Resource Consumption Intensity and the Sustainability of Gold Mining

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Abstract

Gold mining in Australia and globally has a long and variable history. In recent years, due to ongoing public concern over long-term environmental impacts, the mining industry globally has been moving towards a more sustainable framework. This was presented as the 'Mining, Minerals and Sustainable Development' (MMSD) framework at the Johannesburg Earth Summit in 2002. There are a number of fundamental issues and concerns with assessing the sustainability of mining. Firstly, long-term trends show that ore grades for almost all metals and minerals will continue to decline (some rapidly so), increasing waste rock is being produced due to the trend towards large scale open cut mining and more complex ores are commonly now being developed. The impact of these trends on the resource intensity, or unit cost, of gold production is of major concern as it could lead to an increase in energy, water and cyanide consumption and greenhouse gas emissions per unit gold produced. A detailed compilation of these fundamental sustainability indices for gold mining has been undertaken, and is presented with respect to indices over time, ore grade and ore throughput. A clear observation is that the resource intensity of gold mining is extremely sensitive to the ore grade, with energy, water and cyanide consumption and carbon emissions rising rapidly as ore grade decreases. Based on the gold ore resources at operating mines and other known gold deposits, it is most likely that the average gold ore grade will continue to decline in Australia, leading to an increased resource intensity and consequent environmental impacts (assuming no breakthrough new technologies occur). These findings are of major importance to understanding the sustainability of gold mining in Australia, and could be expected to be replicated for other countries given the general similarities of gold mining and milling globally. The final judgement of the sustainability of gold mining therefore must take into account the sensitivity of the ore grade in the resource intensity of gold production.

1 Introduction and Background

The mining and production of gold is indeed an ancient human tradition and presently occurs all over the world. The history of gold mining is commonly associated with social, political, economic and environmental impacts, some of which can lead to significant negative costs. In recognition of the potential and actual impacts of gold mining, the industry has in recent years been moving towards a more sustainable framework, primarily through the 'Minerals Mining and Sustainable Development' report presented by the global mining industry framework at the Johannesburg Earth Summit in 2002. Over the past decade there has also been a rapid increase in the publication of sustainability reports by mining companies, in which they report their social, economic and environmental performance. The prediction of future sustainability issues associated with gold mining, however, must be cognisant of historical production trends as well as the relationships between key aspects such as energy, water and cyanide consumption and greenhouse emissions, herein termed "resource intensity". This paper compiles the available data on gold mining for Australia, North America, Africa and the Asia-Pacific, including ore grades and resource intensity.

2 Methodology and Data Sources

The extent to which data exist as well as its relative availability is quite surprising. The aspects of sustainability investigated in this paper are assessed through the compilation of detailed data sets on :

- **Gold ore grade and gold production** – historical government series/periodicals on mining, industry data sets;
- **Energy, water and cyanide consumption** – recent company annual sustainability reports;
- **Carbon dioxide emissions** – recent company annual sustainability or technical reports.

2.1 Data Sources : Gold Ore Grade and Production

The data on gold ore grade and production are available for :

- **World gold production** – 1851 to 2004 (Kelly *et al*, 2004; ABARE, var.);
- **United States** – 1907 to 1993 (Craig & Rimstidt, 1998);
- **South Africa** – 1893 to 2005 (CMSA, 2006);
- **Australia** – 1859 to 2004 (Mudd, 2006);
- **Brazil** – 1835 to 1994 (Machado & Figueiroa, 2001).

Canadian ore grade data is available from (NRC, var.), however, this has yet to be compiled.

2.2 Data Sources : Gold Mining Resource Intensity

The companies used to compile data on resource intensity are listed in Table 1. All references are the respective company social/environmental or sustainability report. This compilation, although extensive, does not capture all available data from different gold mining companies. There are numerous companies which do not report sustainability data. The companies below, however, represent a significant portion of world gold production, as well as an excellent geographic spread of mines in Africa, North America, Central America, South America and the Asia-Pacific (including Australia). If needed fossil fuels were converted to energy and greenhouse emissions using (AGO, 2005). In general, an increasing degree of data is being reported by mining companies over time (with access facilitated through online resources).

Table 1 – Companies Reporting Sustainability Data for Gold Mines (data from 1991 to 2006)

Company	Company	Company
AngloGold Ashanti Ltd	Homestake Mining Company	Perseverance Corporation Ltd
Barrick Gold Corporation	Leviathan Resources Ltd	Placer Dome Inc
Dominion Mining Ltd	Mt Isa Mines Ltd	Placer Dome Asia Pacific Ltd
Gold Fields Ltd	Newmont Mining Corporation	Resolute Ltd
Goldcorp Inc	Normandy Mining Ltd	WMC Resources Ltd
Harmony Gold Ltd	Oxiana Ltd	

3 Results

3.1 World Gold Production and Ore Grades

The past 150 years of world gold production is shown in Figure 1, including gold ore grades for hard rock mining for South Africa, Australia, Brazil and the United States presented in Figure 2. The California gold rush in 1849, followed by Australia in 1851 and South Africa in 1884 are evident. The development of new cyanide milling technology (carbon-in-pulp) and the major rise in the real price of gold in the 1970's led to a renewed expansion in production.

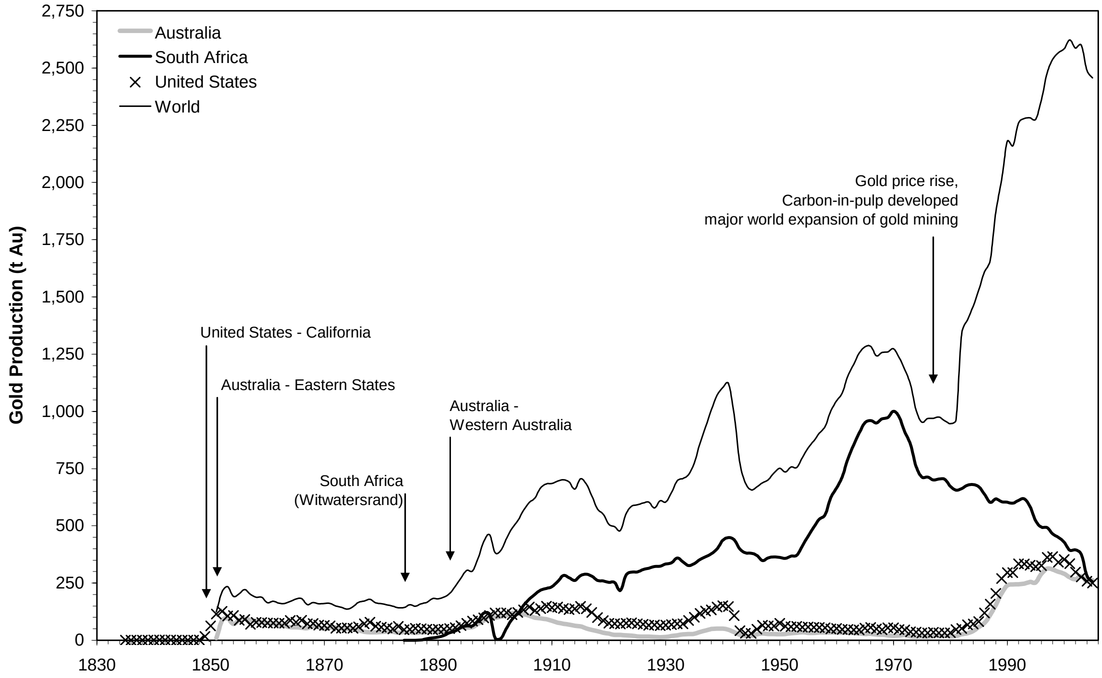


Figure 1 – World Gold Production History

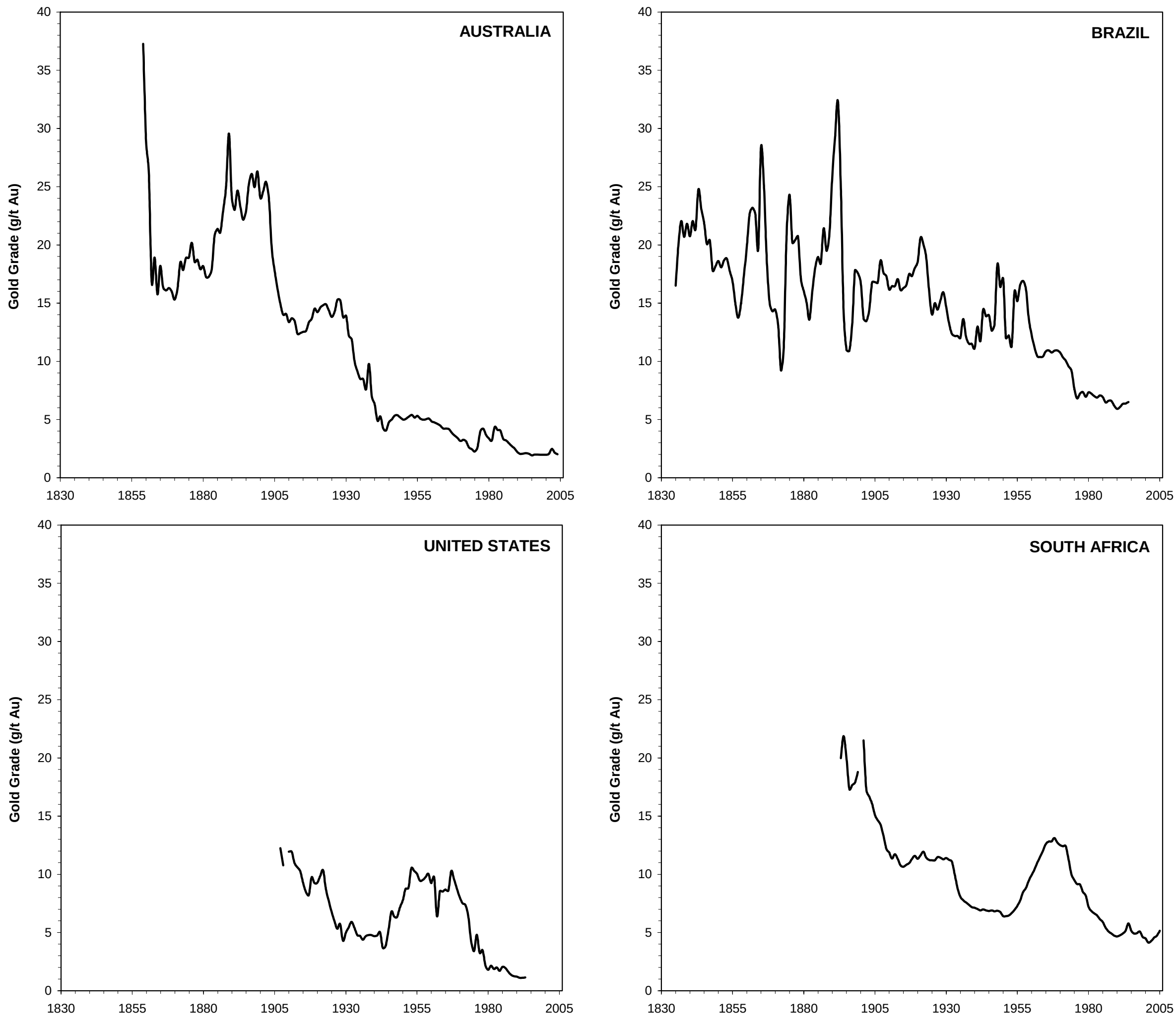
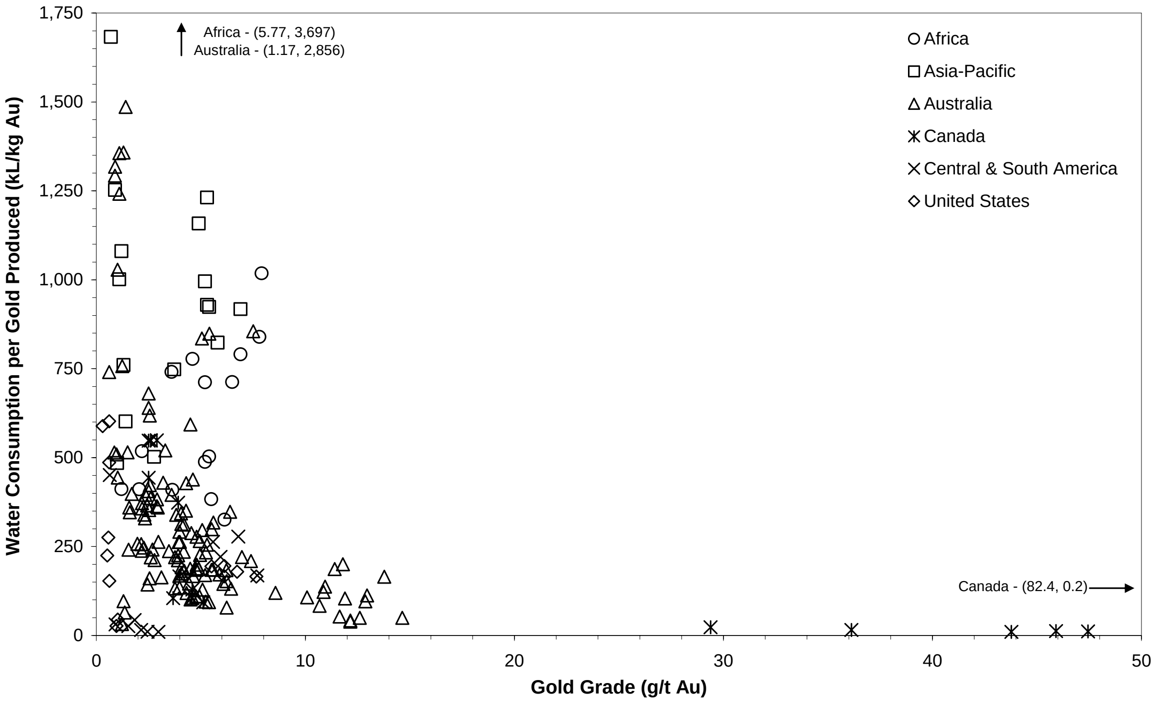


Figure 2 – Gold Ore Grades Over Time (Hard Rock Mining)

3.2 Water and Energy Consumption in Gold Production

The available data for water and energy consumption has been compiled and is presented as unit consumption per gold production with respect to ore grade as well as with unit consumption per tonne of ore milled with respect to mill throughput. In this way, the effects of both mine scale and ore grade can be observed. The resource intensity data for water is given in Figure 3, with energy given in Figure 4. Data over time is summarised in Tables 1 and 2.



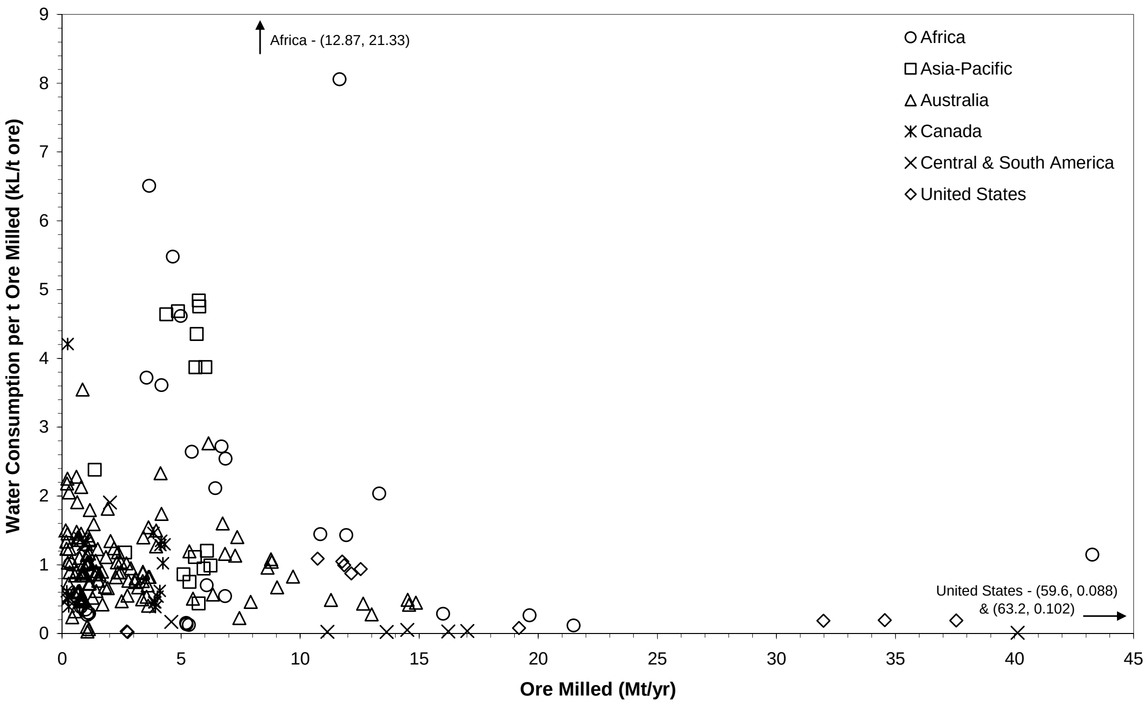


Figure 3 – Water Consumption in Gold Production

(Note : Points off-scale of each graph)

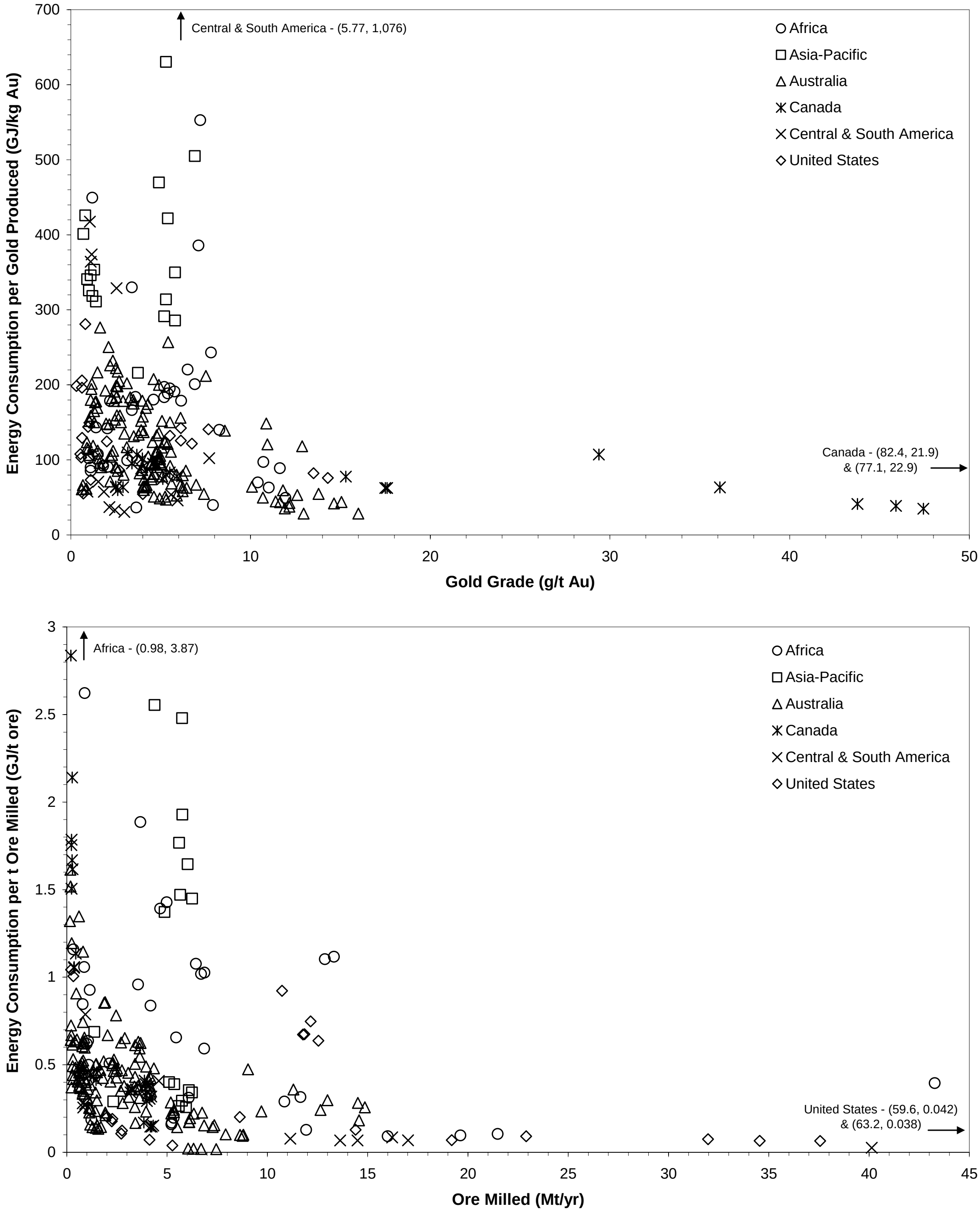


Figure 4 – Energy Consumption in Gold Production

(Note : Points off-scale of each graph)

3.4 Cyanide Consumption in Uranium Mining

The use of cyanide in gold mining is a major environmental risk that needs to be pro-actively managed. Major tailings dam failures in the past decade have led to considerable public scrutiny of cyanide, although at present there remains no efficient alternative. Although some companies publish sustainability reports, including water and energy data, not all include cyanide data. The compiled data is presented, in Figure 5, as unit consumption per gold production with respect to ore grade. Data over time is summarised in Tables 1 and 2.

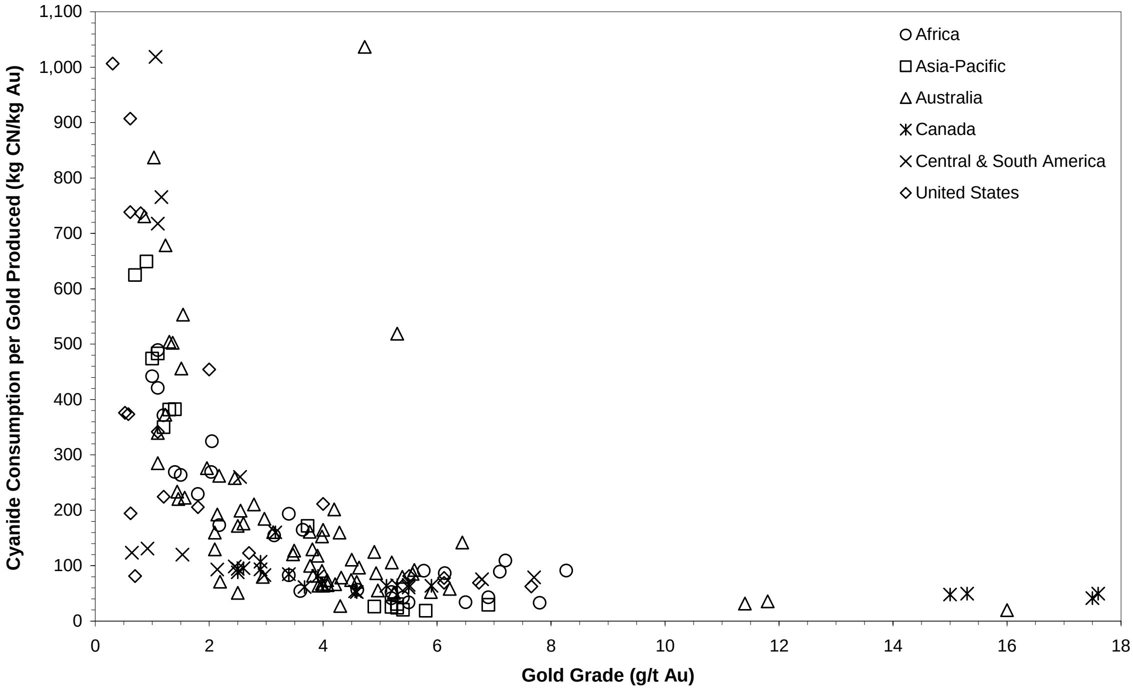


Figure 5 – Cyanide Consumption in Gold Production

3.5 Greenhouse Emissions From Uranium Mining

The extent of greenhouse emissions from mining, primarily through fossil fuels use, is a major environmental challenge for the mining industry globally but particularly for some sectors of gold mining that involve large scale open cut mining. As with water and energy, greenhouse emissions as carbon dioxide is presented as unit release per gold production with respect to ore grade as well as with unit consumption per tonne of ore milled with respect to mill throughput (Figures 6 and 7). Data over time is summarised in Tables 1 and 2.

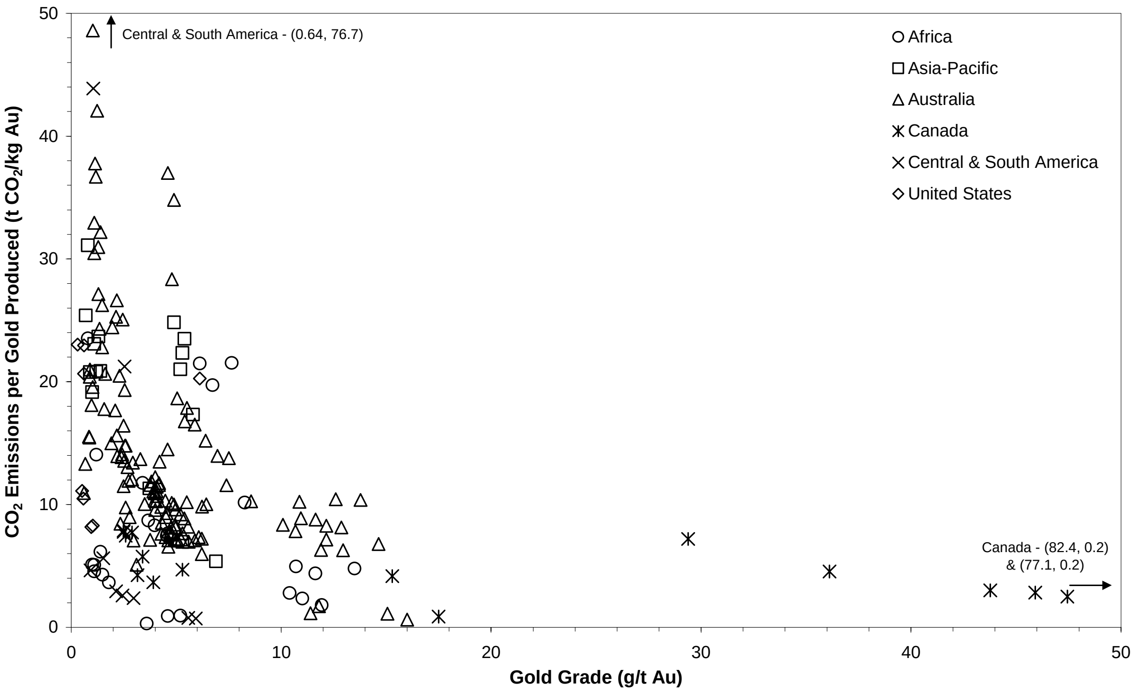


Figure 6 – Greenhouse Gas Emissions per Gold Produced

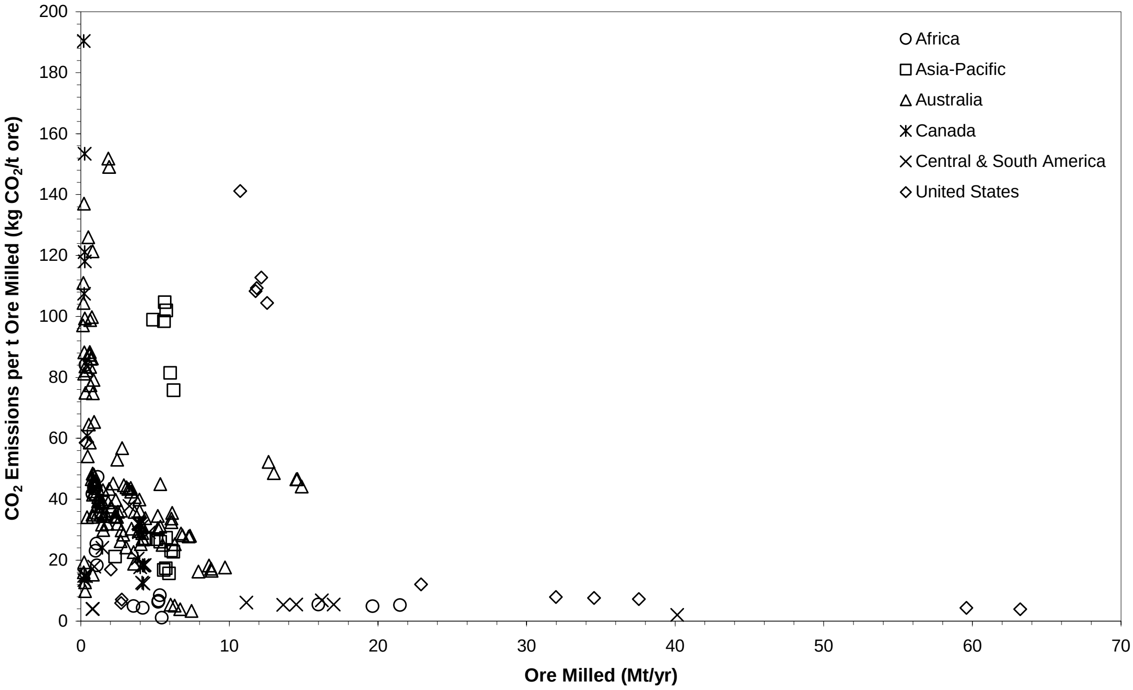


Figure 7 – Greenhouse Gas Emissions per Gold Ore Milled

Table 1 – Resource Intensity of Gold Mining Over Time : Data Summary per Ore Milled

Year	Water Consumption			Greenhouse Gas Emissions			Energy Consumption		
	kL/t ore			kg CO_2/t ore			GJ/t ore		
	Average	Standard Deviation	No. Mines	Average	Standard Deviation	No. Mines	Average	Standard Deviation	No. Mines
1991	1.14		3	36.7		2	0.53		2
1992	0.96		3	38.5		2	0.52		2
1993	1.02		3	40.9		2	0.58		2
1994	1.16		3	38.8		2	0.59		2
1995	1.17		3	26.0	21.6	8	0.21	136	8
1996	0.97	0.239	4	29.8	18.6	10	0.23	139	10
1997	1.92	1.400	9	25.2	17.7	14	0.47	630	14
1998	1.18	1.004	20	21.2	28.5	18	0.41	520	20
1999	1.22	0.865	17	24.1	35.0	11	0.44	388	16
2000	1.30	0.809	19	26.6	27.7	14	0.45	387	19
2001	0.53	0.945	25	28.9	40.7	26	0.31	435	27
2002	0.56	1.147	21	26.4	40.8	23	0.27	530	31
2003	0.61	1.013	17	24.1	36.9	17	0.28	759	27
2004	0.86	1.018	25	23.3	34.3	35	0.35	478	39
2005	1.14	1.666	36	22.8	44.4	23	0.33	568	35
2006	6.18	8.012	6	5.8	1.9	3	0.65	657	6
Average	**1.15**			**24.6**			**0.35**		

4 Discussion

A comprehensive data set has been compiled and presented herein on critical aspects of gold mining around the world, arguably for the first time. A number of issues arise from this data.

The most recent gold mining boom since the late 1970's has been facilitated by the combination of a sustained price rise (especially in real terms) and the development of new carbon-in-pulp ('CIP') milling technology, and to a lesser extent the continuing evolution in large scale bulk earth moving vehicles.

Table 2 – Resource Intensity of Gold Mining Over Time : Data Summary per Gold Produced

Year	Water Consumption kL/kg Au			Greenhouse Gas Emissions t CO_2/t ore			Energy Consumption GJ/kg Au			Cyanide Consumption kg CN/kg Au		
	Average	Standard Deviation	No. Mines	Average	Standard Deviation	No. Mines	Average	Standard Deviation	No. Mines	Average	Standard Deviation	No. Mines
1991	390		3	12.6		2	172		2			
1992	335		3	13.4		2	175		2	456		1
1993	346		3	13.9		2	205		2	130		1
1994	323		3	10.7		2	162		2	223		1
1995	260		3	16.4	8.3	8	142	81,540	8	100		2
1996	224	118	4	15.6	9.2	10	120	58,396	10	80		4
1997	737	871	9	11.4	8.6	14	213	125,882	14	106	143	8
1998	581	369	20	10.0	7.1	18	193	135,248	20	114	183	8
1999	547	415	17	9.9	8.2	11	185	106,882	16	123	183	9
2000	495	418	19	9.7	6.2	14	172	84,429	19	90	210	6
2001	243	381	25	12.7	10.7	27	137	97,373	27	148	242	13
2002	258	329	21	11.6	11.3	30	118	94,615	31	147	241	22
2003	298	414	17	12.1	8.5	17	134	131,514	27	153	217	23
2004	375	231	25	11.0	9.9	35	150	93,401	39	176	303	28
2005	418	242	36	11.6	15.7	23	122	179,788	35	153	187	31
2006	1,783	1,360	6	3.7	2.8	3	187	48,483	6	117	166	6
Avg	**477**			**11.5**			**146**			**150**		

These factors led to a resurgence in exploration, often confined to previous gold producing provinces, along with the development of a raft of new gold mines around the world. These mines have often been based on open cut mining techniques, which allow more complete extraction and processing of all gold-mineralised ore. The average economics of gold mining were radically re-defined during this period, which has generally continued to the present. This pattern is common around the world, and led to an extra-ordinary renaissance in some countries such as Australia (eg. (Close, 2002) and the United States (Craig & Rimstidt, 1998). In South Africa, however, this pattern has not prevailed, due to the deep underground nature of their gold mines, economics and other social issues. From a global view, based on gold resources data in (George, 2006; GA, var.; NRC, var.), there is only sufficient known economic resources to sustain existing levels of production for less than 20 years. The future pattern of economic resources and production is, of course, difficult to predict but will continue to depend on exploration effort, economics, social and environmental issues and technology.

There is a clear trend of declining ore grade in the countries presented, namely Brazil, Australia, South Africa and the United States. Although the data has not been presented in this paper, these ore grades are also reflected by the effective ore grades of these countries economic resources. Further to this, the ore grades of some data sets is yield or extraction only and does not reflect the true assay of the gold ore as mined (eg. South Africa). In Australia, ore grade data is only based on true assay data from about 1980 onwards with generally all data prior to this being yield only (Mudd, 2006).

Over the past 150 years the remaining tailings from gold mining and milling are often easily re-processed to extract further gold as economics and technology evolve. True ore grades in the 1800's and early 1900's are therefore likely to be considerably higher than the data presented, giving a true decline of ore grades which is also more rapid. The pace of future decline in average ore grade is difficult to predict, but it is clear, based on existing operating mines and undeveloped resources, that it is likely to gradually decline, perhaps at a slightly slower pace than recent history (excluding any future technological breakthrough).

With regards to water consumption, there is a degree of scatter in both graphs (per gold and per ore milled). This is most likely due to the varying complexity of gold mines, such as local climate and water resources, metallurgical differences between ores, the type and degree of processing (eg. gold produced as bullion or in an ore concentrate, also heap leaching), the number of active mines supported and their configuration (underground, open cut), and the like. Adding to this complexity are the issues of water quality and the degree of water recycling (some companies only report imported water used and do not account for recycled water). Although gold mining is a relatively well understood industrial enterprise, the demands for water will vary according to these numerous site-specific issues. However, despite this complex variability between mines, the data in both graphs in Figure 3 do suggest overall relationships. Firstly, higher grade gold mines (>6 g/t Au) typically have a very low water cost per gold produced while lower grade mines (<2 g/t Au) generally have a somewhat higher water cost per gold produced. Gold mines with a high throughput are commonly low grade projects, and water use efficiency per tonne of ore milled is most likely due to economies of scale. The total quantity of water consumed, however, may still be very significant locally. There appear to be no noticeable trends with respect to time. Based on the combined average of all available data, gold ore milling typically requires about 1.15 kL/t ore or about 477 kL/kg Au.

Energy consumption shows a slightly lower degree of scatter in both graphs compared to water, with the same general trends also apparent in each graph. High grade mines use less energy per gold produced while high throughputs requiring less energy per tonne of ore milled. Site-specific variability in energy sources between the gold mines analysed in this data set, such as natural gas, diesel and hydro-electric power, could help to explain the data variability. There appear to be no real trends with respect to time. Based on the combined average of all available data, gold ore milling typically requires about 0.35 GJ/t ore or about 146 GJ/kg Au.

The extent of cyanide required to produce gold shows an excellent relationship to ore grade, with very minor scatter. The sensitivity of cyanide consumption per gold produced relative to ore grade is clearly demonstrated – despite a mix of process plant types, heap leaching and other factors involved in gold ore milling. For relatively high grade mines (>6 g/t Au) the cyanide cost is commonly less than 100 kg/ kg Au, while for lower grade mines (<2 g/t Au) the cyanide cost increases rapidly as grade declines, possibly reaching up to 1,000 kg/ kg Au or more. The average ore grade in 1993 in the USA was ~1.14 g/t Au while in 2004 in Australia and South Africa it was ~2.0 and ~4.7 g/t Au, respectively. These average country grades are visible in their relative position in Figure 5.

The release of greenhouse gas emissions is a major global challenge. The extensive use of fossil fuels in gold mining, mainly diesel, leads to significant carbon dioxide emissions. As with cyanide and energy, there is a good correlation between unit carbon dioxide emissions per gold produced and ore grade as well as unit emissions per tonne of ore milled. The ore grade inflection point, at which unit emissions increase rapidly, is also of the order of 5 g/t Au. It is unfortunate that a number of major gold mines and companies do not report carbon dioxide emissions in their sustainability reporting. Based on the combined average of all available data, gold ore milling typically releases about 25 kg CO_2/t ore or about 11.5 t CO_2/kg Au. Although the high mass ratio of CO_2 to gold is due to the relatively small mass of gold produced, the primary function of gold for jewellery leads to a major ethical and social issue in terms of accounting for the greenhouse costs.

5 Conclusion

This paper has compiled and presented broad-ranging data on gold mining and production, with a principle focus on the key aspects of mineral resource sustainability and environmental impacts associated with mining. This includes gold ore grade and energy, water and cyanide consumption and greenhouse gas (carbon dioxide) emissions relative to ore grade and ore throughput. Overall, the long-term decline in gold ore grades is demonstrated, with changes attributable to evolving prices and technology. The resource intensity of gold production, based on a comprehensive data set of global gold mining, shows generally good relationships between unit resource consumption of water, energy and cyanide and greenhouse emissions. As ore grades decline, unit resource cost or releases increase. In terms of sustainability, given long-term decline in ore grades, this points to the resource intensity of gold production beginning to increase substantively in the near future – an aspect of the sustainability of mining which has to be taken more explicitly into account than recognised at present.

6 Acknowledgements

This work is the author's individual work based on broad-ranging research and involvement in the environmental aspects of mining. Numerous companies were very helpful when asked for reports or data (some weren't). Techa, Mineral Policy Institute, deserves many thanks.

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