ENVIRONMENT, INCOME, AND DEVELOPMENT IN SOUTHERN AFRICA

An Analysis of the Interaction of Environmental and Macro Economics

By

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ABSTRACT

It is widely believed that rural forest and agricultural resources in Southern Africa are overused, in the sense that both biomass and harvest levels are significantly below levels of maximum sustainable yield. However, economic theory suggests that high interest and time preference rates cause the economic optimum to coincide with generally-observed patterns. In addition, low income may be the driving factor behind high interest and time preference rates.

In macro-economic terms, Southern Africa may be experiencing a productivity crisis. This leads to a downward shift in the labor demand curve, and an equilibrium result with undesirably low wage rates, high unit labor costs, and high and growing unemployment.

In this context, the imposition of pollution control costs might worsen an already negative macro-economic picture. The mechanism would be a reduction in exports and an increase in imports.

The productivity problem, in turn, may be a result of social factors unique to Southern Africa. Improvement in these social conditions could resolve much of the economic problem of low productivity. A review of the literature on technology transfer and green technologies offers little basis to presume that new technologies can alter this picture.

One approach to positive remedies is to examine international solutions. Three kinds of potential environmental policies are:

(A) tradeable pollution permits,

(B) leveraged World Bank environmental adjustment programs, and

(C) international petroleum taxation and income transfer.

Given Southern Africa's unique position as a source of global industrial raw materials, it should be possible to develop policies that simultaneously enhance income levels and environmental protection.

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CONTENTS

INTRODUCTION

It is generally recognized that environmental concern is income elastic: countries and social groups increase their interest in environmental quality as their incomes rise. This relationship was emphasized by Ruttan (1971), and noted by others (Ciriacy-Wantrup, 1963; Chapman and Barker, 1991).

Crudely put, at population-intensive subsistence levels, rural households are more interested in consuming wildlife than in its protection for the enhancement of future generations. Urban households with high unemployment and low wages for those employed have no economic resources to spare for taxation for public sector activity in water supply or electrification.

In 1991 I had considerable opportunity to visit factories and mines, communal areas, "homelands," squatter camps, and universities in Zimbabwe and South Africa. The observations and discussions originating in that experience have emphasized the significance of the income-environment linkage.

In this paper, I am attempting to understand the interaction between urban income and rural resource degradation and the likely impact of environmental protection on macro economics. An additional focus is the kinds of policies that might enhance both material living standards and environmental protection in the world's poorest countries. The policy discussion will include some consideration of the needed role of technology in offering solutions, the possible impact of climate change on environmental problems in Southern Africa, and the linkage between aid and incentives.

In this region, environmental economics must be seen in a context in which the area's extensive wealth of industrial resources flows to the rest of the world, but economic decline here has been general. By referring to Southern Africa, I mean generally the area from Shaba in Zaire to Cape Town in South Africa. This area is geologically distinct from the rest of Africa and shares a common history of colonial exploitation of mineral resources as well as a modern era that emphasizes raw materials export.

URBAN INCOME AND RENEWABLE RESOURCE DEGRADATION IN RURAL AGRICULTURE

Perrings (1989,1991), Clark (1991), and Ciriacy-Wantrup (1963), have argued that low income causes high discount rates. If this is correct, it may explain the widely shared observation that very poor regions seem to degrade renewable resource stocks far below economically optimal levels (Chapman 1990, Moyo 1991, and others). Perrings' 1991 review article is an excellent summary of our current knowledge.

A typical picture would show a commercial pasture or forest with an apparently healthy level of forest trees or pasture grass. This would adjoin a communal area with no visible grass, much barren ground, few trees or bushes, and goats replacing cattle as the primary grazing stock.

In the communal area, cash income would typically be received from relatives working in mines, factories, and urban areas at low wages. Many residents of communal areas or "homelands" would be residing there after failing to find steady employment elsewhere.

In this situation, credit markets may be organized for barter as well as currency, and time preference rates and interest rates may be very high.

Figure 1. Renewable Resource Biological Growth

Consider figure 1, representing the biological growth function. The horizontal axis M represents biomass, and K represents the biological carrying capacity maximum. H, the vertical axis, shows the amount that can be harvested annually on a sustainable basis for any given stock level M. Beyond K, crowding and disease increase mortality and bring net harvesting H to negative values.

Hmsy is the conventional maximum sustainable yield harvest level. Note that every H on the curve is sustainable, but Hmsy is maximum. In figure 1, the shaded ellipse represents a typical low level of biomass and harvest in a poor rural area.

Whether a forest, pasture, wildlife, or fishery, figure 1 represents a degraded resource with limited output. Stock level M is close to the origin, or extinction of the resource.

An important point to make here is that this can be economically optimal for poor rural areas, and that moving biomass and harvest levels to the right requires higher incomes and lower discount rates.

The basic relationship is expressed in equation 1 and figure 1. The discount rate is i, and the biological growth rate is r. Mec is the economic optimum biomass level. K represents the maximum total amount of biomass, K/2 is the biomass level with maximum harvestable, sustainable yield, which is Hmsy in the figure. Note, in the equation, that if the interest rate is O, the economic optimum biomass Mec becomes the same Mmsy as provides the maximum sustainable yield. Equation 1 is derived in the Appendix.

Equation 1

$$Mec = \frac{K}{2} * \frac{r-i}{r}$$

The resource degradation illustrated here does not depend on excessive private use of a common resource. Figure 1 in fact assumes that the biomass is managed as private property, and, if communally owned, is managed for maximum profit.

Consider a numerical illustration: a small watershed of 500 hectares with a maximum wood (or pasture) biomass of 7500 tons ("i.e.," K = 7500, or 15 tons per hectare). The biological growth rate before crowding is 0.5, and the rural interest rate is 0.4. The maximum sustainable yield would be a Hmsy of 937.5 tons annually at a biomass stock level Mmsy of 3750 tons.

With these values, the economically optimal vegetation level (Mec) is a lower 750 tons. The economically optimal harvest Hec is 337.5 tons annually, much lower than the Hmsy above [note 1].

This follows from received economic theory (especially Clark, 1976 and 1990). It has particular relevance to rural areas in Southern Africa. If it is correct that i is inversely related to income and wages, then it is obvious that protecting rural resources requires higher incomes. Unfortunately, the current reality in Southern Africa is population growth in excess of growth in national income. Thus, for most people in Southern Africa, incomes are declining.

It bears repeating that this analysis does not invoke common property assumptions: here, resource degradation is economically logical where the resource is properly managed for long run profit.

The same logic applies to a change of owners who face different interest rates. Imagine one owner is an owner-manager in the US, with no debt. This owner sells to a heavily debt-leveraged buyer. The new owner, with a much higher time discount rate, will manage harvesting levels very differently than did the first owner.

In equation 1, note that if i rises to or above r, then Mec = O: extinction is optimal.

Climate change or drought in Southern Africa would manifest itself through higher temperatures and lower precipitation. This would collapse both biological growth (r) and carrying capacity (K) in figure 1.

If climate change in Southern Africa occurs in a macro-economic setting of low wages, high unemployment, and high and rising discount rates, then it may become even more frequent for i to exceed r, exacerbating an already severe problem.

In 1991 and 1992, much of Southern Africa experienced continuing unusual drought. There is, of course, no empirical evidence that this is a result of global climate change, but this is the kind of consequence that may be anticipated.

THE MACRO-ECONOMIC EFFECT OF POLLUTION CONTROL

In the previous section, I emphasized the importance of income level in determining the support for environmental protection. In this section, I am considering the macro-economic effects of pollution control on industry.

The industrial pollution controls considered are basically those widely used now in Japan, Western Europe, and North America. For example: soot and particulate removal with electrostatic precipitators, sulphur oxide scrubbing in coal, copper, and oil refining operations, hazardous waste control, etc.

The general setting is a region in which the average GDP per capita was $600 in 1985, and is probably lower today (Chapman 1989). White incomes average 10 times Black incomes in South Africa (Magrath 1991), and the ethnic differential is probably higher in other areas in the region.

The typical industrial enterprise in the region is oriented around pollution-intensive raw materials processing for export. The usual mining sectoral classification understates the role of raw materials. This is because much of the economic activity classified as construction, vehicle manufacture, services, and post-mine smelting is focused on mining. One detailed analysis found that 50% of South African GDP originates in raw materials processing, most of it for export (Jourdan 1991). For the whole region, 95% of the value of raw materials is exported (Chapman, 1989).

Wage levels in raw materials processing range from 50c an hour (in US$) in Zimbabwe to $2 per hour in South Africa.

Although profitability in South Africa has typically been high, it is now very low (Jourdan 1991). In the other countries in the region, the parastatal corporations have operated with significant losses in recent years.

The typical parastatal operation I have visited [note 2] has the following characteristics. It is using colonial vintage capital stock, has no pollution control or worker safety practices, pays low and declining real wages, is over-staffed at the management level, is in debt to international agencies, is losing money, and is managed to produce forex.

In economic terms, my general observation is that economies in the region confront a knotted problem of low productivity, low wages, high unit labor costs, low profit in South Africa, and major financial losses in the region's other countries [note 3]. In South Africa, the productivity problem is exacerbated by a deteriorating educational system and apartheid-linked social hostility (de Beers 1991).

The importance of labor productivity to rural resource degradation is illustrated by figure 2 on page eight. The upper right quadrant (figure 2A) shows the potential impact of higher productivity on wages and income. The declining demand for labor as a function of higher real wages is implicitly defined by the marginal value of labor productivity. Labor supply has a positive response to higher real wages. Equilibrium 1 (L1W1) has both low wages and low employment. A major productivity shift moves the demand for labor curve, and the result is a new equilibrium with higher wages and employment (L2W2).

In the upper left section (figure 2B), the new higher real urban wage level W2 translates into a lower rural interest rate i2.

In the lower left section (figure 2C; rotate the figure) different interest rates translate into different levels of rural resource degradation. The level of degradation is defined by the ratio of the economically optimum biomass (Mec) to the maximum sustainable yield biomass (Mmsy). This has been defined by equation 1. With the first productivity curve equilibria, the Mec/Mmsy ratio is so low as to be near extinction. The new higher urban labor productivity level causes rural resource use to improve by the increase in real wage and the reduction in real interest.

Moving in the opposite direction from figure 2A, figure 2D (below figure 2A) shows the income-elastic nature of the support for environmental protection. "ENV" is public support for environmental policies. As income (defined as WL in the graph) rises, support rises. What has happened is that higher labor productivity in the first panel translates into higher income and more support for environmental protection.

The explanation becomes more complex with the inclusion of per capita GNP, and the relationship between capital investment and labor productivity, but the result doesn't change.

A multiplier approach shows the macro-economic consequences of introducing broad pollution controls on industry with current low productivity. For the following equation 2, the national income terms are defined in table 1. Environmental enhancement is represented by "v". A special term for international donor aid is represented by "B". It is clearly appropriate for macro economics in Southern Africa outside South Africa [note 4].

Equation 2

$$\begin{aligned} GNP = {} & CON(DPI(T,w(l(v))) + INV(int,GNP,v) + GOV \\ & + EXP(Pe(v)) - M(GNP,v) + B(v) \end{aligned}$$

Figure 2 Labor Productivity and Rural Resource Degradation

Environmental impact "v" appears in five of the six terms. It is absent from government expenditures (GOV) because I am focusing on industry. (This is a difficult and potentially controversial assumption which is discussed again in the concluding section.) The GNP multiplier effect of pollution control can be qualitatively represented. The term dGNP/dv is the change in GNP associated with a change in pollution control by industry and mining.

Equation 3

$$
\begin{aligned}
\frac{dGNP}{dv} = \; & \text{environmental impact on labor productivity} * \\
& * \text{ labor productivity impact on wages} * \\
& * \text{ wages effect on disposable personal income consumption} * \\
& + \text{ environmental impact on investment} \\
& + \text{ environmental impact on export prices} * \\
& * \text{ export price effect on exports} * \\
& - \text{ environmental effect on imports} * \\
& + \text{ environmental effect on donor aid} *
\end{aligned}
$$

Table 1. Definition of National Income Accounts and Variables in Equation 2, All Dollar Items in Real Dollars.

- GNP = Gross National Product
- CON = Consumption, expenditure by persons
- DPI = Disposable Personal Income
- T = Taxes
- w = Wage rate
- l = Labor productivity growth
- v = Environmental protection effort by industries
- INV = Investment expenditure
- int = Interest rate
- GOV = Government expenditure
- EXP = Exports
- Pe = Price of exports, including exchange rate factors
- M = Imports
- B = World Bank and international donor aid

It is of crucial importance to note that the two most obvious effects in equation 3 are negative. Export raw materials prices will rise, reducing exports as other suppliers replace Southern Africa. Imports will increase because much of the equipment for Southern Africa's raw materials processing is imported, and this is likely to be higher for pollution control equipment.

The conclusion seems inescapable that, in the absence of countervailing policies, significant application of industrial pollution controls would reduce GNP and accelerate the decline in GNP per capita.

It seems to me that the major implications for international policy are in two areas. First, new research may develop the widely sought "green technologies" [note 5] and thereby resolve the labor productivity/environment dilemma. This is the subject of the next section. Second, donor aid may be essential to impart a positive linkage of environmental protection and economic growth in Southern Africa. This is discussed in the concluding section.

TECHNOLOGY: HOW MUCH HOPE?

As shorthand abbreviation, the macro-economic situation described in the preceding analysis can be termed a productivity problem. In the following discussion "productivity" is meant to summarize the knotted problems of low productivity, low wages, high unit labor costs, low or negative profits, declining industrial employment, accelerating national and regional unemployment, declining GDP per capita, growing rural resource degradation of fuelwood and pasture, and uncontrolled industrial pollution.

The low industrial wages arising from the productivity problem exacerbate the rural problems, and depress consumer demand by industrial workers.

Given this picture, it was argued above that the imposition of industrial pollution control costs on the region would worsen an already negative macro-economic setting by raising export prices, reducing export sales, and raising imports of pollution control equipment. This would cause a further collapse in GNP per capita and even higher unemployment.

To some degree, new technology can solve part of the growth/environment dilemma by developing processes that enhance labor productivity while reducing negative environmental impact.

We are already seeing the impact of induced innovation in many markets as analyzed by Ruttan, Runge, and Chapman and Barker. The promising areas include energy efficiency, renewable energy, and biotechnology.

This is already occurring in illumination; new compact fluorescent bulbs are much more cost-effective than conventional incandescent bulbs in high-income countries. In aggregate, this single technology can reduce world electricity use and energy-based pollution by 11% [note 6]. But, as was seen in the above analysis of rural resource use, the low income/high time preference rate problem is a major obstacle.

The basic economic aspects of the new illumination technology are longer life, lower energy, and higher capital cost. The new compact fluorescent costs $25 for a bulb with equivalent illumination to a 100 watt incandescent. The new bulb lasts 9,000 hours, about 9 years. This compares to 1,000 hours, or one year, for the traditional bulb. But the conventional bulb costs $1.25. The savings are positive in industrialized countries but can be negative in developing countries. Equation 4 shows the basic relationship for annual savings.

Equation 4
{} indicate superscripts

[] indicate subscripts

$$SAV = P * 100 \text{ kWh} + \$1.25 - P * 25 \text{ kWh} - \frac{i(1+i)^{9}}{(1+i)^{9}-1} * \$25$$

SAV is savings in \$(US) per year, P is electricity price in \$/Kwh, and i is the interest rate.

For an industrial country with a real interest rate of 12% for households and P = 15c/Kwh, the savings is \$4.20 per bulb per year. For a household with 10 bulbs, it would be cost-effective to borrow \$250 to install these new lamps. An additional result is the reduction in coal use of 34 kilograms per year. This translates into 1 kg less of acid rain and 75 kg less of carbon dioxide in the atmosphere.

In low-income areas with high interest rates, i, for example, may equal O.5, and the household loses money. In a developing country, the financial loss from buying energy efficiency can be increased if the electricity rates are subsidized, and if exchange rates are too high (Subsidized electric rates reduce household savings. Artificial exchange rates inflate purchase costs.).

Given the linkage between time discount rates and income, the importance of higher income levels for environmental protection is emphasized again.

In terms of renewable energy cost, new technologies are moving within arguing distance of conventional power generating sources. Figure 3 (U.S.DoE, Heaton, Repetto and Sobin 1991) shows costs per Kwh for actual installations. Solar thermal electricity is being produced at 12c per Kwh, only 50% above conventional coal or natural gas sources. Granted that this is in solar-intensive Southern California, and that no provision is made for storage of daytime solar electricity for night use. It is nevertheless clear that large-scale solar thermal generation is feasible, and declining in cost. Solar photovoltaic electricity for household use is being developed by Southern California Edison at an expected cost of 15c/Kwh (Nulty 1991).

In one area, biotechnology has proven spectacularly successful in developing a cost-effective, environmentally beneficial technology that is applicable to industry in Southern Africa. This is the biological enhancement of the fire smelting - sulfuric acid - solvent extraction cycle in copper manufacture. This is shown in a simple schematic form in figure 4.

Twenty years ago most copper was removed from ore by several high-energy furnace processes and sulfur oxide gas was emitted into the atmosphere to form acid rain. This earlier, simple process is highly pollution intensive. In US copper ores, each ton of product copper would release emissions forming 3 tons of acid rain.

Now, sulfur, the former pollutant, is used in a complementary hydroprocess. Sulfuric acid is removed from the smelter exhaust, and applied to ore heaps with a bacterial catalyst [note 7]. The resulting solution is processed to produce copper. In addition, the "flash-smelter" process enhances pollution control and reduces fossil energy use by burning the sulfur in the ore as part of the smelting process.

Figure 3. Electricity Costs for New Generating Capacity
Source: Adapted from United States Department of Energy, 1990

Figure 4. Biotechnology Enhances Environmental Protection and Lowers Costs in Copper Production

Unfortunately, outside of the copper industry, biotechnology and other "green technologies" have developed slowly in resource processing. Debus reports limited biological applications in gold and uranium mining, and potential in coal cleaning.

My general conclusion is that new technologies are greatly needed, and the technologically advanced countries should consider policy incentives to promote their use in developing country industry.

INTERNATIONAL LINKAGE AND INCENTIVES

A discussion of policy and linkage must be preceded by a clarification of important environmental areas that may not be amenable to international policy. First, consider the concept of environmental protection. In the United States, it embraces a broad spectrum of policies from sewage treatment and vehicle pollution control to species and wilderness preservation. It encompasses global policies such as African wildlife and whale protection, and CFC reduction. It might be formalistically defined as the protection of common property national and global resources with significant external values for the enhancement of human health and the natural environment.

In Southern Africa, environmental protection has a different usage. It focuses on the last part of the spectrum, wildlife and park preservation. This is unfortunate because the major environmental problem in the region is clearly contamination of human water supply by human and animal waste. Another significant environmental problem is urban air pollution in squatter camps and high density urban areas. In these areas without electrification, households use fuelwood, charcoal, coal, paraffin, kerosene, and animal waste for cooking, heat, and light. Consequently, on inversion days, these areas are subjected to serious air pollution problems that may be significantly worsened by nearby powerplants or freeways.

Data is absent on the extent of contaminated water or health-threatening air pollution. In fact, in at least one-fourth of the region, it is illegal to discuss or publish data on pollution levels (President's Council 1991).

One basic policy conclusion is that the governments of Southern Africa should be encouraged to establish scientific monitoring systems and publish the results. This is a basic requirement for effective analysis and democratic decision-making.

What is the rest of the world's legitimate interest in the Southern African environment? Is it a Scandinavian concern if a South African child dies of diarrhoea from contaminated water? Is it a US concern if acid rain pollution affects national game parks of international stature? Is it a Japanese concern if its African copper is manufactured by reverboratory furnace workers given towels instead of respirators for sulfuric acid mist control?

I would argue that there are two related reasons why the international community should be concerned about the deteriorating environmental situation in Southern Africa. First, the colonial period developed in direct response to the need for raw materials. In mid-1992, African Blacks in the major industrial center remain unable to vote in their country's elections. This colonial legacy is one reason to consider a special responsibility.

A second reason is the current trade pattern: as noted, 95% of the region's industrial resources are exported for manufacture elsewhere. It is increasingly accepted that the costs of environmental externalities should be internalized in market prices. It is my intention to argue that the international beneficiaries of Southern Africa's resource wealth should pay for some part of the costs of pollution control in the region's industry.

There are three types of international policies that I wish to emphasize for ongoing consideration. In considering these types of policies, the horrendous rural and macro-economic frameworks described above should be seen as the realistic context for international policy.

One method of establishing pollution reduction is tradeable permits. This is visualized most easily with respect to emission rights trading as part of an international agreement to control greenhouse gas emissions. Suppose the agreed goal is to hold carbon dioxide emissions to current world levels [note 8]. An incentive system might be established centered on deviations from per capita energy consumption. World fossil energy consumption per capita is about 60 MBtu (Ibid). Assume that each country above this level must buy a "right" from a country below the level.

The US, for example, consumes about 300 MBtu per capita. If each

MBtu in the tradeable permits market sells for $1, the US would be obligated to pay $240 for each of its 250 million citizens. This would be a purchase of $60 billion annually for energy emissions rights.

In contrast, the low-income economies use about 13 MBtu per capita. The governments representing the 3 billion persons in this World Bank category [note 9] would receive a total transfer of $141 billion for the sale of their emission rights.

The problem for Southern Africa with this approach is that its raw materials exports are energy intensive. South Africa's energy consumption per capita is twice the world's average, and Zambia uses three times that of the low income country average. Essentially, much of Southern Africa's energy use is "embodied" in raw materials exports.

A second form of international policy might be termed leveraged regulation. The model here is the World Bank program for structural adjustment. Given international protocols on major industrial pollutants, the Bank could develop a program for environmental adjustment loans that provide financing for purchase, installation, and operation of pollution control equipment. There is already precedent with respect to the Bank program for CFC reduction.

In macro-economic terms, equations 2 and 3 above show that such a program would have a positive multiplier effect on GNP, and could be designed to counterbalance the negative multipliers.

Similarly, if the environmental factor "v" creates a positive macro-economic "B" in aid flow, then emission permit trading could promote economic growth and environmental protection.

A third form of linkage is taxes and tariffs. Elsewhere, I have advocated a direct international tax on petroleum use, and its transfer to developing countries for forestation and environmental research [note 10]. In terms of administrative simplicity, it may be simpler to organize a tax on international trade in petroleum. An incentive for oil exporting countries would be a provision for some part of the tax to be retained by them, and the remainder provided for linked development and environment programs.

World oil trade is about 14 billion barrels annually, and world use is 22 billion barrels (International Energy Annual 1989). A tax of $5 per barrel of oil traded would create a fund of up to $70 billion for environmental enhancement in developing countries.

Given the complex interaction between low income and environment, there seems to be considerable need for linked policies of pollution control, financial leverage, and new technology. The basic goal for international policy in Southern Africa should be the simultaneous enhancement of living standards and environmental protection.

APPENDIX

Economic Optimum for Biological Resource Use

First, define Q as the amount of resource stock that is sold in addition to the harvesting of growth H: the total is S, all three being in tons per year.

Equation 5
{} indicate superscripts
[] indicate subscripts

$$S_t = H_t + Q_t$$

The economic objective is to find both the value of future sales as well as the current period's sales:

Equation 6
{} indicate superscripts
[] indicate subscripts

$$\max V = ph_t + pq_t + \frac{ph_{t=1}}{i}$$

$$\text{w.r.t. } Q$$

The denominator i arises from the definition of present value for a very long or infinite period of discounting:

Equation 7
{} indicate superscripts
[] indicate subscripts

$$PV = A * \frac{1-(1+i)^{-n}}{i}$$

A is constant annual amount, i is interest, and n is the time period. If n is infinite, PV = A/i.

Although selling current stock Q_t enhances current profit, it reduces future sustainable yield H_{t+1}. The basic logistic harvest function is in equation 8. This defines the growth curve in figure 1 in the text.

Equation 8
{} indicate superscripts
[] indicate subscripts

$$H(M) = rM - \frac{rM^{2}}{}$$

K

Since the amount of current stock which is sold Q can be as low as zero and as high as the full stock M, the objective of maximizing present value V in equation 6 is defined by:

Equation 9
{} indicate superscripts
[] indicate subscripts

$$\frac{dV_{t}}{dQ_{t}} = p + \frac{p}{i} * \frac{dH_{t=1}}{dQ_{t}} = 0$$

Equation 10
{} indicate superscripts
[] indicate subscripts

$$\frac{dH_{t+1}}{dQ_{t}} = r\frac{dM_{t+1}}{dQ_{t}} - \frac{2rM_{t+1}}{K} * \frac{dM_{t=1}}{dQ_{t}}$$

Equation 11
{} indicate superscripts
[] indicate subscripts

$$M_{t+1} = M_{t} - Q_{t}; \quad \frac{dM_{t+1}}{dQ_{t}} = -1$$

Equation 12
{} indicate superscripts
[] indicate subscripts

$$\frac{dV_{t}}{dQ_{t}} = 1 - \frac{r}{i} + \frac{2rM_{t+1}}{iK} = 0$$

Equation 13
{} indicate superscripts
[] indicate subscripts

$$M^{*}_{t+1} = \frac{K}{2} \frac{(r-i)}{r}$$

The asterisk M^{*}_{t+1} denotes the economic optimum level of biomass, which is evidently less than M_{msy}. If M^{*}_{t} also equals the right hand side of equation 13, then $Q^{*}_{t} = 0$. So equation 13 gives the value for sustainable yield at which selling or accumulating stock is unprofitable. As noted in the text, if i is greater than or equal to r, then complete sale of the full current stock is optimal.

NOTES

1. These figures follow from the growth function:

$$F(M) = rM - rM^{**}2/K$$

2. In Zaire, Zimbabwe, South Africa and Zambia.

3. Botswana's Anglo-de Beers diamond operations may be a positive exception.

4. This is a general representation adopted from Branson (1989) and Gordon (1980). The addition of donor aid and environmental economics as macro-economic variables is mine.

5. In other work I've examined in detail the micro economics of international pollution control in some industries (Chapman 1991).

6. Assuming that lighting uses 15% of electricity, and the new technology reduces three-fourths of this for the same illumination.

7. Formally, Thiobacillus ferrooxidans. Debus offers a different explanation of the process, but agrees on the environmental and economic benefit. Oxide copper ores can generally be leached at lower cost than sulfide copper ores.

8. Even an ambitious goal of stabilizing aggregate carbon dioxide emissions at current levels commits the world to a level of energy use which will cause a 3 degree Celsius increase each century (Chapman and Drennen, 1990).

9. World Bank, Tables 1,5

10. Chapman and Drennen.

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