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Can Trade Benefit Natural Resources under Population Growth? The Role of Manufacturing's Returns to Scale

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Abstract

I examine whether trade can improve the impact of population growth on natural resources (*NR*) and welfare over time. Under autarky, population growth results in *NR* and welfare collapse over time for any value of the returns to scale in the manufacturing sector, ϕ. Under trade, *NR* and welfare are unchanged (increase) (collapse) over time for $\phi = (>)(<)1$ – though the decrease in welfare under $\phi < 1$ is dampened relative to autarky. Thus, countries experiencing rapid population growth may benefit from opening up to trade.

Keywords: Population growth; Renewable natural resources (*NR*); Trade vs autarky; Impact on *NR* and welfare.

JEL codes: F16, F18, Q27, Q56

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I. Introduction [1]

Many developing countries obtain a significant share of their income from renewable natural resources (*NR*), including arable land, forests, fisheries, water resources and grazing grounds. Imperfect property rights for *NR* results in excessive pressure and depletion of *NR*, at times dramatically so – e.g., massive deforestation in the Philippines (Bee, 1987). The problem has affected many developing countries and has led to the decline or collapse of some communities – due, among other reasons, to rapid population growth.

The classic case of *NR* depletion is fisheries, and early analyses focused on the sector's open access and optimal regulation (Gordon 1954, Scott 1955). Some more recent studies have extended the analysis, using general equilibrium models to examine steady states and transition dynamics in economies with open-access *NR* (e.g., Brander and Taylor 1997, 1998; López and Schiff, 2013).

An issue of increasing concern in recent years has been trade's environmental impact, with trade viewed as leading to *NR* degradation for commodity exporters (Chichilnisky, 1994; Brander and Taylor, 1997; Smulders et al., 2004; Eisenbarth, 2021; Schiff, 2021).[2] This paper focuses on developing countries with comparative advantage in a *NR*-based commodity under open-access renewable *NR*, and examines the impact of population growth on *NR* and welfare under autarky and trade.

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[1] Early versions of this article are Schiff (2024*a*; 2024*b*).

[2] An overview of studies of trade and *NR* under different types of property rights for *NR* is Bulte and Barbier (2005). Studies by López (1997, 1998) show that the degree of internalization of the negative externalities associated with output of *NR*-based commodities in villages in Ghana and the Ivory Coast decline with the size of the village.

The main findings are as follows. Under autarky, population growth results in *NR* and welfare collapse over time for any value of the manufacturing sector's returns to scale, ϕ. Under trade, population growth has no impact on *NR* and welfare under constant returns ($\phi = 1$), a positive impact over time under increasing returns ($\phi > 1$), while *NR* and welfare collapse over time under decreasing returns ($\phi < 1$) – though the welfare decline is dampened relative to autarky. Thus, countries experiencing rapid population growth may benefit from opening up to trade or at least delay welfare collapse in the case where *NR* collapses.

The paper is organized as follows. Section II provides some population projection figures, Section III presents the model and Section IV solves it. Section V looks at trade pattern reversals, and Section VI concludes.

II. Population Growth

Population has increased across the developing world in recent decades, particularly in Sub-Saharan Africa (SSA) where 15 of the 20 countries with the highest growth rate in the decade 2012-2022 are located. Moreover, the top 23 countries with the highest population growth estimates for 2024 (CIA 2024) are located in SSA, with the rate ranking from 23.8 in the Republic of Congo to 46.5 per thousand in South Sudan. Based on UN (2019) projections, population in 36 – or two thirds of all – SSA countries are expected to increase by at least 50 percent from 2050 to 2100, and to at least double in 10 of them. And of the twelve SSA countries with the highest share of agriculture, forestry and fishing in GDP, the CIA (2024) reports an estimated average population growth rate of 29.0 per thousand.

As for SSA's ten most populous countries, the projected growth rate is 88 percent for 2022-2050, 72 percent for 2050-2100, and 224 percent for 2022-2100. Thus, population growth will be a major issue for many developing countries, until 2100 for SSA and at least to 2050 for many non-SSA countries. The high population growth rates are expected to put considerable pressure on *NR* in SSA and in a number of countries in other developing areas.[3] [4]

III. Model

A model of a small open economy is developed that captures the essence of the problem while being as simple as possible.

1. <u>Production</u>

Assume a two-sector small economy, with a *NR*-based commodity sector, Q, and a manufacturing sector, M, and two factors of production, labor and *NR*. Access to *NR* is open.

Population growth is assumed to be exogenous.[5] Each individual is endowed with one unit of labor. Denote *NR* by N, returns to scale in sector M by ϕ, population (or labor) by L, and employment in sector Q by L_Q and in sector M by L_M, with $L_Q + L_M = L$.

[3] For 2020-2050, these include, among the larger countries, Bangladesh, India, Indonesia, Pakistan, the Philippines and Vietnam in South and Southeast Asia; Argentina, Brazil, Colombia, Mexico and Venezuela in Latin America; Iran, Iraq, Syria, Turkey and Yemen in Western Asia; and Uzbekistan and Kazakhstan in Central Asia. And of the world's 16 most populous low-income to upper middle-income countries, the only ones with negative population growth projections from 2020 to 2050 are China (-2.5 percent) and Russia (-7 percent).

[4] These projections also show enormous disparity across SSA countries: from 27 to 150 percent for 2022-2050, 5 to 143 percent for 2050-2100, and 33 to 508 percent for 2022-2100. This suggests that intra-SSA migration is likely to be important for the rest of the century.

[5] Diamond (2011, Ch. 10) examines some of the causes of Africa's rapid population growth that are exogenous to *NR*, including improved hygiene, preventive medicine, greater vaccination, use of antibiotics, controls for malaria and other endemic diseases, and more. Studies with endogenous population include Brander and Taylor (1997, 1998).

Brander and Taylor (1998), López and Schiff (2013), Schiff (2021) and others have assumed a constant-returns-to-scale production function in manufacturing, M. I assume $M = L_M^{\phi} = (L - L_Q)^{\phi}$, with $\phi \gtreqless 1$.

In the case of $N > 0$, and following Schaefer's (1957) seminal article and many *NR* studies thereafter (e.g., López and Schiff 2013), *NR* growth is specified as $\dot{N} \equiv dN/dt = \rho N\left(1 - \frac{N}{K}\right) - \mu Q, N > 0$, where $\rho > 0$ is the *NR*'s natural growth rate, K is the environment's carrying capacity – or the maximum sustainable *NR*, given the environment – and $\mu > 0$ is the rate of *NR* depletion per unit of commodity output Q.

NR enter the production of the commodity, Q, as conventionally done in the literature (Gordon 1954; Schaefer 1957; Copeland and Taylor 1994; and many others), namely $Q = L_Q N$. Thus, $\dot{N} = \rho N\left(1 - \frac{N}{K}\right) - \mu L_Q N, N > 0$, with $\dot{N} = 0$ for $N = \left(1 - \frac{\mu L_Q}{\rho}\right) K$.

Denoting K by α and $\frac{\mu K}{\rho}$ by β, we have:

$$N = \alpha - \beta L_Q \geq 0, Q = L_Q N = L_Q(\alpha - \beta L_Q); M = L_M^{\phi}, \phi \gtreqless 1, L_M = L - L_Q > 1, \qquad (1)$$

where α is the environment's carrying capacity (or maximum sustainable *NR* level), L's negative externality is $MP_L - AP_L = (\alpha - 2\beta L_Q) - (\alpha - \beta L_Q) = -\beta L_Q$ – which is also equal to the impact of L_Q on N – and $L_M > 1$ ensures M increases with ϕ.

Assume also that once *NR* are totally depleted, they cannot grow back, i.e., $N = 0 \Rightarrow \dot{N} = 0$.[6] Manufacturing is chosen as the numéraire.

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[6] For instance, once all the fish in a lake have been caught, their stock remains nil. Also, the forest in Easter Island was destroyed centuries ago and never grew back (Brander and Taylor 1998).

2. Preferences

Individuals have Cobb-Douglas preferences over $m = M/L$ and $q = Q/L$. Denoting the share of income spent on q by γ, preferences are given by:

$$U = q^{\gamma} m^{1-\gamma}, 0 < \gamma < 1. \tag{2}$$

IV. Solution

The autarky case is examined in Section 1 and the trade case in Section 2.

1. Autarky

Q's demand price, relative to M, is $p_d = \frac{U_q}{U_m} = \frac{\gamma m}{(1-\gamma)q} = \frac{\gamma M}{(1-\gamma)Q} = \frac{\gamma(L-L_Q)^{\phi}}{(1-\gamma)L_Q(\alpha-\beta L_Q)}$, where the last equality makes use of the fact that demand equals supply under autarky. The supply price is Q's average cost over M's marginal cost, i.e., $p_s = \frac{AC_Q}{MC_M} = \frac{\phi(L-L_Q)^{\phi-1}}{\alpha-\beta L_Q}$, where commodity producers care about average product and average cost since access to the *NR* is open.

In equilibrium, $p_d = p_s = p$, implying:

$$L_Q = \frac{\gamma L}{Z}; L_M = L - L_Q = \frac{\phi(1-\gamma)L}{Z};\ Z \equiv \gamma + \phi(1-\gamma) \gtreqless 1 \Leftrightarrow \phi \gtreqless 1, \tag{3}$$

where L_Q increases with γ, the preference for Q, and declines with ϕ, the returns to scale in M.

From (3), we have $0 < \frac{\partial L_Q}{\partial L} = \frac{\gamma}{Z} < 1$, and $0 < \frac{\partial L_M}{\partial L} = \frac{\phi(1-\gamma)}{Z} < 1$. Population's impact on *NR*, and its impact on welfare, which is provided in Appendix 1, and its impact on *NR*, are:

$$\frac{\partial N}{\partial L} = -\frac{\beta\gamma}{Z} < 0;\ \phi \leq 1 \Rightarrow \frac{\partial U}{\partial L} < 0;\ \phi > 1 \Rightarrow \frac{\partial U}{\partial L} \gtreqless 0. \tag{4}$$

Thus, *NR* decline with L, irrespective of the value of ϕ, with the rate of decline of the *NR* inversely related to ϕ. The possibility that $\frac{\partial U}{\partial L} > 0$ for $\phi > 1$ arises from the fact that both L_Q and L_M increase with L and the gains from the rise in L_M in the increasing-returns sector M may be greater than the increase in the negative externality associated with the rise in L_Q.

Results in this paragraph are derived in Appendix 1. Antweiler and Trefler (2002) find economy-wide $\phi = 1.05$, implying $\frac{\partial U}{\partial L} < 0$ if the negative externality βL is at least 3.2 percent of α, the *NR* level when *NR* are unexploited ($L_Q = 0$), i.e., if $N \leq 96.8\alpha$. In other words, population growth reduces welfare as long as commodity output reduces natural resources by at least 3.2 percent. And $\frac{\partial U}{\partial L} < 0$ is also likely to hold for $\phi = 1.15$, the level obtained by the authors for one third of the industries, as long as βL is at least 9.1 percent of α, i.e., if $N \leq 90.9\alpha$. These are plausible values for many *NR*-based commodity sectors. [7]

The main autarky results are summarized in Proposition 1.

<u>Proposition 1</u>. Under autarky, i) population growth leads to a decline in *NR* and a likely decline in welfare; and ii) it leads to a collapse of *NR* in the long run, and thus to a collapse of commodity output and welfare, irrespective of the value of ϕ, the manufacturing sector's returns to scale – though the speed of decline is inversely related to ϕ.

[7] While Antweiler and Trefler (2002) found increasing returns in one third of industries and constant returns in two thirds of them, returns to scale are generally found to vary with the sample countries, sectors, and methodology selected. For instance, Wang and Zhou (2020) examined Chinese industrial enterprises in 2000-2013 and found decreasing returns in seven sectors and increasing ones in two, with a mean value of .995, not significantly different from one. Baoping and Wei (2019) found constant or decreasing returns in China's supply structure, with decreasing returns overall. Wang (2008) found either constant or increasing returns in a study of China and five OECD countries. van Dijk (2002) found increasing returns for Indonesian firms and Elleithy (1997) found increasing returns in carpentry firms in a region of Ghana. Crompton and Lesourd (2008) examined the global iron-making industry in integrated steel plants in developed, developing and transition economies and found a significant scale effect averaging 1.17 (with $\partial U/\partial L < 0$ as long as $\beta L \geq 0.1\alpha$).

2. Trade

Denote variables by subscript T and the world price by p_w. The trade case differs from the autarky case in two ways: *i*) The relative price p_w is exogenous for the small open economy; and *ii*) Supply need not equal demand.

Supply price $p_s = p_w = \frac{\phi(L-L_{Q,T})^{\phi-1}}{\alpha-\beta L_{Q,T}}$. Since p_w is exogenous, one can derive the impact of L on $L_{Q,T}$. The solution, derived in Appendix 2, is:

$$\frac{\mathrm{d}L_{Q,T}}{\mathrm{d}L} = \frac{(1-\phi)(\alpha-\beta L_{Q,T})}{(1-\phi)(\alpha-\beta L_{Q,T}) + \beta(L-L_{Q,T})}. \quad (5)$$

The cases of constant, decreasing and increasing returns are examined below.

Note that individual income $y_T = y_T^s = y_T^d$, i.e., $y_T = p_w q_T^s + m_T^s = p_w q_T^d + m_T^d$.[8] From (2), $p_w q_T^d = \gamma y_T$ and $m_T^d = (1-\gamma)y_T$. Thus, $q_T^d = \left(\frac{\gamma}{p_w}\right) y_T$, and

$$U_T = \left(\frac{\gamma}{p_w}\right)^{\gamma} (1-\gamma)^{1-\gamma} y_T,\ y_T = \left[p_w L_{Q,T}\left(\alpha - \beta L_{Q,T}\right) + (L - L_{Q,T})^{\phi}\right]/L. \quad (6)$$

2.1. Constant returns to scale: $\phi = 1$

In this case, $MP_{L_{M,T}} = \phi(L - L_{Q,T})^{\phi-1} = 1$ is independent of L and so is U_T. Since $p_w = \frac{1}{\alpha-\beta L_{Q,T}}$, equation (6) implies $y_T = 1$. Hence:

[8] Thus, $p_w\left(q_T^s - q_T^d\right) = m_T^d - m_T^s$, i.e., trade is balanced.

$$U_T = \left(\frac{\gamma}{p_w}\right)^{\gamma} (1-\gamma)^{1-\gamma}. \tag{7}$$

Also, $p_w = \frac{1}{\alpha - \beta L_{Q,T}}$ implies that $L_{Q,T} = \frac{1}{\beta}\left(\alpha - \frac{1}{p_w}\right)$, which is a function of p_w and not of L. This result, as well as equation (5), imply that $\frac{\partial L_{Q,T}}{\partial L} = \frac{\partial N_T}{\partial L} = \frac{\partial Q_T^S}{\partial L} = 0$, and $\frac{\partial M_T^S}{\partial L} = \frac{\partial L_{M,T}}{\partial L} = 1$. The reason is that since $MP_{L_{M,T}} = 1$ and p_w is given for a small open economy, $AP_{L_{M,T}}$ is given as well. Thus, any population increase is fully absorbed by the manufacturing sector and does not affect $L_{Q,T}$, NR_T or Q_T^S. And from (7), $\frac{\partial U_T}{\partial L} = 0$, i.e., changes in L do not affect welfare.

What is the initial impact of opening up to trade? Under autarky and $\phi = 1$, $Z = 1$, and $L = \gamma L$. Thus, the relative price $p = \frac{1}{\alpha - \beta L_Q} = \frac{1}{\alpha - \beta\gamma L}$ and $\frac{\partial p}{\partial L} > 0$, i.e., p increases with L. Given the comparative advantage in Q, it follows that $p < p_w$. Thus, the country exports Q to the rest of the world and import M. Note also that under autarky, $U = \left(\frac{\gamma}{p}\right)^{\gamma} (1-\gamma)^{1-\gamma}$ for $\phi = 1$. Since $p_w > p$, we have $L_{Q,T} > L_Q$, $N_T < N$, and $U_T < U$ (see (7)). Thus, opening up to trade *reduces NR* and welfare.[9]

How does trade evolve over time? As L increases, the autarky price p increases. This reduces the country's comparative advantage in Q and its exports decline. At some level of $L = L_A$, the autarky price reaches the world price ($p = p_w$) and trade is nil. Thereafter, i.e., for $L > L_A$, $p > p_w$, and the pattern of trade is reversed, i.e., Q is imported and M is exported, and trade increases with L.

[9] Various studies have examined exports' negative impact on *NR*, both theoretically (e.g., Chichilnisky 1994; Brander and Taylor 1997) and empirically (e.g., Eisenbarth 2021).

In the absence of negative externalities, opening up to trade raises welfare. However, since access to *NR* is open, $p_w = AC_Q$ and the commodity sector's producer surplus is nil, while the consumer surplus declines with price. Thus, opening up to trade reduces welfare.[10] Equation (7) also implies that an improvement in the terms of trade p_w reduces welfare.[11]

Since $\frac{\partial L_{Q,T}}{\partial L} = \frac{\partial N_T}{\partial L} = \frac{\partial Q_T^s}{\partial L} = \frac{\partial U_T}{\partial L} = 0$, it follows that opening up to trade under population growth prevents *NR* and welfare collapse – though it reduces *NR* and welfare in the short run as p_w is initially higher than p.

2.2. Decreasing returns to scale: $\phi < 1$

In this case, numerator and denominator of (5) are positive, implying that $\frac{\mathrm{d}L_{Q,T}}{\mathrm{d}L} > 0$ and $\frac{\mathrm{d}N_T}{\mathrm{d}L} = -\beta \frac{\mathrm{d}L_{Q,T}}{\mathrm{d}L} < 0$. Thus, as in the case of autarky, *NR* and welfare collapse in the long run.

As N_T declines with L, so does the country's comparative advantage in Q. Thus, autarky price p also increases with L in this case, reaches p_w where trade is nil, and eventually $p > p_w$, where M is exported and Q is imported. As L and $L_{Q,T}$ increase, N_T eventually reaches zero, with $Q_T^s = 0$ and $\dot{N}_T = 0$. Then, $VAP_{L_T} = p_w Q_T^s / L_{Q,T} = 0$ and labor moves to sector M, with $L_{M,T} = L$.

At that point, $Y_T = M_T^s = L^\phi$ and $M_T^d = (1-\gamma)L^\phi$, so exports $M_T^X = \gamma L^\phi$ and imports $p_w Q_T^I = p_w Q_T^d = \gamma L^\phi$, i.e., $Q_T^d = (\gamma / p_w) L^\phi$. Individual values are as follows:

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[10] The impact on Q is ambiguous and depends on the sign of $MP_{L_{Q,T}}$.

[11] Commodity-exporting countries typically view terms-of-trade improvements as beneficial because of positive income and foreign exchange effects. Under open access to *NR*, an increase in terms of trade reduces *NR* and welfare, though these short-term effects are typically less visible than the effects on income and foreign exchange.

$$y_T = m_T^s = L^{\phi-1}, m_T^d = (1-\gamma)L^{\phi-1}, q_T^d = \left(\frac{\gamma}{p_w}\right)L^{\phi-1} = q_T^I, U_T = \left(\frac{\gamma}{p_w}\right)^{\gamma}(1-\gamma)^{1-\gamma}L^{\phi-1}. \tag{8}$$

Since $\phi < 1$, it follows that all variables in (8) decline with L, just as they do under autarky. However, though welfare is nil when the *NR* is nil under autarky, it is positive under trade because, though $Q_T^s = 0$, commodity Q_T is imported, i.e., $q_T^d = q_T^I > 0$ (while $q^d = q^s = 0$ under autarky). Nevertheless, as shown in (8), since $\phi < 1$, welfare declines (asymptotically towards zero) as L increases.

2.3. Increasing returns to scale: $\phi > 1$

In this case, equation (5)'s numerator is negative and, as shown in Appendix 2, its denominator must be positive for a stable interior equilibrium (for a given population level L), i.e., $\frac{\mathrm{d}L_{Q,T}}{\mathrm{d}L} < 0$. The reason is that an increase in $L_{M,T}$ raises its marginal product. Hence, $L_{Q,T}$'s average product must increase as well. This implies that $L_{Q,T}$ must decrease as L increases. Thus, $\frac{\mathrm{d}L_{M,T}}{\mathrm{d}L} > 1$. At some point, $L_{Q,T} = Q_T^s = 0$, so $L_{M,T} = L$, $\frac{\mathrm{d}L_{M,T}}{\mathrm{d}L} = 1$, and the country exports the manufacturing product M_T and imports the commodity Q_T.

The functions for y_T, m_T^d, q_T^d and U_T are identical to those in equation (8) in Section 2.2. The difference is that $\phi > 1$, which implies that income, consumption of the two goods and welfare increase over time as $\mathbb{L}$ increases.

The results under trade are summarized in Proposition 2.

Proposition 2: Under trade, population growth has no impact on *NR* and welfare over time under constant returns ($\phi = 1$) in the manufacturing sector, a positive impact on *NR* and welfare under increasing returns ($\phi > 1$), and a negative impact on and collapse over time of *NR* and welfare under decreasing returns ($\phi < 1$) – though the welfare decline is dampened relative to autarky.

V. Trade Pattern Reversal

A question is the extent to which trade pattern reversal prevails. Regarding Africa's food trade, Rakotoarisoa et al. (2011) report declining net food exports turning into net imports in the mid-1970s, with total and per capita net imports growing since trade reversal occurred. Total net imports grew in real terms by 3.4 percent annually from 1980 to 2007, with 2.6 percent or over three quarters of net import growth associated with population growth, and per capita net imports growing at 0.8 percent annually.

With per capita food production growing at less than 0.1 percent, increases in per capita consumption had to be satisfied by increased per capita imports. Thus, high population growth and low output growth seem to have played a major role in the early trade reversal and in the growth of net food imports in Africa.[12] Moreover, Ng and Aksoy (2008) report that the largest reversal occurred in the 51 (non-oil-exporting, non-civil-conflict, non-small-island) "Other middle-income countries," with net food exports turning into net imports in the early 1980s.[13]

FAO (2012) confirms that the population increase played an important role in the increase in Africa's import demand for food. And the weakness of domestic production, especially for Sub-

[12] The causes of Africa's rapid population growth are examined in Diamond (2011, Ch. 10) – see fn. 5.

[13] Akiwumi (2020) reports for the 2000-2006 period that the vast majority of Africa's low-income countries, most of which located in SSA and whose population amounted to two thirds of that of the continent, were net food importers by then. Moreover, African countries still imported the bulk of their food from outside the continent in 2016-2018.

Saharan Africa, lies mainly in its inability to deal with an eventual sustained increase in per capita consumption.

Reversal in the case of fish trade occurred more recently. According to an African Development Bank report (AfDB 2016), Africa's fish trade changed between 2001 and 2014 from a surplus of US$ 1.172 billions to a deficit of US$ 294 millions, or a net fish trade decline of US$ 1.466 billions. The decline in SSA's net fish trade was greater still, falling from a surplus of US$ 372 millions to a deficit of US$ 1.650 billions, or a net trade decline of US$ 2.022 billions.

VI. Conclusion

It is well-known that a country with open-access *NR* and a comparative advantage in the *NR*-based commodity sector which opens up to trade raises the sector's relative price and employment, thereby contributing to a decline in *NR* and welfare. The paper's objective was to examine whether trade might help prevent their collapse over time in the case of population growth.

Studies using dynamic general equilibrium models of *NR* have typically assumed, for simplicity, a constant-return-to-scale technology for the manufacturing sector. By relaxing this constraint, I obtain some new results regarding the impact of population growth. While *NR* and welfare collapse in the long run under autarky, I find that the impact under trade depends critically on the returns to scale in the manufacturing sector. Under constant or increasing returns to scale, trade can help prevent *NR* and welfare collapse. Under decreasing returns, trade does not help prevent the collapse of *NR* in the long run, though the possibility of trading dampens its negative welfare impact.

Thus, if the country's *NR* can sustain the initial shock of opening up to trade, which is clearly the case for *NR*-based commodity exporters, trade should either prevent *NR* and welfare collapse under population growth, or at least delay welfare collapse in the case where *NR* collapses.

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Appendix 1. Impact of Population on Welfare

Given the solution for L_Q in (3), welfare U and the impact of population L on U are:

$$U = q^{\gamma} m^{1-\gamma} = \left[\frac{L_Q(\alpha-\beta L_Q)}{L}\right]^{\gamma} \left[\frac{(L-L_Q)^{\phi}}{L}\right]^{1-\gamma} = \left[\frac{\gamma}{Z}\left(\alpha - \frac{\beta\gamma L}{Z}\right)\right]^{\gamma} \left\{\left[\frac{\phi(1-\gamma)L}{Z}\right]^{\phi} /L\right\}^{1-\gamma} = AL^{Z-1}\left(\alpha - \frac{\beta\gamma L}{Z}\right)^{\gamma}, A = \frac{\gamma^{\gamma}}{Z^{Z}}[\phi(1-\gamma)]^{\phi(1-\gamma)} > 0, Z = \gamma + \phi(1-\gamma), Z-1 = (\phi-1)(1-\gamma); \qquad \text{(A1)}$$

and

$$\frac{\partial U}{\partial L} = B\left[(Z-1)\left(\alpha - \frac{\beta\gamma L}{Z}\right) - \frac{\beta\gamma^2 L}{Z}\right] = B\left[(Z-1)\alpha - (Z-1+\gamma)\frac{\beta\gamma L}{Z}\right],$$

$$B = AL^{Z-2}\left(\alpha - \frac{\beta\gamma L}{Z}\right)^{\gamma-1}, \frac{\beta\gamma L}{Z} = \beta L_Q. \qquad \text{(A2)}$$

As $Z-1 = (\phi-1)(1-\gamma)$, we have $Z-1 \gtreqless 0 \Leftrightarrow \phi \gtreqless 1$. Thus, as $\alpha \geq \beta L_Q = \frac{\beta\gamma L}{Z}$, we have:

$$\phi \leq 1 \Rightarrow Z-1 \leq 0 \Rightarrow \frac{\partial U}{\partial L} < 0;\ \phi > 1 \Rightarrow Z-1 > 0 \Rightarrow \frac{\partial U}{\partial L} \gtreqless 0.$$

We examine the second expression in square brackets in equation (A2) above. Taking Antweiler and Trefler's (2002) result of an average return to scale of $\phi = 1.05$, and the average value of $\gamma = .6$,[14] it follows that the coefficient of α, namely $Z-1$, is $.02$. Moreover, the coefficient of $\beta L_Q = \frac{\beta\gamma L}{Z}$ is $-(Z-1+\gamma)$ or $-.62$. Thus, the *ratio* of the average values of the coefficients of βL_Q and α is -31. So, $\frac{\partial U}{\partial L} < 0$ as long as the negative externality is at least 3.23 percent of α, the *NR* stock

[14] The share of the 2022 consumer expenditures spent on food, γ, was over 40 percent in low-income African and South Asian countries, over 50 percent in a number of countries in those regions (e.g., Bangladesh, Benin, Kenya, Myanmar, Mozambique, Sudan), some 60 percent in Nigeria, and 73 percent in Burundi (USDA, 9/28/2023). Moreover, the formal forest sector contributes more than 10 percent to GDP in many developing countries – including in at least 19 SSA ones – and as much as 20 percent of daily livelihood needs of rural families (OECD 2008). Thus, the share spent on food, γ, is between 0.4 and 0.6 in SSA, and once the share spent on forestry products is included, γ is likely to be between 0.5 and 0.7, or 0.6 on average.

when $L_Q = 0$. In other words, $\frac{\partial U}{\partial L} < 0$ as long as production reduces *NR* by at least 3.23 percent, relative to its value when $L_Q = 0$.[15]

Appendix 2. Impact of Population $\mathbb{L}$ on Commodity Employment L_T Under Trade

The supply price, p_s, equals the world price p_w, i.e., $p_w = \frac{\phi(L-L_{Q,T})^{\phi-1}}{\alpha-\beta L_{Q,T}}$. As p_w is exogenous for the small open economy, we have $\mathrm{d}p_w = \left(\frac{\partial p_w}{\partial L_{Q,T}}\right)\mathrm{d}L_{Q,T} + \left(\frac{\partial p_w}{\partial L}\right)\mathrm{d}L = 0$, or $\frac{\mathrm{d}L_{Q,T}}{\mathrm{d}L} = -\frac{\partial p_w/\partial L}{\partial p_w/\partial L_{Q,T}}$.

Since $\frac{\partial p_w}{\partial L_{Q,T}} = \frac{\phi(L-L_{Q,T})^{\phi-2}[(1-\phi)(\alpha-\beta L_{Q,T}) + \beta(L-L_{Q,T})]}{(\alpha-\beta L_{Q,T})^2}$, and $\frac{\partial p_w}{\partial L} = \frac{\phi(\phi-1)(L-L_{Q,T})^{\phi-2}}{\alpha-\beta L_{Q,T}}$, it follows that:

$$\frac{\mathrm{d}L_{Q,T}}{\mathrm{d}L} = \frac{(1-\phi)(\alpha-\beta L_{Q,T})}{(1-\phi)(\alpha-\beta L_{Q,T}) + \beta(\mathbb{L}-L_{Q,T})}. \tag{A3}$$

Appendix 3: Stability of Short-Term Equilibrium for $\phi > 1$

The condition for equilibrium stability when $\phi > 1$ is $(1-\phi)(\alpha - \beta L_{Q,T}) + \beta(L - L_{Q,T}) > 0$.

<u>Proof</u>: Population at time t is L_t and the labor market equilibrium condition is $p_w AP_{L_{Q,T}} = MP_{L_{M,T}}$, or $p_w(\alpha - \beta L_{Q,T}) - \phi {L_{M,T}}^{\phi-1} = 0$, $L_{Q,T} + L_{M,T} = L_t$. Say manufacturing employment, L_{M0}, is above its equilibrium level, i.e., $L_{M0} > L_{M,T}$. As $L_{Q0} + L_{M0} = L_t$, we have $L_{Q0} < L_{Q,T}$. The equilibrium $(L_{Q,T}, L_{M,T})$ is stable if, at (L_{Q0}, L_{M0}), $p_w(\alpha - \beta L_{Q0}) - \phi {L_{M0}}^{\phi-1} > 0$, in which case

[15] Antweiler and Trefler's (2002) find that $\phi = 1$ for two thirds of the industries and $\phi = 1.15$ in one third of them. The result $\frac{\partial U}{\partial L} < 0$ is also likely to hold in the latter case, where the coefficient of α is $.06$ and that of βL is $-.66$, with a ratio of the coefficients of βL and α of -11. Thus, $\frac{\partial U}{\partial \mathbb{L}} < 0$ as long as production reduces *NR* by 9.1 percent or more, relative to its value when $L = 0$.

labor moves from the manufacturing to the commodity sector and its allocation moves to equilibrium values $\left(L_{Q,T}, L_{M,T}\right)$. [16]

Thus, for any value of L_t, the equilibrium is stable if $\frac{\partial\left[p_w(\alpha-\beta L_{Q,T})-\phi L_{M,T}{}^{\phi-1}\right]}{\partial L_{M,T}} = \beta p_w + \phi(1-\phi)L_{M,T}{}^{\phi-2} > 0$. Since $p_w = \frac{\phi L_{M,T}{}^{\phi-1}}{\alpha-\beta L_{Q,T}}$, we have $\phi L_{M,T}{}^{\phi-2}\left[\frac{\beta L_{M,T}}{\alpha-\beta L_{Q,T}} + (1-\phi)\right] > 0$. Thus, the stability condition is $\beta(L - L_{Q,T}) + (1-\phi)\left(\alpha - \beta L_{Q,T}\right) > 0$. QED.

[16] The same logic applies for $L_{M0} < L_{M,T}$, in which case stability implies that $p_w\left(\alpha - \beta L_{Q0}\right) - \phi L_{M0}{}^{\phi-1} < 0$.