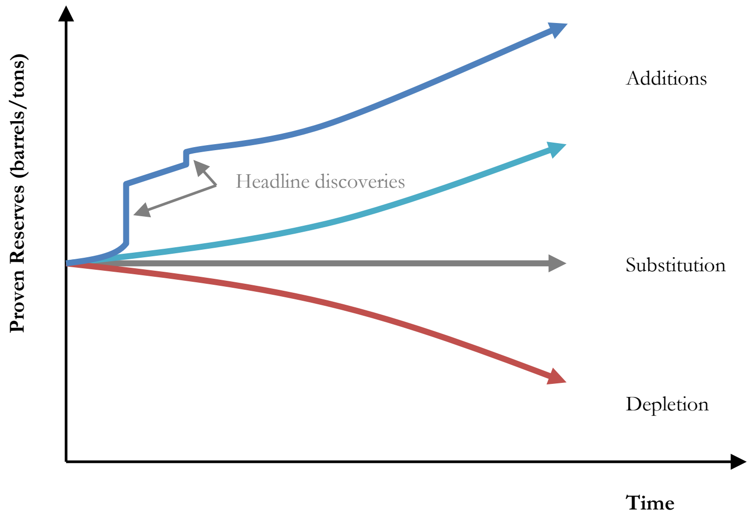
Discovery is, of course, only a small part of the overall challenge posed by resource-based development. Better management of rents is needed along the entire resource chain if more countries are to benefit from their resources, while climate change, groundwater and other environmental concerns may pose serious constraints. However, the discovery record suggests that many countries will continue to be resource dependent long after their currently-proven reserves have been depleted.

The Concept and Process of Discovery

Discovering new petroleum or mineral reserves involves both "extensive" (greenfield) and "intensive" (brownfield) processes. New reservoirs or deposits can be identified through the *extensive* exploration of large areas. Detailed geological information is necessary to determine the prospects for a particular resource or a group of associated resources. Geologists begin with a combination of remote sensing, geochemical soil analysis, seismic analysis, and modeling based on known information on comparable areas. Once a resource find is likely, intensive appraisal begins to better delineate and quantify it. Appraisal typically involves drilling wildcat wells or excavations depending on the type of resource.

Intensive discovery takes place as a result of the development of already producing areas (brownfield sites). Through production, companies learn more about the terrain and reserves at hand. The infrastructure they put in place to extract the resources allows them to better assess their quantity and quality, as well as to identify adjacent areas with similar geological characteristics. As considered later, companies (and governments) may have incentives to explore and prove reserves only to a certain point; often just enough to maintain existing reserve levels.

Figure 1. Potential Country Proven Reserve Trajectories



Source: Authors

Figure 1 presents a stylized model of different potential trajectories. The lowest line reflects the rundown of proven reserves due to extraction.[2] The second, intermediate, trajectory sees proven reserve levels remaining constant, with replacement resulting from growing knowledge and extraction efficiencies. The third line reflects a growing trajectory of proven reserves, with net additions or new finds that offset depletion mostly through an incremental process of intensive development of producing areas. In the case of the highest line, proven reserve additions are driven by a combination of new "headline" finds due to extensive exploration and more gradual increments due to learning.

The probability of taking one path or another will depend on a host of belowground and aboveground factors including availability of geological information, the level of maturity of the industry, the state of technology, fiscal incentives, economic feasibility, including access to markets, and the credibility of the host government. Technological innovation can unlock known resources that were previously inaccessible or too costly to extract. Political factors can impede exploration or encourage it, opening up the prospects of headline discoveries. In general, the unit costs of discovery would be expected to increase over time as cumulative extraction rises, and to fall as a result of cumulative learning and improvements in technology. It is not clear which of these effects will dominate at any particular moment.[3]

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[2] Net declines in reserves can also be due to certain reserves simply becoming uneconomic. In these instances the physical resources would still be known, if no longer classified in the proven reserves category.

[3] There has been debate about how to model the resource discovery process given that the notion of a fixed mineral stock has been questioned in practice (Adelman et al. 1991). Pindyck 1978 modelled potential reserves as unlimited but with diminishing returns to exploration as a function of depletion. The discovery of new reserves

Several cases help to illustrate these alternative trajectories. For the lowest line, Mexico's proven oil reserves have decreased sharply in the past three decades, falling from 60 years of production in 1980 to 10 years in 2010. Heavy taxation of the sector, a national oil monopoly and the absence of a competitive environment have resulted in low investments in exploration and technology, and have driven reserves down (Diaz Cayeros 2009).[4] Moving to the second lowest line, Trinidad and Tobago's proven oil reserves were some 10 years of output in the late 1970s and are a little higher today, despite 30 years of production. Another set of countries has steadily made small yearly additions to their reserves. Even though Saudi oil production has increased more than 70 percent since the late 1980s, its overall level of reserves has continued to grow slowly despite not having made more spectacular finds. For the top line, several countries have added to their reserves through single or multiple new discoveries. Between 2005 and 2009, Brazil reported 170 oil discoveries, including pre-salt deposits in excess of 50 billion barrels (Formigli 2007, GlobalData 2010). Venezuela reported a new oil deposit in the Orinoco belt in 2008 which added 94 billion barrels to its existing reserves. Once these major finds are made, other additions resulting from intensive exploration typically follow. For example, at the time a major ore body of copper, gold, and molybdenum was discovered in Alaska's Pebble Beach, it was estimated to hold 500 million tons of low-grade copper. A subsequent study of the controversial project estimated 1 billion tons, and proven reserves are currently reported as closer to 6 to 8 billion tons.

Most analyses report either resource extraction or changes in reserves. We define *imputed discovery* to include all reserve additions; those that replace extracted resources and those that

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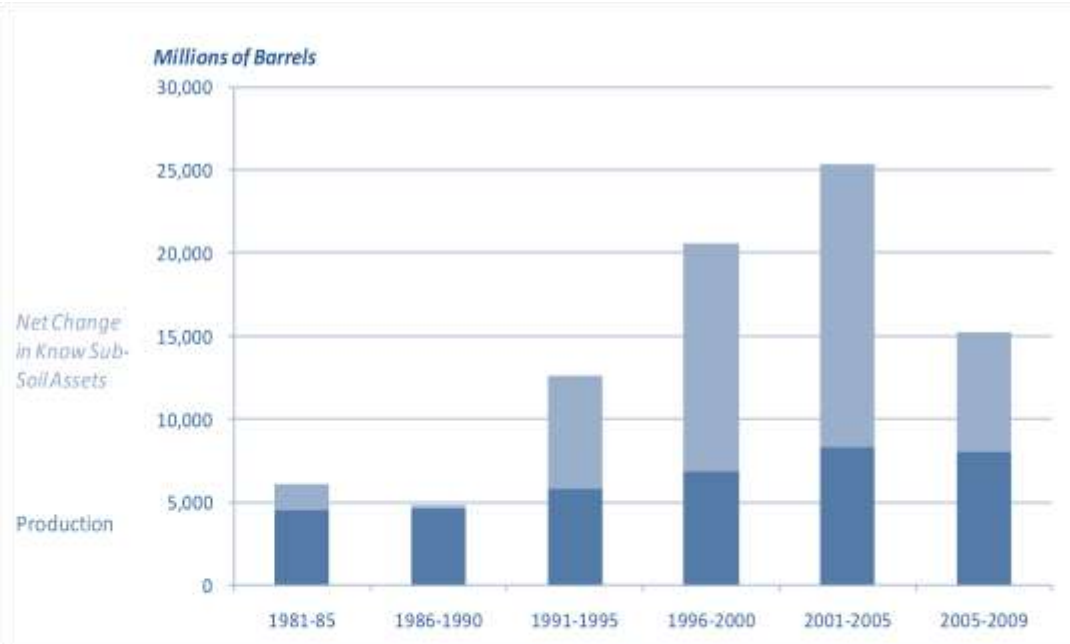
can be modelled as an increasing function of current and of accumulated expenditures on exploration, and as a declining function of accumulated extraction (Arrow et al 2003). Resources are therefore non-renewable rather than exhaustible, and with optimal production and exploration rates that are interrelated. The relationship between rent and marginal discovery cost has also been researched. Krautkraemer 1998 assumes that exploration will be pushed to the point where the marginal cost equals the marginal value of reserves but Devarajan and Fisher 1982 paint a more complex picture. Boyce 2009 notes that technological change driven by learning-by-doing can countervail depletion, so challenging the inevitable "peak mineral" patterns predicted by other theories. The extractive industries have indeed seen huge technological change including remote sensing satellites and processing technology that have increased the efficiency of exploration in new regions. Technological change in the oil and gas industry has advanced both on and off-shore, where notable innovations include three dimensional seismic technology as well as horizontal drilling technology. Evidence from oil and gas exploration in the Gulf of Mexico from 1947 to 1998 suggests that since the mid-1970s technology has increased the yield per unit of effort in discovery, offsetting the countervailing impact expected from depletion (Managi, et al., 2005). The copper industry too has seen growing scale of operations (such as large open pit mines) and metallurgical developments that have allowed for the production of copper at the mine site, which have reduced operating costs and cut-off grades (Doggett, 2007). Some foresee a slowdown in future production gains, partly because of environmental constraints (CO2 emissions, water) leading to an era of persistently high prices (Dobbs, Oppenheim and Thompson 2011).

[4] The Gulf of Mexico offers a natural experiment on the effect of institutional conditions and fiscal regimes. With similar geology and resource endowments, the territory that belongs to the United States has thousands of wells in production, compared to a few hundred on the Mexican side of the border. Nevertheless, even in the United States, additions to proven reserves in oil and gas have mostly resulted from revisions to recovery rates rather than new discoveries (Morehouse 1997).

increase proven reserves. Figure 2 stacks production and net reserve change to show imputed discovery for oil in Sub-Saharan Africa for five-year segments over the past 30 years.[5] Production has been on a rising trend, from around 5 to some 7 billion barrels, but imputed discovery has been much higher, averaging about 18 billion barrels since the mid-1990s.

Figure 2. Imputed Discoveries in Known Petroleum Reserves in Sub-Saharan Africa



Source: British Petroleum (BP) Statistical Review of World Energy (2010).

Reserve Trends and Extraction Rates

In this section we summarize trends in proven reserves and extraction. While recognizing the conceptual and empirical challenges, we have made efforts to bring together the best available estimates. Proven reserve estimates are compiled annually for oil, gas, and coal (British Petroleum 2010) [6] and metals (U.S. Geological Survey, 2010)[7] for individual

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[5] The latest period accounts for only four years, pending data for 2009.

[6] Oil and gas estimates are also drawn from OPEC Secretariat Annual Reports, *Oil and Gas Journal*, and an independent estimate of Russian reserves based on information in the public domain. Mineral reserve estimates are taken from the International Copper Association, the International Energy Agency, and the World Energy Council, among others. A number of alternative sources are available for oil and gas. These include the World Energy Council's Survey of Energy Resources and the U.S. Geological Survey's *World Petroleum Assessment* (2000) for oil and gas, and USGS Commodity Summaries for minerals. The World Energy Council's *Survey of Energy*

countries. Data for the BP and USGS compilations are collected from a combination of primary official sources (governments and producing companies) and third-party organizations, including commodity boards and sectoral institutions. BP's data on coal reserves are drawn from the London-based World Energy Council.

Finding consistent time series data on mineral reserves is challenging owing to the limited availability of primary data. For these reasons, estimates are just that, rather than an indicator of the actual resource endowment (Krautkraemer and Toman 2003). Reserve estimates are subject to both downward and upward biases. Since proving reserves is a costly process, companies may not have incentives to do it beyond the 10 to 15 years of production that is needed to sustain their operational plans. Operators face disincentives to share information, which reduce their enthusiasm for reporting reserves on a unilateral basis (Mirza and Zimmer 1999), although industry-specific reporting requirements (such as U.S. Securities and Exchange Commission rules) or voluntary reporting norms (as in Australia) can reduce the cost of sharing information by making it applicable across all companies (Craswell and Taylor 2006).

Environmental regulation and fiscal instruments can also incentivize companies to under- or over-report reserves. Different taxes have different effects on cutoff grades and the profitable level of extraction (Deacon 1993). Declared reserve levels may be subject to fees, encouraging companies to report only holdings with a medium-term perspective of extraction. Depletion quotas, in contrast, may encourage companies to over-report the mineral potential of their areas. Governments may also have an incentive to change their reserve estimates depending on the implications for decision-making power in organizations regulating production and prices. For example, in the 1980s, almost all members of the Organization of Petroleum Exporting Countries (OPEC) increased their reserve estimates (in total by more than 300 billion barrels) as a result of changes in the production quota system which is based on the level of proven reserves (IEA, 2005).

Table 1 summarizes global reserve and extraction data for key energy and other subsoil assets. We include all minerals reported in the WoN database as well as others such as diamonds, cobalt, and rare earths. Columns 1 and 2 show reserve levels in 2000 and 2008 respectively. Column 3 shows cumulative extraction during the past century, drawing from

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Resources (2010) presents data on the status of 15 sources of energy worldwide, including resource and reserves assessments and other relevant information. The principal difference between these sources and BP Statistical Review (2010) is that the BP data are presented as a cross-section rather than as a time series. USGS, the International Copper Association, the International Energy Agency, and the World Energy Council report production and consumption data, including in some cases from 1990 onward.

[7] USGS follows the McKelvey model to identify reserves, which distinguishes subsoil assets by the degree of certainty and feasibility of economic recovery. *Reserves* are characterized by the highest degree of certainty and recoverability, whereas *resources* may enjoy a high degree of certainly but may be limited in the feasibility of extraction, given prevailing technological and market conditions. *Inferred* as opposed to proven reserves note a lower level of geological certainty (Skinner 2011).

USGS Historical Commodity Statistics. Column 4 shows extraction during the period 2000-2008, column 5 net percentage reserve changes for 2000-2008, and column 6 imputed discovery over 2000-2008, also expressed as a percentage of reserves in 2000. Negative imputed discovery (reserves fall by more than production) is not recorded for reasons noted below.

Table 1.

Oil, Gas, and Mineral Reserves Changes (Global, 2000–2008)

Global		Reserves		Extraction		Net Reserve Change	Imputed Discovery
		2000 1	2008 2	1900-2008 *,** 3	2000-2008 (WoN)*** 4	2000-2008 (percent) 5	2000-2008 (percent) 6
Energy	Oil (billion barrels)	1,105	1,333	1,007	229	21	41
	Gas (trillions of cubic meters)	159	191	74	24	20	35
	Coal (billion tn)	984	826	157	49	-16	
	Hard (anthracite/bituminous)	509	411	121	41	-19	
	Soft (sub-bituminous and lignite)	475	415	37	8	-13	
Minerals (WoN)	Bauxite (million tn)	24,640	25,200	4,937	1,480	2	8
	Copper (million tn)	393,500	540,000	526,298	128,423	37	70
	Gold (million toz)	45	48	133	22.9	5	56
	Iron (million tn)	142,600	162,500	57,096	13,115	14	23
	Lead (million tn)	64	79	217	29	23	69
	Nickel (million tn)	45,680	67,090	48	13	47	47
	Phosphate (million tn)	11,500	17,912	6,711	1,290	56	67
	Silver (thousand tn)****	420	570	820	175	36	78
	Tin (million ton)	7,720	6,072	19	2.5	-21	
	Zinc (million tn)	188	182	407	83	-3	41
Other	Diamond industrial (million metric tn)	580	580	6.4	5.1	0	1
	Cobalt (million tn)	5,475	6,424	1.9	0.5	17	17
	Rare earth metals (million tn)	103,956	107,786	2.5	1	4	4

* Boyce (2009, Table 3/p. 25) presents 20th century cumulative extraction for 77 minerals, from which oil gas (iii) are drawn.

** Coal from WoN refers only to 1970-2008 extraction.
*** Gas extraction is drawn from BP (2010). Industrial diamond, cobalt, and rare earth metals (reserve base) are drawn from USGS Mineral Commodity Summaries.
**** Silver from USGS annual reporting, US Bureau of Mines Mineral Yearbooks and The Silver Institute, as summarized by the Eagle Institute (http://www.gold-eagle.com/editorials_05/zurbuchen011506.html). Reserve definition used is base reserve, which includes silver found in association with a range of other metals. Two thirds of silver is found in such association.

Sources: BP (2010), USGS Mineral Commodity Summaries (2011), USGS Historical Commodity Statistics 1990-2009.

Despite accelerating extraction, net proven reserves increased between 2000 and 2008 for most commodities, including oil, gas, iron, copper, gold, phosphate, lead, nickel, silver and rare earth metals.[8] Conversely, aggregate reported net reserves of coal, tin, and zinc show declines. For most commodities, imputed discovery has been very large. The average of the figures in column 6 is 40 percent of reserves in 2000, so that discovery has averaged over 4 percent per year.

Table 2 shows USGS estimates of "known unknowns", undiscovered but probable reserves of oil and gas (USGS 2000)[9], together with proven reserves, production, area and coastal shoreline. Whereas Sub-Saharan Africa and Asia Pacific regions have comparable land areas, the latter has five times the coast. These "known unknown" estimates rely heavily on geological extrapolation. The USGS projections suggest that 31 percent of undiscovered petroleum resources lie in the Middle East and Northern Africa, an area of particular reserve concentration. Europe and Central Asia and North America are each expected to have at least a fifth of future petroleum reserves and two-fifths of gas reserves.[10] Even with limited geological knowledge, Sub-Saharan Africa accounts for at least 10 percent of undiscovered oil and 3 percent of undiscovered gas reserves, compared to only 5 and 3 percent of existing reserves, and 5 percent of cumulative extraction. In the future it could outpace other regions in discoveries, at least relative to existing activity.

[8] Proven reserves of silver declined by 3% when considered in isolation. However, reserves including silver recoverable in association with other metals (base reserves) increased.

[9] The 2000 USGS *World Petroleum Assessment* provides estimates on undiscovered resources or resources whose existence is only postulated, including hypothetical resources (undiscovered resources that are similar to known mineral bodies and that may reasonably be expected to exist) and speculative resources (resources that may occur either in known types of deposits in favourable geological settings or types of resources whose economic potential is unrecognized). The data reported include reserves that "geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions." For more discussion see Charpentier and Klett 2005.

[10] The surprisingly high estimates for North America result from USGS estimates of large undiscovered reserves in the US, including Alaska and the continental shelf. This could reflect a genuinely exceptional reserve endowment or greater precision in mapping due to better data.

Table 2.

Proven and Projected Oil Reserves by Geographic Area (2000–2009)

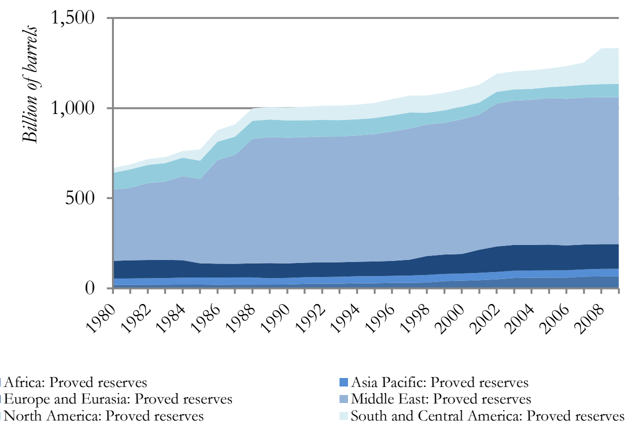
	Regional Reference Sizes		*Extraction (1965-2009)*		*Proven Reserves (2009)*		*Projected Additional Reserves (2000)*	
	Land Area millions sq. km 1	**Coastal Area** thousand km 2	**Extraction** billion barrels 3	**Extraction** barrels/sq. km 4	**Proven Reserves** billion barrels 5	**Proven Reserves** barrels/sq. km 6	**Undiscovered Reserves** billion barrels 7	**Undiscovered Reserves** barrels/sq. km 8
Africa (Sub-Saharan)	23.6	30.6	47	1,948	66	2,729	72	2,947
(percentage)	*18%*	*4%*	*5%*		*5%*		*10%*	
Asia Pacific (including Oceania)	28.9	229.2	92	3,686	42	1,697	33	1,342
(percentage)	*22%*	*30%*	*9%*		*3%*		*5%*	
Europe and Central Asia	27.5	211.4	226	7,954	137	4,820	138	4,869
(percentage)	*21%*	*27%*	*22%*		*10%*		*19%*	
Latin America and the Caribbean	20.2	59.4	83	4,034	199	9,726	105	5,139
(percentage)					*15%*		*14%*	
Middle East and North Africa	11.1	18.4	365	32,536	816	72,674	230	20,482
(percentage)	*9%*	*2%*	*35%*		*61%*		*31%*	
North America (US and Canada)	18.3	222	224	11,405	73	3,735	153	7,824
(percentage)	*14%*	*29%*	*22%*		*5%*		*21%*	
World	**130**	**771**	**1,036**	**7,736**	**1,333**	**9,953**	**732**	**5,465**

Source: BP (2010) and USGS World Petroleum Assessment (2000). CIA World Fact Book for coastal area.

Notes: Eurasia includes Turkey and Eastern Europe.

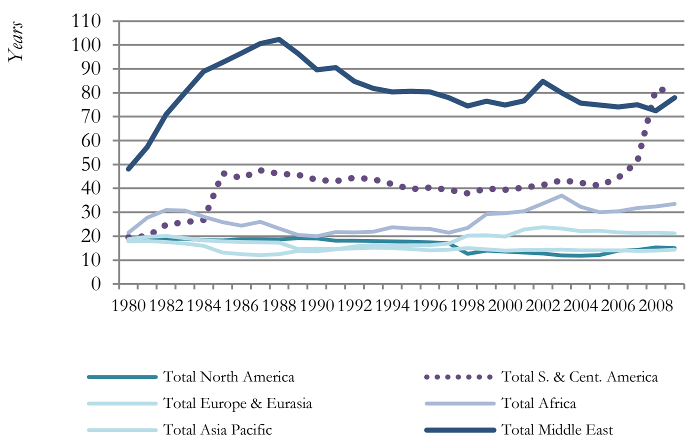
Returning to the analysis of proven reserves, we consider some details underlying Table 1 for three sets of commodities: oil and gas, copper, and the group of minerals for which proven reserves appear to have decreased. For oil and gas, reserve growth has continued to outpace production (Figure 3). The Middle East has consistently seen large expansions in reserves in the past half-decade; Iran and Qatar have reported significant increases in both their petroleum and gas reserves, and these additions account for much of the regional change. OPEC members, which account for 77 percent of known reserves, increased their oil reserves 20 percent in the 2000s. Major finds in Brazil and Venezuela lead to significant oil reserve expansions for Latin America, which doubled its reserves.

Figure 3. Petroleum Proven Reserves



Source: BP (2010).

Figure 4. Reserves to Production



Source: BP (2010).

Nevertheless, the biggest increase has been observed in countries that formerly belonged to the Soviet Union, with 40 percent growth in oil reserves as well as 15 percent in gas reserves, with the Russian Federation and Kazakhstan in the leading positions. North America increased reserves by 6.4 percent, with Canada offsetting negative trends in both the United States and Mexico, which witnessed decreases of 6.6 percent and 42 percent in oil reserves, respectively. Gas reserves grew 17 percent in the United States, in part because the growing use of new technology (hydraulic fracturing) allows producers to access known but previously unrecoverable resources.

Between 1998 and 2006, 19 countries became new oil and gas exporters, of which most were low- or lower-income countries (Ross 2011). Several were in Africa, where petroleum reserves increased by 58 percent, and gas reserves increased by 25 percent. Nigeria continues to have the highest levels of known petroleum and gas reserves in the region, but production remains at levels similar to that of Angola, which has about 36 percent of Nigeria's level of reserves, mainly offshore. Congo (Brazzaville) also reported new discoveries between 2006 and 2008, which doubled its known reserves.

The reserve picture differs greatly by country. The reserves-to-production (R/P) ratio, calculated as year-end reserves divided by the production in that year, provides a projection of the length of time that remaining reserves would last if production were to continue at that rate (see British Petroleum 2010). Figure 4 suggests that the highest R/P ratios in petroleum reserves have been in the Middle East and that these are slowly declining, even as major finds have increased the ratio sharply in South and Central America. In other regions, it is lower and with little definitive trend.[11]

Copper reserves and production have both continued to expand for many years, as shown in Figures 5 and 6. The short period between 2000 and 2008 accounted for approximately a third of total production since 1900. Nonetheless, reserves have increased more than six times since 1930 and are still rising. The most recent reserve additions were reported in Australia, China, Indonesia, Kazakhstan, Mexico, Peru, Poland, and Zambia, with discoveries ranging from 73,000 to 4,000 tons. Mongolia has also had major finds, as discovered by Russian exploration through the 1990s, and is now on track to become a

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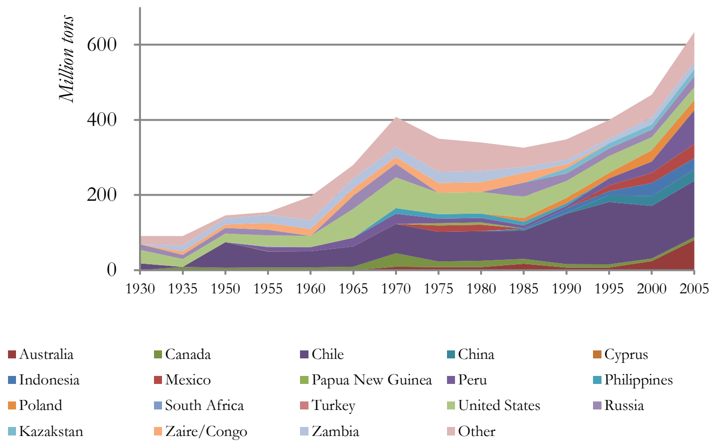
[11] There is no consensus on whether global oil reserves have peaked relative to demand. Some argue that reserve estimates exaggerate recoverable oil, others that total recoverable oil reserves are about three times the level of current proven reserves and that peak oil is unlikely before 2030. In any event, high mineral prices are driving investors and governments to develop new technologies and explore frontier regions, both in the sense of more geologically challenging areas and of low-governance and fragile states. Significant exploration efforts are being undertaken in more mature producing regions. The number of new oil blocks under development quadrupled in the first eight years of the century, reaching 75,000 in 2008, of which 40,000 were located in advanced and 35,000 in developing countries (GlobalData 2010). Since 2000, the number of active oil blocks has increased nearly four times in developing countries, with the highest increases in Latin America and Europe and Central Asia (GlobalData 2010).

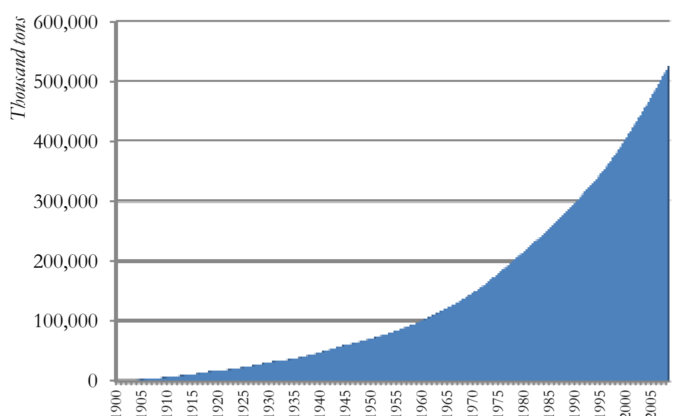
leading copper and gold producer.[12] Recent estimates, which are not yet fully reflected in global data, will place it second only to Chile, which accounts for more than a quarter of global reserves.

Figure 5. Copper Known Reserves



Source: USGS Commodity Summaries.

Figure 6. Copper Cumulative Production (1990–2008)



Source: USGS Historical Commodity Statistics.

[12] The Oyu Tolgoi is reported to be the largest known undeveloped copper and gold deposit in the world and was estimated to have total reserves and resources of 3.2 billion metric tons of ore, with 30.8 million metric tons of contained copper and close to 1 million kilograms of contained gold (USGS 2011). Not all of this, nor the recent finds in Afghanistan, are believed to be reflected in the reserve data used for this paper.

Turning to the resources where proven reserves appear to be declining, the most important case is coal. It remains an important energy source, with huge reserves equivalent to 122 years of current production (versus 42 and 60 years for oil and gas respectively). Eighty five percent of estimated coal reserves are concentrated in United States, Russia, India, China, Australia, and South Africa. Reported reserves fell by 158 billion tons over 2000-2008, more than three times total extraction over the period (World Coal Institute 2009). While there is limited information on the drivers of this change it appears to reflect a political decision to demonstrate the intention to phase out the use of coal. For example, in 2004 Germany downgraded its reported hard coal reserves by 99 percent (from 23 to 0.18 billion tons). In the absence of cost-effective carbon capture technology, concern over climate change is depressing reserve estimates and discouraging discovery efforts, especially in light of the already high levels of proven reserves.[13] Reductions in reported proven reserves therefore probably do not imply a world that is actually running out of coal, though they may accurately reflect the decisions of some countries not to exploit some part of their national mineral wealth.[14] In the case of the other commodities, falling proven reserves seem to be mainly a response to market conditions, particularly relative to the boom times of the 1980s. [15]

How Costly is Discovery?

As outlined above, additions to proven reserves can result from both extensive (greenfield) and intensive (brownfield) discovery. At first sight, intensive discovery raises the question of attribution. How much of total imputed discovery is actually due to exploration? However, extensive and intensive discovery are linked. Just as past exploration enabled current production and so led to current intensive discovery, so current exploration, if successful, will not only produce new proven reserves but production activities that unlock further reserves. All discovery, whether extensive or intensive, can therefore be attributed to exploration, although the intensive phase does introduce some imprecision in matching exploration costs over a particular period with total imputed discovery over the same period.

Metals data allow for a detailed breakdown of capital costs into exploration and extraction components. Total capital spending in the metals sector was $393 billion over 2005-2008,

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[13] Massachusetts Institute of Technology 2007 discusses the essential role of carbon capture and storage in reconciling the incentive to use low-cost coal with emissions reduction.

[14] There is still some uncertainty on reserve trends, since China's coal reserves have not been updated for 20 years (Zittel and Schindler 2007).

[15] Some previously known reserves have been struck from proven reserves for tin and zinc because of market conditions. In constant prices, tin collapsed from US$ 20.68 to $4.24 per kg in 2002, and only in 2010 has it rebounded to $15.48 per kg. While silver prices have appreciated sharply from an extended low period, they are still below their peak levels of 1978-80. World Bank 2010 data suggests that for a large portion of producers operating at average cost structures, rental values for tin, silver, and phosphates would have turned negative (Kaiser and Viñuela 2011b, figure 3), leading to the mothballing or closure of uneconomical mines and lower reported reserves. Zinc too has faced a less buoyant market than many other commodities.

and exploration costs were $37 billion (Table 3). Over the same period, if total imputed discovery is valued by the current rent embedded in discovery (the CR approach) it amounts to 17 times exploration costs or $617 billion, more than half of which is due to copper.

Data for oil and hydrocarbons do not break out exploration costs to permit a similar estimate of the relationship between these costs and discovery value. As an extreme case, we can make the assumption that *all* investments in the oil and gas industries are exploration spending. At $2.6 trillion over 2005-2008, these investments compare with imputed oil and gas discoveries valued at $20.7 trillion and $7.9 trillion respectively, using the CR valuation method. Imputed discoveries would then be about 11 times the costs. Using the lower rental values that prevailed in 2002 and 2005 still yields the high value of 3 for discovery value relative to costs.[16]

[16] In the most mature region, North America, the ratio approaches 1.25, again under the extreme assumption that all investments are exploration. .

Table 3.

Non-Ferrous Metals: Exploration and Discovery 2005-2008[17]

Period: 2005-2008	Total Exploration: ($billion)	Imputed Discovery Mining ($billion)	Exploration Costs/Discovery (percent)	Memo: Imputed Discovery Copper ($billion)
Sub-Saharan Africa	5.9	26	23	10
Asia-Pacific	4.0	196	2	62
Europe/Oceania	6.1	57	11	36
Canada/US	9.6	113	8	49
South/Central America	8.9	183	5	156
Other	2.5	42	6	32
World	37.0	617	6	345

Source: Raw Metals Group, World Bank 2006, 2010, authors' calculations.

The assumption that exploration accounts for *all* capital spending is clearly extreme. One approach to a better estimate is to consider the five largest oil and gas majors. These have generally been successful in sustaining their levels of proven reserves with a ratio of discovery investments to production investment of less than 10 percent, which suggests a high multiple between discovery value and discovery investment. Applying the 10 percent ratio to total capital spending for the industry would produce the very high multiple of 110 for CR imputed discovery value to exploration costs.

Another example is to consider the case of Uganda's recent oil find. The exploration investments made by Heritage, Tullow and Neptune oil companies built on modest earlier exploration and total somewhat less than $1 billion. As of 2010, proven reserves stood at about 1 billion barrels, or up to 2 billion barrels according to company estimates. Uganda's oil is less valuable than most other deposits: its location in the center of Africa's landmass and its "waxy" constituency increases the difficulty of getting it to market. Options under consideration include a heated pipeline and a refinery close to the production areas. The estimated investment costs, at $10 – 13 billion, would then represent some $5- $13 per barrel, depending on recoverable reserves. Given these challenges and the quality discount, one might conservatively value the rent on Uganda's reserves at only $40 per barrel, for a total CR value of $40 - 80 billion, or 40 - 80 times exploration costs. Uganda has certainly been a successful exploration investment in terms of producing proven reserves, but it is not remarkable by the standards of the industry.

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[17] Regional breakdowns are approximate, since the annual reporting of exploration expenditures by listed companies, which provide the most specific measure of (mostly extensive) discovery effort are compiled by various industry research groups at the global level; companies typically do not report exploration spending by country. The high estimate of exploration costs to imputed discovery for Sub-Saharan Africa may reflect delays in updating reserve data or possibly lower intensive discovery due to a lower volume of on-going production.

Why is investment in exploration not pushed to the point where the marginal value of discovery equals the marginal cost? We suggest three main factors: discounting and the valuation of marginal reserves, taxation, and advances in technology.

The Valuation of Extraction and Discovery. Resource extraction or discovery may only affect production far into the future, especially for a country with large reserves. Unless the unit rent rises at or above the rate of time discount, valuing extraction or discovery at its current rent value will overstate it. Hamilton and Ruta (2009) recognize this, and introduce two alternative valuations, under the simplifying assumptions of constant real unit rents and per-period extraction. The El Sarafi method (ES) defines resource wealth as the discounted sum of future rent flows from the reserve; extraction is then valued by its impact on wealth.[18] The Change in Real Wealth method (RW) embeds the assumption of constant extraction in an asset equilibrium framework. Hamilton and Ruta find that, except when the discount rate or reserve life approaches zero, the ES method values depletion less than the RW method, which itself values depletion less than the CR method.[19]

Building on Hamilton and Ruta 2009, Table 4 shows three sets of valuations. We assume uniform annual extraction with rent value 100 and reserves with lives of 1, 8, 20 and 30 years. Discount rates are 2 percent, 4 percent (the social discount rate used by Hamilton and Ruta) and 15 percent. The latter is a proxy for private discounting; it reflects the recommendation of Australia (2003) on the carry-forward rate for risky exploration expenses[20] Both ES and RW valuations are lower than CR unless reserve life is only one year, but with modest social discounting they are still reasonably high. Even reserves that will not be used for 20 or 30 years are still valuable from a social perspective. The use of the alternative valuation methods will therefore reduce both the dis-saving effect of extraction and the value of discovery, but will not change the conclusion that discovery is very valuable relative to the typical costs of exploration. From the private perspective things look different. After about eight years (a typical lag from minerals exploration to production) the value of discovery drops off sharply. It will not be privately attractive to invest funds in risky prospecting for minerals that are not expected to be produced for many years.[21]

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[18] This approach underlies a new approach for national resource accounting currently being developed (UN DESA 2011 a,b,c). We are grateful to Ole Gravgard Pederson for making the draft papers for this new approach available.

[19] World Bank 2010 uses the RW approach with the social discount rate set at 4% and a horizon of 25 years (Table A2).

[20] The recommendation is for a 15 premium on top of a risk-free interest rate, and for five years.

[21] The rate of extraction may of course increase as a result of the discovery, but sometimes it may not, especially for an incumbent already stretched to exploit large reserves.

Table 4.

Valuation of Depletion or Discovery

(Uniform rent of 100 per year)

Reserve Life	Discount rate 0.02			Discount rate 0.04			Discount rate 0.15		
(years)	CR	ES	RW	CR	ES	RW	CR	ES	RW
1	100	100	100	100	100	100	100	100	100
8	100	87	93	100	76	87	100	38	65
20	100	68	83	100	47	71	100	7	36
30	100	56	76	100	32	59	100	2	25

Source: Authors' calculations. For definitions of ES and RW see Hamilton and Ruta (2009).

Taxation. As noted by Bohn and Deacon 2000, with efficient mining taxes, the bulk of the rents should accrue to host governments rather than to the private investors. The latter may anticipate a reasonable risk-adjusted return on investment, but not the large rents that accrue on high-quality deposits. Their returns are therefore truncated on the upside. The more progressive are rent taxes in creaming off the surplus when prices are high, the less attractive is exploration relative to total expected value. Expected value is also lower the greater the likelihood that countries will impose *de facto* rent taxes by changing the tax code to increase the national take when resource prices are high, as many have done.

Advances in Technology. Especially if proven reserves are already large, the prospect of advances in exploration technology increases the option value of delaying further exploration. Why prospect now when in several years it will probably be possible to do it better and more cheaply and safely? This question can apply to public decisions on opening up areas for exploration (Center for Public Policy 2011), but it will also be relevant for a private firm unless the right to explore a given tract is limited in time.[22] Most concessions do include provisions to limit the hoarding of resource tracts and to force tenements to turn over after a reasonable period.

The divergence the social value of discovery and exploration cost therefore cannot easily be accounted for simply by different valuation methods. However, the combination of other factors – high private discounting of risky investments with long payback periods, rent taxation, and the option value of waiting, can plausibly account for a substantial reduction in the expected private returns to exploration. The policy question is then how countries can best encourage exploration while still maximizing their social payoff from discoveries.

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[22] For further discussion, see http://blogs.reuters.com/felix-salmon/2011/04/20/the-option-value-of-not-drilling-for-oil/. It can be argued that by discovering now countries diminish the option value of waiting and discovering later, with better technology. At the same time, for reasons previously discussed it is difficult to factor this option value into estimates of national wealth.

Questions Arising from Discovery

We now consider three questions related to discovery. The first concerns estimates of the evolving wealth of nations. The second relates to countries' decisions on how much of the rent flow to consume, rather than save. The third considers the arguments for encouraging exploration, in particular by the public provision of geoscience data.

1. Does "Green Accounting" under-estimate sustainability?

Conventional national accounting paints a misleading picture of the evolving wealth of nations. Gross National Savings (GNS) does not take into account capital depreciation. Education spending is conventionally classed as consumption rather than an investment in human capital. Environmental damage is not included; neither is the extraction of natural resources, which is seen as running down national reserve assets. The measure of Adjusted National Savings (ANS) (World Bank 2006, 2010) adjusts for these factors, providing a more accurate picture of the evolution of countries' national balance sheets. ANS is often viewed as an indicator of economic sustainability, and is frequently low for major mineral producers because reserve extraction is a loss of wealth.

ANS does allow for the discovery of new reserves, but only through the inclusion of exploration investments, leading to a corresponding measure of national saving. . This would not be an issue if the value of discovery were well-reflected by the investments in exploration. But it can make a difference if the value of reserves discovered exceeds the costs of discovery by a large margin. In that case, national wealth, as reflected in the rent value of reserves, can be increasing even as minerals are being extracted.[23]

Table 7 illustrates the effect of including discovery in estimates of national savings, with the latter estimated on the basis of changes in national wealth, for a selected set of oil exporting countries. The analysis is illustrative and only for the year 2008; reserve data are not updated continuously so that a full treatment would need to average the estimates over a more extended timeframe. The first two measures are conventional GNS and ANS as estimated in World Bank 2010. Particularly for major resource exporters such as those in Table 7, the differences between GNS and ANS are very large. Although the average GNS of these five countries is 37 percent of GNI, their average ANS is negative, at -12.8 percent. This suggests that they are eating up their capital at an alarming rate.

[23] Both developed and developing countries have sought to improve their consideration of sub-soil assets in national balance sheets and national accounts (Nordhaus and Kokkelenberg 1998, United Nations 2009, World Bank 2010). Countries such as Indonesia and Mexico now regularly compile minerals and energy accounts. In some circumstances it may not, of course, be appropriate to include the full rent value of proven reserves in national wealth. Countries may decide not to exploit reserves because of environmental or other reasons (coal), or foreign mining companies might cream off the rents because of inadequate tax agreements (Zambia). In the latter case, reserve rent counts as domestic wealth but not national wealth.

Adding in imputed resource discovery, measured as the sum of the values of energy depletion and changes in oil reserves, suggests a somewhat different picture, as shown by the third measure, Discovery Adjusted National Savings (DANS) in Column 3.[24] This is positive for most of the countries and, in some cases, very high reflecting the value of large additions to proven reserves.[25] For some countries DANS is larger than GNI, which is not itself adjusted to include discovery.[26] Venezuela's additions to reserves in 2008 are clearly exceptional; their value is equivalent to eight times unadjusted GNI. Clearly care must be taken not to read too much into "outlier" years and the exceptional values that a single year will show for particular countries. But averaging discovery over longer time periods will produce qualitatively similar effects for many countries, with DANS substantially higher than ANS.

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[24] These estimates adjust the CR valuation to RW using the conversion factors derived from Table 4 with a 4% discount rate and a maximum reserve/production ratio of 25 years. Energy depletion includes not only oil consumption but also natural gas and coal. A more precise treatment would require separating out each component of resource depletion and adding back in the change in the value of reserves of that resource. For these countries the overwhelming bulk of depletion is oil, so that the omission of the other fuels will have little effect.

[25] In cases where non-marginal resources are discovered, DANS is an over-estimate because the new discoveries can be exploited only further into the future. This is, however, due to the lumpy nature of registered discoveries in one year; it is less of a problem when we consider the average annual trend of discoveries which, from Table 1, has been some 4% of the stock of proven reserves.

[26] It may seem strange to have savings rates of greater than 100 percent of GNI but these do not of course represent actual savings out of income received during the year. They are the savings rates that correspond to the observed increase in natural wealth taking into account discovery, relative to "normal" GNI. An alternative approach would be to include discovery value into the income measure in the denominator, much as an individual winning a lottery would include its value in total income for that year. This will constrain savings measures to less than 100 percent of total income, but will obscure the comparison relative to "normal" GNI.

Table 7. Measures of National Saving: 2008

(Percentage of GNI*)

	GNS 1	ANS 2	DANS 3	DANS2 4	DANS3 5	Imputed Discover y
Equatorial Guinea	55.8	-38.4	24.7	18.4	12.1	63.1
Republic of Congo	26.7	-56.5	-11.0	-15.5	-20.1	45.5
Angola	24.1	-41.3	-1.6	-5.5	-9.5	39.7
Saudi Arabia	48.3	-1.1	25.0	22.4	19.9	26.1
Gabon	48.8	3.6	143.6	129.6	115.6	140.0
Ecuador	31.8	0.4	175.6	158.2	140.7	175.2
Venezuela	34.6	6.5	834.1	751.4	668.6	827.7
Russia	32.8	1.6	17.4	15.8	14.3	15.8
Vietnam	30.4	10.0	69.7	63.7	57.7	59.7
Average	37.0	-12.8	142.0	126.5	111.0	154.8

Source: World Bank 2010 and sources for Table 1; authors' calculations

* GNI is not adjusted to include the value of discovery.

DANS is an overestimate because it double-counts the value of reserve discovery and investments in discovery which are already reflected in savings. We introduce a second measure, DANS2, which deducts a hypothetical discovery cost of 10 percent of the value of imputed discovery. As noted above, comprehensive data on discovery investment cost is lacking for hydrocarbons, but this is a reasonable estimate in the light of the previous section. DANS2 is lower than the previous measure, but not by much.

DANS may also be an overestimate if the quality of the reserves discovered is lower than that of those extracted. As high-grade deposits are used up first, we might expect a trend towards higher extraction costs, reducing the rental value per unit of reserves over time. Improvements in technology and, in some cases, increased scale economies of mining have so far worked to counterbalance this effect. However, to allow for the possibility that reserve quality declines over time, we introduce a third measure, DANS3 that includes a further 10 percent decrease in the quality of discovered reserves relative to extracted reserves, as measured by the fall in the unit rent.[27] While DANS3 is lower, it is still larger than ANS for

[27] This assumption would imply a sizeable increase in the costs of production for new reserves. Consider an oilfield with production costs of $12 per barrel and a product price of $92, yielding a rent value of $80/bbl. With constant price and a 10% lower rent value, costs of production would be $20 per barrel, an increase of 67% over existing costs. In the long run of course, product prices would be expected to rise if the effects of exhaustion outpace those of technology.

all countries. Nevertheless, the adjusted measures suggest that some countries such as Republic of Congo and Angola are indeed dis-saving, even allowing for increases in their proven reserves.

These conclusions suggest that a less mechanical approach to account for discovery and the potential reserve trajectory of a country would be useful. Some countries which appear to be dissaving with abandon are actually finding valuable reserves and raising their national wealth. But in other cases the trajectory of reserves is indeed downwards, flagging the need for more understanding of why imputed discovery is low or zero. This could reflect both geological and regulatory factors. Mexico stands out as an example of the latter, with severe regulatory obstacles to discovery.

2. How much should resource-rich countries consume?

A second question is how discovery can better be integrated into long-term fiscal policy. Governments have a choice of how to use resource income. They can finance public consumption or transfers to citizens; they can also save and invest, either domestically or abroad. The optimal policy will be influenced by several factors: the need to build a buffer of precautionary reserves to reduce vulnerability to adverse shocks, absorptive capacity, and the return on domestic investments versus those on external savings. Collier et al. (2009) consider the case of a capital-constrained low-income country. Contrary to the "Norway" model, saving abroad might not be an appropriate strategy because investing domestically can produce a higher payoff in terms of growth.

Assuming that the best investments are made, the fundamental question is how much to consume or save. Especially in cases where the resource sector is an enclave with low employment and few linkages with the rest of the economy it can be considered as simply a source of exports and fiscal revenue for exporting countries, rather than an essential input into overall production.[28] In this case, benchmarks for long-run sustainable consumption can be derived from estimates of the permanent income stream from resource rents. Some countries, such as East Timor, base their fiscal planning on such an approach. Sustainable consumption depends on the return on investments made out of resource rent savings and the number of years before the resource is exhausted. For example, with constant technology, production, costs and prices, an investment return of 3 percent and a production horizon of 10 years, sustainable consumption is only 25 percent of the value of resource rents. If the other 75% is invested, the permanent income stream after the reserves are depleted will be just sufficient to sustain this level. If the production horizon is longer, at 30 years, the level rises to 59 percent of resource rent income. For a country like Venezuela,

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[28] This differs from the formulation that leads to the Hartwick rule, where resources enter as inputs into the production function together with produced capital. For a review of literature that recognizes the implications of the open-economy model for sustainability, see Krautkraemer and Toman 2002.

with reserve-production ratios around a century, permanent income will be very close to actual income, which argues for a reasonably high consumption ratio.

Prudence dictates a high savings and investment rate, particularly in the earlier stages of resource discovery. But if the future is anything like the past, many resource exporters are likely to find that permanent resource income is greater than that estimated on the basis of known reserves. It would not be prudent to anticipate major new discoveries; absent good supporting information on subsoil assets, Haiti cannot plan for its future on the assumption that it could be the next Saudi Arabia. But the dynamics of incremental discoveries and the long lead times before reserve depletion might support more expansive use of rents to improve the current welfare of citizens, including through direct transfers.[29]

3. Should geoscience information be supported as a public good?

> *"Many resource discoveries are made by explorers who apply new ideas and add to existing data generated by earlier companies who have worked the area. Frequently it is not until after a succession of seven or eight explorers have surveyed a particular area unsuccessfully and often repetitively, that a discovery is made*." (Australia 2003, 6-39).

A third question is whether governments should encourage investments in exploration and, if so, how?. Exploration spending is a form of research and development, an activity which is often encouraged by corporate tax codes because not all of the benefits are appropriable by the investor. If the social valuation of new reserves is higher than the private valuation because of rent taxes and different rates of discount, the difference creates a similar wedge between the costs that companies can absorb in exploration and the social benefits of discoveries as valued by the value of additional reserves, especially if future intensive reserve growth is factored in. This argues for encouraging exploration, especially if the country has a tax system capable of recovering most of the natural rent on mining output.

The divergence between social and private value may be greater in developing countries because of a higher risk premium seen by private investors. With large upfront investments, any mining agreement is a potential "obsolescing bargain" (Vernon 1980), so that part of the task of the government is to compensate investors for its own inability to commit to agreed policies in the future.[30] Many leading mining countries do have policies to encourage exploration, including flow-through share schemes and generous carry-forward interest

[29] For an overview of this approach and related research, see Moss 2011.

[30] A current example of the uncertainty faced by investors is the question of whether Uganda should refine oil for local use rather than build a pipeline for export. While both options involve risks, the first one would imply a slower extraction path than anticipated by the mining companies (http://www.standardmedia.co.ke/InsidePage.php?id=%202000045084&cid=14&story=Uganda%20to%20start%20refining%20its%20own%20oil%20in%202014).

rates.[31] As the earliest inputs into the exploration process, geoscience data costs will be more upfront than other exploration spending, and therefore the least attractive to private investors relative to delayed returns.

Countries therefore face the choice of either offering heavy subsides to companies' spending on geoscience data or the provision of such data as a public good. The latter has the advantage of reducing barriers to entry, increasing the possibilities of crowding in more rounds of exploration and the likelihood of discovering more reserves. Most countries have measures to ensure "tenement turnover" at regular intervals; in addition, some countries, including Australia, require companies to make public the geological information ("legacy data") they have collected after a specified period. These measures can encourage competition to reveal resource value.[32] If, as sometimes argued for developing countries, governments and private companies have asymmetric information or different capacities to interpret the commercial value of common information, active competition may be the only way to reveal the likely mining value of the tract and provide a fair return to the government.

Many developed-country governments allocate considerable resources to the provision of "pre-competitive" geo-scientific data. Australia's states have provided them for over 150 years, and more than $270 million were committed for data over 1992-2005 (Australia 2000). Yields to these types of investments, expressed as their impact on private investment, are reported to be high at 5-15 times the level of public spending (Australia 2000). [33] Canada, too, spends substantial resources to the provision of public geoscience knowledge. It is reported that every dollar spent on geoscience exploration leads to $5 in private investment and to discovered resources valued at $125.[34]

There is some evidence for developing countries too that public investments can deliver significant returns in stimulating private investments by extractive industries (Australia 2010; Reedman et al. 2002). The latter report by the British Geological Society includes three case studies of major systematic geoscience information production; Bolivia (220,000 km2 and

[31] McKenzie and Mintz (2011) show that the marginal effective tax rate for exploration and development (E&D) spending in three Canadian provinces (excluding oil sands) is -30.1 percent. This is less negative than for R&D in non-resource sectors (the average marginal effective tax rate for R&D in non-resource sectors in three Canadian provinces is -50.7 percent), but at the same time E&D is not exploration alone; it represents a far larger share of total spending (64-79 percent) than R&D for non-resource sectors (5 percent).

[32] Another approach is to encourage exploration by offering exclusive rights to long-term development, but this has a high cost in terms of reducing competition among mining companies. Competition is usually stronger in more mature regions, and those where geology is well known. The Gulf of Mexico (US section) is an example of a very competitive environment.

[33] These studies do not however appear to adequately consider the counter-factual of what would have happened in the absence of these investments, or provide alternative estimates of associated benefit streams (fiscal, rental value, etc.

[34] See Canada Mining Exploration and Industry New Investment in Mineral Exploration Geoscience: http://paguntaka.org/2011/03/10/canada-mining-exploration-and-industry-new-investment-in-mineral-exploration-geoscience/.

8,185 steam and soil geochemical samples), Indonesia-Sumatra (524,000 km2 and 22,000 geochemical samples), and northern Peru (25,000 km2 of geochemical exploration), as well as a smaller effort in Zimbabwe. It finds that public geoscience date is likely to generate a high investment response in less developed countries but that the associated ministries are typically under-resourced to provide it. Anecdotal evidence suggests that developing countries with better geoscience data are in a better position to attract extractive investments as well as negotiate better agreements. The World Bank has over the past decade committed almost USD 130 million dollars internationally to public geo-science components as part of its projects, but these components, some of which are ongoing, have typically not yet been subject to formal cost-benefit analysis.

More research is needed on the returns to information, and on the case for donor support. If the potential returns to investments in this area are so high, why are low-income developing countries not making these investments on their own? One possibility is that the countries are credit-constrained and that the chain from knowledge to enhanced completion and then to higher mining output and taxes is too long and indirect to finance data collection commercially. Another is that the culture of open information and transparent competition for mineral concessions is not yet well rooted in many developing countries. If so, assistance with open data might be an important incentive to open up the system.

Conclusion

Discovery is, of course, only a small part of the overall challenge posed by resource-based development. Better management of rents is needed along the entire resource chain if more countries are to benefit from their resources (Barma et al 2011a, Collier 2010). However, the discovery record suggests that many countries will continue to be resource dependent long after their currently-proven reserves have been depleted. Indeed, climate change and groundwater and other environmental concerns may pose more serious constraints to the resource-driven model of development than reserve exhaustion.

Despite its importance, particularly for low-income countries, resource discovery has received relatively little attention and is also less frequently stressed in minerals data, which usually focus on extraction and changes in proven reserves – the "known knowns" of the mineral sector. This paper sets out some building-blocks and considers the record of imputed discovery, defined as the sum of extraction and changes in proven reserves. While exploration effort accounts for only part of total discovery, it is vital because further, intensive, discovery cannot take place without previous exploration and development.

For oil, gas and most minerals, discovery has outpaced extraction even though resource use has accelerated. On average, and considering the majority of resources for which discovery has been positive, over the period 2000-2008 it has represented 40 percent of initial proven reserves, over 4 percent per year. For oil and gas it is 40 percent and 35 percent respectively; for copper 70 percent even though reserve totals do not account for new finds in Mongolia and Afghanistan that will someday come on stream. For coal and a few minerals discovery has been negative, reflecting economic factors and political decisions. Reserves have been declassified, in the case of coal, apparently as a signal of political commitment to fight climate change. Estimates of probable, but not proven, reserves for oil and gas suggest that future finds will be large relative to past production, including in less-explored regions such as Sub Saharan Africa but also in some mature regions, especially if minerals continue to experience strong demand.

Discovery raises the question of how to measure changes in national resource wealth. Current approaches consider extraction as a decrease in wealth and account for discovery only through investments in exploration. However, when valued by current rent value, discovery has been very valuable relative to exploration spending; some 17 times as much for hard minerals. Data do not permit the same calculation for oil and gas but partial information suggests a comparably high value ratio there also. Changing the valuation method to value both extraction and discovery by their impact on wealth -- the net present value of future rents discounted by a modest social discount rate -- reduces these ratios, unless unit rents are expected to increase at or above the rate of discount. However, with reasonable assumptions, including a slow decline in resource quality, discovery is still very valuable relative to exploration. Countries where discovery is substantially greater than extraction are therefore probably increasing their national wealth rather than reducing it. These calculations do of course reflect recent market conditions; the picture could look different with a major slump in minerals markets.

Should countries factor discovery into their accounting in this way? It can be argued that simply discovering what is already there does not represent an actual increment to wealth. This approach does not, however, lead to a useful definition of wealth, since much of what is underground, or in rivers or coastal seas, will never be extractable in the foreseeable future. In this case, it is not reasonable to add resources to national wealth, at least until technology or market conditions make them economic; national resource wealth is not simply a physical concept. At some point – when new technology or buoyant markets open up new mining possibilities – the country becomes wealthier. But in some cases it may be misleading to simply add the rent component of discovery into national wealth, for example, if foreign mining companies capture most of or if countries choose not to exploit their reserves for environmental or social reasons.

One implication of including discovery into wealth accounting will be to reconsider measures of wealth-adjusted national savings. Adjusted National Savings (ANS) rates which consider only extraction and (modest) exploration investment are often low or negative for resource exporters. For some countries the picture changes a great deal when savings are further adjusted for discovery, even when estimates of exploration costs are netted out to avoid double-counting and when an allowance is made for a fall in the quality of reserves over time. Some countries with low or negative ANS are actually building up national wealth. These dynamics, including the reasons for declining reserves, could be better factored in. In some cases, reserve declines do not reflect geology so much as political factors and policy decisions, either not to use the resource (German coal), or to restrict the right to explore for nationalistic reasons (Mexican oil).

Another implication of discovery is that, while it is not prudent to anticipate major resource finds or to expect high resource prices to continue forever, the record suggests that for many countries, levels of sustainable long-run consumption out of resource rents are probably higher than those derived only on the basis of current proven reserves. Policy recommendations towards high savings might not be fully credible in countries which have good reason to believe that further resource finds are very likely.

The final question addressed is whether there is an argument for providing geoscience information as a public good. We argue that there is a large difference between the private and social values of discovery. Private firms are likely to discount resource finds heavily, especially in risky environments; they also face a truncated distribution of expected returns if the fiscal system succeeds in taxing away a large share of high natural rent. It can also be argued that host governments have less information than companies on the mining value of concessions, or less ability to interpret such information. Optimal policy should therefore seek to encourage both exploration and competition between mining companies, to help reveal value, especially as turnover of concessions (which can be seen as inter-temporal competition between mining companies) also facilitates discovery. Providing geoscience information as a public good, as well as requiring companies to reveal information gained by their own efforts after a period of time, may be the least-cost way to resolve the tension between the two objectives. It is noteworthy that major high-income mining countries allocate considerable resources to providing information. In developing countries, some 13 World Bank operations have included funding for geoscience information but their impact in this dimension has not been assessed. More research needs to be done on estimating the benefits relative to the costs.

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