

Trade and Resource Sustainability with Overlapping Generations*

Larry Karp[†] Armon Rezai[‡]

July 23, 2014

Abstract

Trade changes incentives to protect an open-access natural resource. In an OLG setting, the capital asset market transfers policy-induced future gains or losses to the current asset owner. The asset market creates incentives for agents currently alive to protect the natural resource under autarchy. Trade reverses these incentives. We study a dynamic political economy using both open loop and Markov Perfect equilibria. In both settings, equilibrium policies protect the resource and increase welfare under autarchy and have the opposite effect in the open economy. This difference arises from the interplay of the asset market and general equilibrium effects.

Keywords: endogenous property rights, trade, open-access resource, two-sector overlapping generations, sequential game, Markov perfection

JEL, classification numbers: F1, E24, H23, Q28, Q56

*The paper benefitted from comments by Emma Aisbett, Thibault Fally, Sverre Jensen, Leo Simon, Christian Traeger, and seminar participants at Berkeley, Vienna, SURED 2012, and the EARE 2013 meetings in Toulouse. Financial support from the Austrian Marshall Plan Fund Foundation and from the Ragnar Frisch Centre for Economic Research is gratefully acknowledged.

[†]Department of Agricultural and Resource Economics, University of California, Berkeley, email: karp@berkeley.edu.

[‡]Department of Socio-Economics, Vienna University of Economics and Business, Welthandelsplatz 1, 1020 Vienna, Austria; email: arezai@wu.ac.at. Also affiliated with IIASA. Armon Rezai thanks the Department of Agricultural and Resource Economics at UC Berkeley for its hospitality and the OeNB Anniversary Fund grant on Green Growth (no. 14373) for financial support.

I. Introduction

Societies manage natural resources using different types of property regimes, ranging from restricted access with private property or government control, to common property and open access. Research pioneered by Ostrom (1990, 2007) challenges the view that strong property rights are needed in order to avoid the Tragedy of the Commons (Hardin, 1968; Gordon, 1954). Common property institutions appear to successfully manage natural resources when the socio-ecological system is stable, outsiders can be easily prevented from using the resource, and communities accept monitoring and enforcement (Dietz, Ostrom and Stern, 2003). Abrupt changes, such as those arising when a closed economy opens to international trade, might either erode common property management regimes or encourage sustainable management due to a higher value of a resource (Copeland, 2005, Bulte and Barbier, 2005, Ruta and Venables, 2012). We provide a novel perspective on the relation between trade and endogenous resource management in the absence of formal property rights.

Our model of trade and natural resources rests on three claims: trade liberalization frequently increases pressure on natural resources under imperfect property rights; environmental protection and even property rights regimes respond to trade; and asset prices respond to environmental and policy changes. The next section reviews empirical evidence for these assertions. First, we review previous theory relating trade and resource sustainability and we sketch our contribution.

The standard model of trade and the environment starts from the premise that imperfect property rights to a sector-specific resource, e.g. fish or forests, attract too many mobile factors to the resource sector even under autarchy. Resource-rich countries with weak property rights therefore tend to have a low autarchic price for the resource good. If such a country liberalizes trade, its domestic price for that good rises, attracting still more mobile factors to the sector, exacerbating the market failure and possibly lowering welfare even in the absence of changes in the resource stock (Chichilinsky, 1994). Reductions in future resource stocks, caused by higher current harvest, aggravate this welfare cost (Brander and

Taylor, 1997a,b, 1998; and Karp, Sacheti and Zhao, 2001).

Hotte, Long and Tian (2005) and Copeland and Taylor (2009) extend the basic model by allowing resource policy (or de facto property rights) to change with trade, thus creating another conduit for trade to change resource use and welfare. In both of these papers, an infinitely lived agent (ILA) adopts a policy to protect de jure property rights. Trade, by raising the price of the resource good, increases the benefit to the agent of protecting her de jure rights. But the higher price also attracts poachers, increasing the difficulty and the cost of protecting these rights. Trade has an ambiguous effect on the equilibrium protection of property rights (e.g. on monitoring and on penalties for poaching) and on equilibrium resource extraction. Both papers analyze only steady state effects.

Given the intuitiveness of the basic model and of the extensions that endogenize property rights, and their ability to rationalize the range of observed outcomes, any new and more complicated theory faces a high hurdle; it is not enough to provide another mechanism that explains why things might go up or might go down. Our alternative, based on overlapping generations (OLG), is arguably more descriptive than an ILA model, but what matters more is that the alternative reveals useful and different insights, which ILA models obscure.

Weak property rights limit both the ability and the incentives of titular owners to control resource extraction. Various assumptions in the ILA settings above produce time-consistent optimization problems, in which today's decisionmaker has the same degree of control over current and future actions.¹ In our OLG model, those currently alive collectively decide how much of the resource to extract, and how to distribute the rents amongst themselves. This assumption eliminates the monitoring and enforcement problems that underlie most of the literature on resources and imperfect property rights. As is true in general, currently living agents' incentives to protect the resource depend on future actions. If current agents could choose future actions, not just current actions, we have the scenario with perfect property rights. However, the political decision in any period determines the distribution of current resource rents amongst the currently living, in addition to the level of protection of the

resource. Future generations care about the latter, but not the former; in a political equilibrium with imperfect property rights, the two decisions are entangled. Even though currently living agents have a first best means of controlling current extraction, the lack of property rights means that they can neither allocate future rents, nor choose future extraction.

Currently living agents have no bequest motive, and maximize their own aggregate lifetime welfare. Agents play a sequential game with their successors because of their inability to choose future actions, and because those future actions affect current incentives to protect the resource.² The primary insight is that, in autarchy, agents' self-interested behavior causes them to limit resource use, benefitting their successors; but under trade, these agents worsen the open-access externality by adopting environmentally destructive policies.

The mechanism responsible for this relation involves two steps. First, trade changes the incidence of taxes (McAusland, 2003, 2008). Commodity prices are endogenous in the closed economy, but fixed for a small open economy. With fixed commodity prices, there is no distinction between real and nominal returns to a factor. Here, an agent's real income (utility) from renting a factor of production rises if and only if the nominal (= real) return to that factor increases. Under autarchy, where the commodity price varies with the relative supply of the commodity, real and nominal returns are generally different. A policy change can cause the real and nominal returns to a particular factor to change in opposite directions, especially if the commodity price effect is strong.

The second step involves an asset market.³ Our model has three productive factors: an endogenously changing open access resource stock, a constant *flow* of labor, and a constant *stock* of capital. Both labor and capital are privately owned, but capital (unlike labor) is an asset, because of its durability. The old generation, the current owner, sells capital to the young generation, and therefore cares about the asset price even if it has no bequest motive. Under rational expectations, the asset price depends on capital's future returns. Via general equilibrium effects, these returns depend on future levels of the resource stock. Thus, even selfish agents have an incentive to control the evolution of the resource stock, because of its

effect on the asset price. Those incentives differ in open and closed economies.

A comparison of natural resource management under common property in the hilly regions of Nepal and the flatlands of Malawi illustrates the mechanism described above. The poor transportation network in Nepal limits access to external sources of energy and soil nutrients, making inhabitants vulnerable to degradation of forest resources. Inhabitants therefore have a strong incentive to protect these resources. The miombo woodlands in Malawi are located in flat areas with roads providing access to markets. Otsuka and Place (2001, ch. 10) ascribe the relative lack of success in Malawi common property management partly to the superior market access, which diminishes incentives to protect the resource.

II. Evidence

We first review the evidence of the link between trade and natural resource use, and then discuss the endogeneity of property rights or policy, and the relation between asset prices and environmental policy. Data limitations and the associated difficulty of establishing causal relations discourages the use of cross country econometric analysis; Ferreira (2004), an exception, finds that trade is positively correlated with forest degradation where property rights are weak. Even with better data, the fact that trade under weak property rights involves a second-best environment, with a range of plausible outcomes, means that empirical regularities can be weak, further limiting the ability of cross country econometrics to identify them. Most of the evidence linking trade to local resource degradation is based on case studies, chosen for their prima facie evidence of such a link. Therefore, the fact that these studies often identify this link does not suggest that trade liberalization typically harms natural resources. There is general understanding that trade has complicated effects on natural resources, sometimes benefitting and sometimes harming them.

Mammal stocks provide persuasive examples where trade, coupled with weak property rights, harms natural resources. These examples include seals (Patterson and Wilen, 1977), beaver (Carlos and Lewis, 1999), the Arctic Bowhead whale (Allen and Keay, 2004), buffalo

(Taylor, 2011), elephants and rhinos.⁴ In all of these cases, the prima facie evidence is compelling, but data limitations complicate the empirical problem. For example, for buffalo, an innovation in tanning made buffalo and cattle hides close substitutes; at the time of the great buffalo hunts, there was a global market for cattle hides. Here, the primary empirical challenge was to confirm that the US was integrated into this particular market.

The trade-resource nexus is probably more important for forests, fish stocks, and water supplies. In these cases, identifying the role of trade is particularly difficult, because of the presence of confounding factors such as increased population pressure. Lopez (1998, 2000) finds evidence that trade aggravates resource degradation in Ghana and Cote d'Ivoire. Abaza and Jba (2002) and Larson and Nash (2010) each synthesize six case studies, involving different countries in Africa, Asia, and South America. These 12 case studies demonstrate the complexity and richness of the trade-resource nexus. In some cases, e.g. in Argentina and Senegal, trade and investment liberalization contributed directly to overharvesting of fish stocks. Here, the problem of weak domestic property rights was compounded by an additional distortion, EU subsidies to their domestic fleets. Other examples show why there is not a simple relation between trade and resource use. An EU policy to stimulate livestock production in Ile de la Reunion led to a temporary surge in maize exports from Madagascar, accelerating deforestation; however, previous import *restrictions* in Madagascar, aimed at increasing domestic production of food, were responsible for even greater deforestation. In regions of China and Vietnam, shrimp farming for the export market contributed to the decline of mangroves. EU biofuel policy contributed to deforestation (to develop palm oil plantations) in Southeast Asia, eliciting calls for EU policy changes and subsequent complaints of unfair practices to the WTO, by palm oil producers (Gerasimchuk and Koh, 2013).

Besley (1995) summarizes evidence that property rights are malleable. Otsuka and Place (2001) provide numerous examples of property rights responding to increased market access or factors such as increased population pressure. Although the general trend is that increased trade leads to stronger property rights, there are exceptions. Fenske (2012) documents that

Igbo groups in Nigeria moved from private to common property rights over palm trees in response to increased palm oil trade in the late 19th and early 20th century. Trade increased the value of the palm trees, and monitoring was cheaper under common property than under individual or family property rights. Different monitoring and enforcement costs under different types of property rights comprise a major explanation for the equilibrium form of property rights. Abaza and Jba's (2002) and Larson and Nash's (2010) syntheses document many cases of trade liberalization creating the need for, and then inducing, changes in natural resource management policies.

Recent empirical studies also find significant links between environmental policy and the prices and profitability of private assets, e.g. stock prices (Konar and Cohen, 2001), house prices (Chay and Greenstone, 2005), and firm profits (Linn, 2010; Bushnell, Chong, and Mansur, 2013). These results, like many of the trade-resources examples, show that the assumptions that drive our model are empirically relevant.

III. Model

We begin by describing the economy and showing that resource protection has the same qualitative effect on real returns to capital and labor in the closed economy, but opposite effects in an open economy. This difference is the basis for the trade regime's role in determining agents' incentives to protect the resource stock (Section IV.). Understanding those incentives helps explain the relation between the trade regime and resource management in the subgame perfect equilibrium setting (Section V.). Our simple model implies that moving from autarchy to free trade causes perverse resource policies to replace beneficial ones, harming the resource stock and typically lowering welfare. As Section II. emphasizes, the actual trade-resource nexus is much more complicated and ambiguous than suggested by our result. Section VI. discusses a number of extensions, some of which strengthen our conclusions, and some of which reverse them. The point of this model is not to establish that trade is bad for natural resources – a claim that is manifestly not *generally* true – but to reveal some of the

general equilibrium effects of trade on the incentive to protect resources.

The OLG economy consists of two sectors: manufacturing, M , and a resource sector, F . The population and capital stock are both constant. Agents live for two periods, so in each period there is an equal number of old and young agents. We normalize the stock of capital and the size of each generation to 1. Labor is mobile across sectors, capital is specific to sector M , and the resource stock, x_t , is specific to sector F .

A. Competitive equilibrium

The manufacturing good is the numeraire and the price of the resource good is p_t . In the small open economy this price is exogenous, and in the closed economy it is endogenous, a function of the resource stock and the resource policy. The representative price-taking manufacturing firm chooses capital, K , and labor, L^m , to solve

$$\max_{K_t, L_t^m} [m(L_t^m, K_t) - w_t L_t^m - \pi_t K_t]$$

$$\text{with } M_t = m(L_t^m, K_t) = \left[\beta (L_t^m)^{1-\frac{1}{\eta}} + (1-\beta) K_t^{1-\frac{1}{\eta}} \right]^{\frac{1}{1-\frac{1}{\eta}}}.$$

The rental and wage rates and the amount of labor in sector M are endogenous.

The representative price-taking resource firm maximizes profits, using a constant returns to scale (in labor, L) production function, $F_t = \gamma x_t L_t$, and taking the resource stock as predetermined. Under open access, this firm ignores the effect of harvest, F_t , on future stocks. Society can manage resource use by imposing an ad-valorem tax, T_t , on production of the resource good (a “resource tax”). This tax is a first-best instrument for managing resource use: there is no “static distortion”, as would occur with imperfect monitoring or enforcement. The policy failure arises because today’s decisionmakers cannot choose future taxes. Given the resource price p_t , and the tax, the representative resource firm obtains

$p_t(1 - T_t)$ units of revenue per unit of harvest. The firm's problem is

$$\max_{L_t} [(1 - T_t)p_t \gamma x_t L_t - w_t L_t].$$

Society returns the tax revenue, $R_t = T_t p_t \gamma x_t L_t$, in a lump sum, giving the fraction $\chi_t \in [0, 1]$ to the young and $1 - \chi_t$ to the old in period t . If the tax is negative (a subsidy), then $R_t < 0$, and the policy has a fiscal cost; χ_t determines the generations' share of this cost.

Agents have the single period utility function $u(c_{F,t}, c_{M,t}) = \frac{1}{\mu} c_{F,t}^\alpha c_{M,t}^{1-\alpha}$ with scaling parameter $\mu = \alpha^\alpha (1 - \alpha)^{1-\alpha}$. Agents spend a constant share, α , on the resource good. With price p and expenditures e , the indirect utility function, $v(e, p) = p^{-\alpha} e$, is linear in expenditures. The old agent owns the manufacturing asset, and the young agent owns one unit of labor. A young worker divides income, $w_t + \chi_t R_t$, into current consumption and saving for retirement, achieved by purchase of shares of capital ($s_t \in [0, 1]$) at price σ_t . A young agent who buys s_t shares of capital in period t spends $e_t^y = w_t + \chi_t R_t - s_t \sigma_t$ on consumption. The old agent spends all her income, obtained from tax revenue and renting for a period and then selling her assets, so her expenditure is $e_t^o = (1 - \chi_t) R_t + s_{t-1} (\pi_t + s_t \sigma_t)$. A young agent's life-time savings decision solves

$$\max_{s_t} p_t^{-\alpha} (w_t + \chi_t R_t - s_t \sigma_t) + \frac{1}{1 + \rho} p_{t+1}^{-\alpha} ((1 - \chi_{t+1}) R_{t+1} + s_t (\pi_{t+1} + s_{t+1} \sigma_{t+1})),$$

where $\rho > 0$ is the pure rate of time preference. With positive savings ($s_t > 0$), the agent's optimality condition is

$$(1) \quad p_t^{-\alpha} \sigma_t = (1 + \rho)^{-1} p_{t+1}^{-\alpha} (\pi_{t+1} + s_{t+1} \sigma_{t+1}).$$

Because the supply of the asset is perfectly inelastic, in equilibrium $s_t = 1 \forall t$. The simplicity of equation (1) is due to agents' infinite intertemporal elasticity of substitution. For a time horizon $H \leq \infty$, the price of capital (measured in numeraire units of good M)

equals the present discounted stream of future real returns, converted to current numeraire units:⁵

$$(2) \quad \sigma_t = p_t^\alpha \sum_{i=1}^H (1 + \rho)^{-i} p_{t+i}^{-\alpha} \pi_{t+i} \quad \forall t < H \text{ and } \sigma_H = 0.$$

Equilibrium welfare for the young and old generations, W_t^y and W_t^o , equals:

$$(3) \quad \begin{aligned} W_t^y &= p_t^{-\alpha} [w_t + \chi_t R_t] + \frac{1}{1+\rho} p_{t+1}^{-\alpha} [(1 - \chi_{t+1}) R_{t+1}] \\ W_t^o &= p_t^{-\alpha} [\pi_t + (1 - \chi_t) R_t + \sigma_t]. \end{aligned}$$

The first line of this system follows by substituting equation (1) into the young agent's maximand. In equilibrium, this agent's welfare equals the present value utility obtained from the wage and tax revenue, and is independent of σ_t . An unanticipated change in the asset price does not affect the young generation's welfare. For example, a higher current asset price reduces their current consumption expenditures and thus reduces their current utility; their utility gain in the next period, made possible by the higher next-period asset price, and higher consumption expenditures, exactly offsets the current utility loss.

The static equilibrium is conditioned on the resource stock, the asset price, and the tax, x_t , σ_t and T_t . In a closed economy, both sectors must operate in order for the goods markets to clear. We assume that the parameters of the manufacturing sector satisfy $0 < \beta < 1$ and $\infty > \eta > 0$, to ensure that, because of rents in sector M , capital is fully employed and this sector always operates in an open economy. For sufficiently low (exogenous) p_t , the open economy specializes in sector M ; in that case, $L_t = 0$. The two factors earn their value of marginal product, implying $\pi_t = m_K(L_t^m, 1)$ and $w_t = m_{L^m}(L_t^m, 1)$. Full employment of labor requires $L_t^m + L_t = 1$. If both sectors operate ($L_t > 0$), labor arbitrage requires $w_t = (1 - T_t)p_t\gamma x_t$. In the closed economy, the equilibrium relative price equalizes supply and demand. This market clearing condition, and the constant expenditure share under Cobb Douglas preferences imply that the autarchic price satisfies $p_t = \frac{M_t}{F_t} \frac{\alpha}{1-\alpha}$, a function of x_t and

T_t ; in an open economy, $p_t = P$, which we assume is constant.

The natural resource stock is predetermined in each period, but changes endogenously over time. The stock obeys a logistic growth function with intrinsic growth rate r :

$$\begin{aligned}
 (4) \quad x_{t+1} &= x_t + rx_t \left(1 - \frac{x_t}{C}\right) - L\gamma x_t = \left(1 + r \left(1 - \frac{x_t}{C}\right) - L\gamma\right) x_t \\
 &= (1 + \bar{r}(x_t, T_t)) x_t; \text{ with } \bar{r}(\cdot) \equiv r \left(1 - \frac{x_t}{C}\right) - L(x_t, T_t)\gamma;
 \end{aligned}$$

C is the carrying capacity, the function $\bar{r}(\cdot)$ is the actual growth rate of the resource, and $L = L(x_t, T_t)$ is the amount of labor in the resource sector.

Given a sequence of taxes, $\{T_{t+i}\}_{i=0}^H$ and the initial condition x_0 , a competitive equilibrium is defined by a sequence of static equilibria and sequences of the environmental stock, $\{x_{t+i}\}_{i=1}^H$, and asset price, $\{\sigma_{t+i}\}_{i=0}^H$, satisfying equations (2) and (4).

B. Comparative statics

We use the comparative statics of this model to determine equilibrium tax policy in different political economy settings. Real factor returns, $p^{-\alpha}w$ or $p^{-\alpha}\pi$, equal the amount of utility an agent obtains by renting one unit of labor or capital. Aggregate utility, or real national income, equals the sum of utility of the old and young generation.

Proposition 1. *In a closed or a diversified open economy: (i) A small tax has a 0 first order and a negative second order effect on current aggregate utility. A higher resource stock has a first order positive effect on aggregate utility. (ii) A higher tax decreases L , the labor in sector F , increasing the next period stock. (iii) In the open economy, a higher resource stock increases the real return to labor and decreases the real return to capital. (iv) In a closed economy, a higher resource stock increases the real return to both factors.*

(Appendix A contains all proofs.) The first two parts of the proposition are intuitive. Part (i) holds with general homothetic preferences and convex technology. A zero tax maximizes single period aggregate utility, so a small tax leads to a second order utility reduction.

A higher stock makes labor more productive in sector F , shifting out the production possibility frontier, and increasing aggregate utility. Part (ii) is obvious for an open economy, where the commodity price is fixed. The higher tax decreases the return to working in sector F , causing labor to leave the sector and reducing current harvest, thereby increasing the next period stock. The endogenous commodity price in the closed economy moderates but does not reverse this effect.

The notable feature is that a higher stock has opposite effects on the real factor returns in an open economy, but increases both real returns in a closed economy. In both economies, the higher stock increases labor productivity in the resource sector, attracting labor away from manufacturing, increasing the nominal wage and decreasing the nominal return to capital. This “factor price effect” tends to make labor’s and capital’s interests antagonistic. There is no offsetting effect in the open economy, where the fixed commodity price makes nominal and real returns equivalent. In a closed economy, a larger resource stock and the resulting increased labor in the resource sector both increase the supply of the resource good, lowering its relative price; we call this the “output market effect”. The higher nominal wage and lower relative price both increase the real wage in the closed economy. The effect of the higher stock on the real return to capital, $p^{-\alpha}\pi$, involves a balance of opposing forces. The higher stock lowers π (the factor market effect) but it also lowers p (the output market effect). For Cobb Douglas preferences, the output market effect dominates the factor price effect: on balance the higher stock increases the real return to capital. Thus, in the closed economy but not in the open economy, owners of the two factors tend to have similar interests.

IV. Open loop equilibrium

We are primarily interested in the relation between the trade regime and the equilibrium management of the natural resource when agents are fully rational. A complete analysis of this issue, using numerical methods, yields a quantitative assessment of the trade regime, but does not provide intuition for the forces at work (Section V.). To provide that intuition,

we begin by asking how the trade regime influences agents' incentives to choose a policy in the current period, when they take as given future taxes or subsidies. Here we consider a time consistent but not subgame perfect *open loop* Nash equilibrium. We find that in the closed economy open loop equilibrium, agents use a resource tax, protecting the resource stock and benefiting their successors. In the open economy, these agents use a resource subsidy, damaging the resource stock and harming (at least) some of their successors. We confirm numerically that the Markov Perfect equilibrium shares these properties.

Consistent with our assumption of no altruism, the current tax and sharing rule maximize the weighted sum of the lifetime welfare of agents currently alive. Let the weight on the old generation's welfare equal 1, and the weight on the young generation's welfare equal $1 + \delta$, where δ is a parameter. The relative consumer price of the resource good is p_t , a constant, P , in the open economy and a function, $p(x_t, T_t)$, in the closed economy. The period t nominal value of aggregate income is $Y_t = Y(x_t, T_t) = p_t F_t + M_t = \pi_t + w_t + R_t$, and aggregate utility (real national income) is $p_t^{-\alpha} Y(x_t, T_t)$. National income is independent of χ_t , a variable that merely affects the allocation of tax revenue. Agents in the current period choose the current tax and revenue allocation, T_t and χ_t .

The time- t optimal revenue share and tax maximize the political preference function,

$$\begin{aligned} \tilde{W}_t &\equiv W_t^o + (1 + \delta) W_t^y \\ &= p_t^{-\alpha} [Y_t + \sigma_t + \delta (w_t + \chi_t R_t)] + \frac{1+\delta}{1+\rho} [p_{t+1}^{-\alpha} (1 - \chi_{t+1}) R_{t+1}]. \end{aligned}$$

There are several models for which the equilibrium can be obtained by maximizing a weighted sum of agents' welfare: a Nash bargaining model with transfers or a probabilistic voting model (as in Lindbeck and Weibull, 1987, or Persson and Tabellini, 2000). Our results do not depend on the particular micro-foundations of this political preference function.

Because \tilde{W}_t is linear in χ_t , for $\delta \neq 0$ the equilibrium value of χ_t is on the boundary of its feasible set, which we take to be $[0, 1]$. The parameter δ is fixed, but R_t is endogenous, and has the same sign as T_t . Our principal result does not depend on whether χ_t^* equals 0

or 1, and therefore does not depend on the sign of δ . The optimal revenue split, χ_t^* , is

$$(5) \quad \chi_t^* = \arg \max_{\chi_t} \tilde{W}_t = \begin{cases} 0 \\ \text{indeterminate} \\ 1 \end{cases} \text{ if } \begin{cases} \delta R_t < 0 \\ \delta R_t = 0 \\ \delta R_t > 0 \end{cases}.$$

We assume that $\delta \neq 0$, and $|\delta|$ is small. The assumption $\delta \neq 0$ eliminates the indeterminate case in equation (5), because in equilibrium $R_t \neq 0$. The assumption that $|\delta|$ is small means that agents choose the current tax or subsidy to increase the aggregate lifetime welfare of those currently alive, not to transfer income from one currently living generation to the other. For $\delta \approx 0$, the value of χ_t has a negligible effect on the optimal tax, because χ_t only transfers income between the current generations, which have essentially the same weight in the political preference function. In contrast, even for $\delta \approx 0$, χ_{t+1} has a non-negligible effect on the optimal tax; χ_{t+1} determines a transfer between the current and the next period young; the latter are not represented in the current political preference function.

The assumption that $\delta \approx 0$ allows us to replace the political preference function \tilde{W}_t with its approximation, W_t :

$$(6) \quad W_t(x_t, T_t) \equiv \tilde{W}_t \Big|_{\delta=0} = p_t^{-\alpha} Y_t + p_t^{-\alpha} \sigma_t + \frac{1}{1+\rho} p_{t+1}^{-\alpha} [(1 - \chi_{t+1}) R_{t+1}].$$

The function $W(\cdot)$ is the sum of three terms: the real income associated with period t production, the utility value of wealth, and the present utility value of the next period tax receipts received by the current young. The last two of these terms depend on future taxes.

We study the open loop Nash equilibrium in order to provide intuition about the subgame perfect political economy equilibrium, where agents are fully rational in managing the resource. In view of this limited objective, we put a premium on simplicity, and adopt:

Assumption 1. (i) *The taxes are constrained to lie in the interval $[-\varepsilon, \varepsilon]$ with $\varepsilon > 0$, $|\varepsilon|$ small.* (ii) (**Diversification**) *The open economy is diversified for all taxes in this*

interval. (iii) (**Monotonicity**) A small decrease in current extraction, and the consequent small increase in the next period stock, also increases all future stocks outside the steady state. (iv) (**Concavity**) For small taxes, the maximand $W_t(x_t, T_t)$ is concave in T_t .

Assumption 1.i limits the scope of the analysis by restricting attention to small policy-induced changes in the stock. Assumptions 1.ii & 1.iii are statements about model primitives, the parameters and the initial condition, x_0 . Assumption 1.ii allows us to focus on the interesting cases, where the economy is diversified, i.e. the resource sector is active. Appendix A provides the restrictions on model primitives under which Assumption 1.iii holds. Assumption 1.iv enables us to determine the sign of the optimal policy by evaluating the derivative of welfare at a zero tax.⁶ We use two lemmas:

Lemma 1. For a **fixed** sequence of future resource taxes/subsidies that satisfy Assumption 1.i–iii: (i) A current tax increases the utility value of the asset, $p_t^{-\alpha}\sigma_t = \sum_{i=1}^H(1+\rho)^{-i}p_{t+i}^{-\alpha}\pi_{t+i}$ in the closed economy, and decreases the utility value of the asset in the open economy. (ii) In both trade regimes, an increase in the current tax increases the utility from next-period tax revenue, $p_{t+1}^{-\alpha}R_{t+1}$, if and only if $T_{t+1} > 0$.

Lemma 1.i identifies an “asset market effect”: a tax has the opposite effect on wealth in open and closed economies. This difference is key to understanding why agents use a resource tax in the closed economy, but not in the open economy.

Taking as given future taxes, we denote \bar{T}_t^j as the optimal period t tax in trade regime $j \in \{\text{open, closed}\}$:

$$(7) \quad \bar{T}_t^j(x_t) = \arg \max_{T_t} W_t^j(x_t, T_t).$$

That is, \bar{T}_t^j is the best response to the future sequence of taxes, given the current stock x_t .

Lemma 2. For a **fixed** sequence of future taxes/subsidies that satisfy Assumption 1.i–iv, with ε small, a sufficient condition for $\bar{T}_t^{\text{closed}} > 0$ is that $T_{t+1}^{\text{closed}} \geq 0$; a sufficient condition for $\bar{T}_t^{\text{open}} < 0$ is that $T_{t+1}^{\text{open}} \leq 0$.

We define the open loop Nash equilibrium for the sequential political economy game, and then use Lemmas 1 and 2 to characterize the equilibrium and derive our chief analytic result. Let H denote the length of the horizon at the beginning of the game, and let $h \leq H$ denote the number of periods to go in a game that, at the initial time, has H periods. At $h = 0$, the economy is in the last period. The vector $\mathbf{T}^H \in \mathbb{R}^H$ is the list of tax levels in the H -horizon game, and the scalar ${}^hT \in \mathbf{T}^H$ is the tax used when there are h periods to go. (The left superscript h avoids confusion with the right superscript j , which denotes the trade regime.) An open loop Nash equilibrium is a trajectory of taxes, in which each element is a best response to all other elements:

Definition 1. (*OLNE*) *An open loop Nash equilibrium in the H -stage sequential game is a vector $\mathbf{T}^H \in \mathbb{R}^H$ with the property that ${}^hT \in \mathbf{T}^H$ maximizes currently living agents' joint welfare when there are h stages-to-go, given that both past and future taxes equal the corresponding elements of \mathbf{T}^H . An OLNE of the infinite horizon model is a limit, as $H \rightarrow \infty$, of an equilibrium \mathbf{T}^H .*

The optimal decision in a period where $h > 0$ depends on the current stock and future taxes. The current stock depends on the initial stock and actions in previous periods. Under either trade regime, in the last period the asset price is 0 and the equilibrium tax is also 0, the value that maximizes current real national income. Thus, for any $H \geq 0$ and under either trade regime, we have ${}^0T = 0$. Using Lemma 2 and induction, we have ${}^iT > 0$ in the closed economy, and ${}^iT < 0$ in the open economy, for $i > 0$. This argument establishes:

Proposition 2. *Under Assumption 1, the policy in every period except for the last in any H -stage OLNE: (a) involves a tax in the closed economy, and (b) involves a subsidy in the open economy.*

Any OLNE in the infinite horizon model shares these characteristics, except of course that it has no last period. Equation (5) and Proposition 2 imply

Corollary 1. *Under Assumption 1, Table 1 gives the relation between the sign of δ and the equilibrium χ^* . If the young have more weight than the old in the political preference function ($\delta > 0$) they receive all of the tax revenue in the closed economy, and pay none of the fiscal cost of the subsidy in the open economy. The opposite holds if $\delta < 0$.*

	$\delta > 0$	$\delta < 0$
closed economy (where $R_t > 0$)	$\chi^* = 1$	$\chi^* = 0$
open economy (where $R_t < 0$)	$\chi^* = 0$	$\chi^* = 1$

Table 1: Relation between sign of δ and equilibrium value of χ^*

Incentives In a closed economy OLNE, agents tax resource use; in an open economy OLNE, they subsidize resource use. Agents are not altruistic, so they choose the current policy without considering its effect on their successors' welfare. Of course, the current policy affects future stock levels, thus affecting future welfare. Through the asset market effect, future policies affect the current asset value, thus affecting current welfare.

A resource tax affects the utility associated with ownership of the asset and future tax receipts. In the open economy, a higher future stock lowers future returns to capital, thus lowering the price (and the utility value) of the asset, and encouraging current agents to subsidize resource extraction. In addition, if successors use a subsidy, then current agents anticipate fiscal costs of the policy ($R < 0$), and they understand the current young generation will pay the fraction $1 - \chi_{t+1}$ of those costs. By lowering the next period stock (thus lowering labor productivity in the resource sector), they decrease output of the resource sector in the next period. Because the subsidy is incurred for each unit of the harvest, the lower stock lowers the next period fiscal cost, thus weakly lowering the current young generation's future obligation. The closed economy reverses these incentives.

Under both trade regimes, the current policy creates capital gains or losses. The change in the asset price, induced by the resource policy, transfers some of the future costs or benefits of the policy to those currently alive. In the closed economy, the incentives operate to increase future welfare, i.e. to protect the resource stock. Here, the current policy increases

the “intertemporal pie”, and the higher asset price benefits those currently living. In the open economy, the incentives operate to shrink the “intertemporal pie”, by reducing the resource stock. Those currently living nevertheless benefit from the subsidy.

The welfare effect of moving from a BAU equilibrium to an OLNE are ambiguous. In a closed economy, a sequence of small taxes increases aggregate lifetime welfare of those alive in the first period. The lifetime welfare of agents born in the future, W_t^y , equals the real income associated with the sum of their wage and share of tax revenues (equation (3)). The stock trajectory in a closed economy OLNE is above the BAU trajectory (Proposition 2), increasing future real wages; but the future taxes lower those real wage, so the welfare comparison in a closed economy, between OLNE and BAU, is ambiguous. An open economy OLNE stock trajectory is lower than the BAU trajectory, lowering future real wages; but the future subsidies increase those wages, again making the welfare comparison ambiguous.

V. Markov Perfect equilibrium

The OLNE is time-consistent but not subgame perfect: if any agent uses a non-equilibrium tax or subsidy, the trajectory of the resource stock departs from the trajectory that agents assumed when choosing their policy. The continuation of the OLNE, obtained in the initial period, would not be an equilibrium following the deviation. In a subgame perfect equilibrium, agents not only form (point) expectations about the level of successors’ actions, but also form expectations about how those actions would change if the current agent were to deviate from equilibrium. We study a Markov Perfect equilibrium (MPE), in which actions and point expectations about successors’ actions are conditioned on the “directly payoff-relevant state variable”: the resource stock. Using numerical methods, we obtain the MPE to the infinite horizon model without restricting policies to be small or assuming concavity; we choose parameter values so that the BAU adjustment path is monotonic and the open economy remains diversified. We thus dispense with Assumption 1. Numerical methods also make welfare comparisons possible.

We describe the MPE for the generic problem and then specialize to obtain the MPEs in the two trade regimes. Denote $\Upsilon(x_t)$ as an *arbitrary* policy function, mapping the period- t resource stock into the period- t tax. If the current stock and tax equal (x_t, T_t) , and all future taxes equal $T_{t+i} = \Upsilon(x_{t+i})$, $i \geq 1$, then $\Upsilon(x_t)$ induces an asset price function (a functional in Υ). This function, $\sigma(x_t, T_t)$, is defined recursively:

$$(8) \quad p_t^{-\alpha}(x_t, T_t) \sigma(x_t, T_t) = (1 + \rho)^{-1} \{ p_{t+1}^{-\alpha}(x_{t+1}, \Upsilon(x_{t+1})) [\pi(x_{t+1}, \Upsilon(x_{t+1})) + \sigma(x_{t+1}, \Upsilon(x_{t+1})))] \}.$$

Equation (8) restates the equilibrium savings condition, equation (1), highlighting the dependence of the endogenous function $\sigma(x_t, T_t)$ on x_t, T_t , and the function $\Upsilon(x_{t+1})$.

A MPE is a function $\Upsilon(x)$ for which: $\Upsilon(x) = \arg \max_T W_t(x, T)$, with $\sigma(x_t, T_t)$ the solution to equation (8), where χ_{t+1} satisfies equation (5), x_{t+1} satisfies equation (4), and next period tax is evaluated using $T_{t+1} = \Upsilon(x_{t+1})$. Finding $\Upsilon(x)$ is a standard fixed point problem, which can be solved using the collocation method and Chebyshev polynomials (Judd, 1998; Miranda and Fackler, 2002). We present further details in Appendix B

For each trade regime, we solve the model for two cases, with constant $\chi = 1$ and with $\chi = 0$. We find that for both values of χ , and for all x , the equilibrium policy is always a tax in the closed economy and always a subsidy in the open economy, just as in the OLNE. Therefore, we can use Table 1 (or equation (5)) to determine the sign of δ that leads to a particular value of χ . For example, in the open economy with $\delta > 0$, the equilibrium sharing rule is $\chi^* = 0$: the young pay none of the fiscal cost of the subsidy.

Social planner To provide a benchmark, we also compute the equilibrium to a social planner with the same pure rate of time preference as individuals. This planner has a standard (time consistent) control problem:

$$(9) \quad \max_{\{T_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} (1 + \rho)^{-t} p(x_t, T_t)^{-\alpha} Y(x_t, T_t)$$

subject to equation (4) and an initial condition on the stock. The social planner has the same problem as agents with perfect bequest motives and the ILA.

Calibration Our baseline calibration sets both α , the share of the resource-intensive commodity in the consumption basket, and β , the wage share in manufacturing, equal to 0.5. Production in manufacturing uses Cobb Douglas technology, $\eta = 1$. We use an annual pure rate of time preference of 1%/year, which gives $\rho = 0.41$ assuming that one period lasts 35 years. The carrying capacity is $C = 1$, so x equals the resource capacity rate. We set $r = 0.68$, implying an uncongested growth rate of 1.5%/year, and we choose γ so that the closed economy BAU steady state is $x_\infty = 0.5$, implying that $\gamma = 0.513$. We set the world price at $P = 3.377$, implying that the open and closed economy steady states are equal under BAU. System (10) collects these baseline parameter values:

$$(10) \quad \alpha = 0.5; \beta = 0.5; \eta = 1; \rho = 0.41; r = 0.68; \gamma = 0.513; P = 3.377.$$

For this parameter set and $x > 0.5 = x_\infty$, production in the open economy remains diversified. For $1 > x > x_\infty$, the endogenous relative price p in the BAU closed economy ranges between $1.688 < p < 3.377$. Thus, for $1 > x > x_\infty$, opening the BAU closed economy to trade causes a jump up in the relative commodity price. At the steady state, x_∞ , opening the BAU closed economy to trade has no effect by calibration. The baseline results we report here are representative of those from a much larger set of parameter values reported appendix B

A. *The MPE*

The six panels in Figure 1 show the MPE corresponding to $\chi = 0$ (solid) and $\chi = 1$ (dashed) and to the social planner (dot-dash) and BAU (dotted). The left panels correspond to the open economy and the right panels correspond to the closed economy. We first discuss the MPE and BAU.

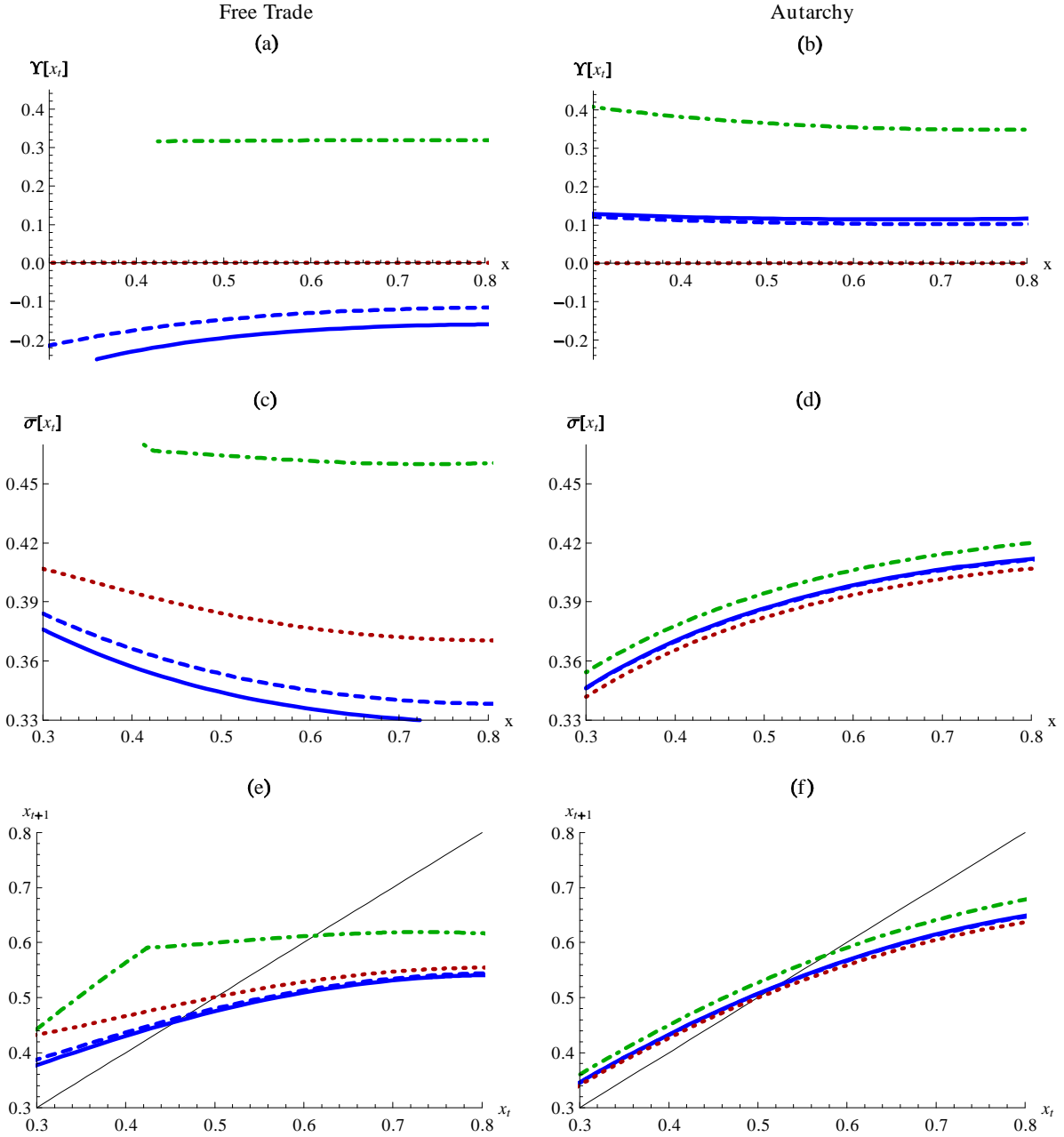


Figure 1: Left panels correspond to free trade and right panels to autarchy. Dashed graphs correspond to $\chi = 1$ and solid graphs to $\chi = 0$ in the MPE. Dotted graphs correspond to BAU and dot-dashed to social planner. The top panels show policy functions, the middle panels show the utility-denominated asset price, and the bottom panels show the equilibrium relation between current and next period stock.

The major conclusion is that, for both $\chi = 0$ and $\chi = 1$, the MPE policy is a tax in the closed economy and a subsidy in the open economy, just as in the OLNE. The closed economy equilibrium ad valorem tax is approximately 10%, and the open economy resource subsidy is approximately 20%, depending on χ and x .

The equilibrium policy function (Figure 1, panels *a* and *b*) and asset prices (Figure 1, panels *c* and *d*) are insensitive to the value of χ in the closed economy, and moderately sensitive to χ in the open economy. In the open economy, where the equilibrium is a subsidy, Table 1 shows that $\chi = 0$ corresponds to $\delta > 0$: the old bear the fiscal cost of the policy. Changing from $\delta < 0$ to $\delta > 0$, i.e. giving the young generation greater weight in the preference function, slightly decreases the resource tax in the closed economy, and increases the resource subsidy in the open economy: greater political weight on the young harms the resource under both trade regimes.

Lemma 1 notes that a higher resource stock increases the asset price in the closed economy and decreases the asset price in an open economy. Panels *c* and *d* in Figure 1 confirm that this also holds in the MPE. In the closed economy MPE, generations alive today want to tax resource use, because they know that the resulting higher stock increases future taxes, increasing the asset price. The closed economy MPE asset price is greater than the BAU asset price.

In the open economy, agents alive today want to use a subsidy, in order to lower the resource stock, and thereby increase the asset price. If these agents could commit to a tax, they could raise the asset price and their welfare (as occurs under the social planner discussed below). This type of commitment is not feasible in a MPE. Agents alive today understand that agents in the future have an incentive to subsidize production in the resource sector. Knowing this, agents alive today want to use a subsidy (just as in the OLNE). Agents face a version of the prisoner's dilemma in an intergenerational setting. The attempt to transfer welfare from the future toward the present backfires. The equilibrium subsidy reduces wealth (relative to BAU), reducing young agents' willingness to pay for the asset.

Panels *e* and *f* of Figure 1 show x_{t+1} as a function of x_t , together with the 45^0 line used to identify the steady state. These mappings are insensitive to χ . In the closed economy, the next period stock is higher in the MPE compared to BAU; free trade reverses this relation. The BAU steady state stock level equals 0.5 by calibration regardless of the trade regime. The steady state increases by 4% in the closed economy MPE and falls by 11% in the open economy MPE.

In the closed economy MPE, the domestic consumer price, $p(x_t, \Upsilon(x_t))$, equals the world price at $x_t = 0.54$. If the economy were to open to trade at this value of x , the consumer commodity price remains constant, but the domestic resource tax switches to a subsidy, increasing harvest and causing the stock to fall more rapidly and toward a lower steady state. In previous papers, trade liberalization increases resource use because of differences in domestic and external prices. In our framework, trade reverses the direction of equilibrium policy and increases resource use even in absence of current commodity price changes.

Figure 2 shows present and future agents' lifetime welfare under the MPE with $\chi = 1$, relative to BAU levels. For future periods ($i \geq 1$) the figure shows the young agent's lifetime welfare change, and for the initial period ($i = 0$) it shows the aggregate lifetime welfare change for the current young and old generations. The dashed curve corresponds to the initial condition $x_0 = 0.5$ and the solid curve corresponds to $x_0 = 0.9$. For intermediate initial conditions, the welfare gain lies between these two curves. These conventions also apply to Figures 3 and 7.

We first discuss the closed economy case (the right panel in Figure 2). The MPE increases agents' welfare because the equilibrium management of the resource increases future and present wealth by protecting the resource. In the open economy, however, agents in period 0 and in every period after period 1 are worse off in the MPE compared to BAU, because the endogenous policy exacerbates the absence of property rights. If, in the open economy, the initial stock is sufficiently high, the young agent in period 1 has higher welfare in the MPE compared to BAU. This agent has no capital loss; see the comment below

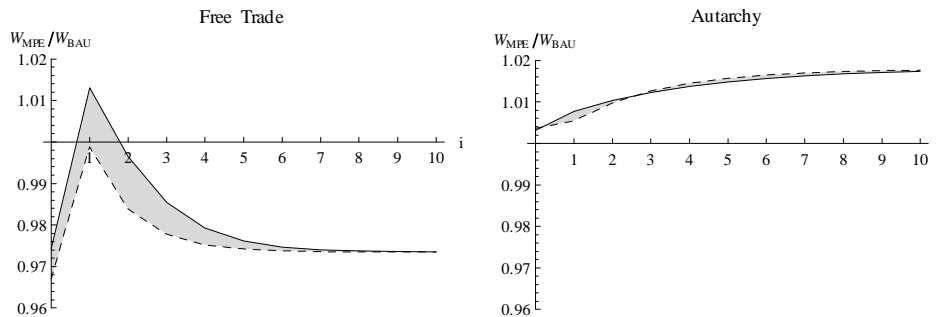


Figure 2: Welfare in MPE relative to BAU with initial resource stock $x_0 = 0.5$ (dashed) and $x_0 = 0.9$ (solid); free trade left panel and autarchy right panel, for $\chi = 1$. Period 0 shows combined lifetime welfare of old and young; subsequent periods show lifetime welfare of young.

equation (3). Due to the high initial condition for x , the stock during this agent's lifetime is still relatively high, so she does not suffer (much) from the subsidy-induced fall in the stock; the subsidy-induced increase in her wage more than offsets the stock-related loss.

Trade liberalization creates the usual static utility gains, but has complicated dynamic welfare effects. Under BAU, at initial stocks above the steady state, the move from the closed to the open economy causes a fall in the asset price (Figure 1, panels *c* and *d*). Nevertheless, due to the usual static utility gain, trade increases BAU lifetime welfare of agents in the initial period. The lower future stock due to higher harvest reduces agents' welfare in all subsequent periods, except in the steady state (which under BAU is the same in both trade regimes, by calibration). The welfare effect of trade in the MPE is more pronounced than under BAU. The switch from a tax (in the closed economy) to a subsidy (in the open economy) causes a large fall in asset value; except for very high initial stocks, even the generations in the initial period have lower welfare in the open compared to the closed economy. All later generations have lower welfare under trade, even at the steady state, because the economy under trade continues to use a resource subsidy. Appendix B further discusses the welfare effects of trade liberalization (holding the policy regime fixed).

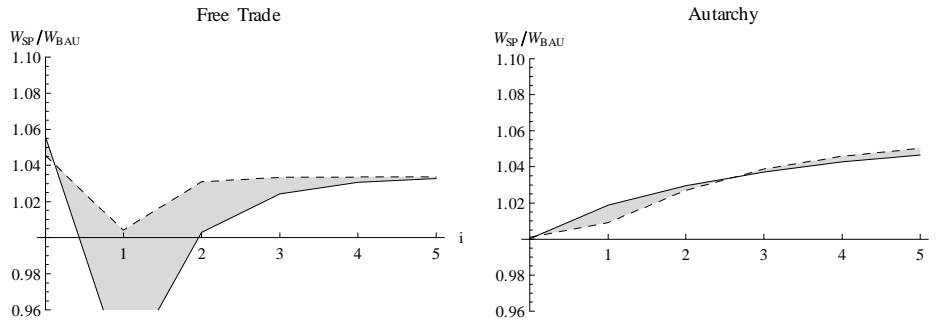


Figure 3: Welfare under the social planner relative to BAU with the initial resource stock $x_0 = 0.5$ (dashed) and $x_0 = 0.9$ (solid) for free trade (left) and autarchy (right).

B. The social planner

The dot-dash graphs in Figure 1 show the equilibrium policy functions, asset prices, and state transitions for the social planner. In both the open and closed economies, the planner (and the ILA) uses a resource tax; in both trade regimes, the equilibrium stock and tax trajectories are higher under the social planner compared with both BAU and MPE. Under free trade for $x < 0.42$, the social planner uses a prohibitive tax, allowing the resource to grow as fast as possible. Under diversified production, the tax remains close to its steady state level, $T_\infty = 0.32$, at $x_\infty = 0.61$. The closed economy steady state tax is higher, $T_\infty = 0.36$, but the steady state stock is lower, $x_\infty = 0.58$. The social planner achieves greater protection of the resource at a lower tax, in the open compared to closed economy.

In Ramsey models, optimal resource policy requires that currently living agents sacrifice to benefit future agents. Our social planner solves the standard intertemporal problem (9), so it is no surprise that her program lowers aggregate period 0 *utility*. The planner's policy function induces a trajectory of welfare for the old and young agents. The planner's program in the closed economy leads to a slight increase in period 0 aggregate lifetime *welfare* for initial conditions $x_0 < 0.91$ (Figure 3) and a small loss at larger stocks. The planner's program increases the asset price (Figure 1, panels *c* and *d*), and the old generation alive in period 0 obtains these capital gains. The young generation alive in period 0 also benefits

from the higher stock in the second period of their life.

Those alive in the initial period have a more pronounced policy-induced welfare increase in the open economy, compared to the closed economy. This difference arises because the socially optimal policy creates a larger increase in the asset price in the open economy, compared to the closed economy. Without these capital gains, the initial generations suffer large losses in welfare under the social planner (compared to BAU), in the open economy. In both open and closed economies, the planner's intervention increases the steady state level of welfare, because intervention increases the steady state resource stock. In the closed economy, the planner raises welfare for all generations, if $x_0 < 0.91$. In the open economy, the planner reduces intermediate generations' welfare if the initial resource stock is high. Those generations would not have suffered much from a low stock under BAU, but they have a lower real wage when the planner taxes the resource.

The social planner corrects the open-access distortion. Opening the economy to trade eliminates the remaining distortion, necessarily increasing the maximand, the discounted stream of welfare. Some of this increased welfare appears as capital gains, which the first old generation appropriates. The planner's objective is to maximize the discounted stream of utility, not, for example, steady state utility. Thus, even in a standard Ramsey model, there is no presumption that trade, or any other movement from second to first best, increases utility in every period, e.g. in the long run steady state. In our calibration, except for initial conditions above 0.9, trade lowers all subsequent generations' welfare under the social planner. Appendix B contains further discussion of the welfare effects of trade liberalization.

VI. Extensions

Our functional assumptions make the asset market effect transparent, leading to a simple conclusion: opening a closed economy causes perverse resource management policies to replace beneficial policies, harming the environment and reducing welfare for most or all agents. As previously emphasized, we know that the trade-resource nexus is in fact much

more complicated and ambiguous. This section briefly considers extensions, some of which can overturn our conclusion.

International trade in factors. If commodity trade is associated with international factor mobility, then the international market fixes factor prices, eliminating agents' incentive to use *any* resource policy under trade. The movement from autarchy to commodity + factor trade changes the equilibrium resource-protecting tax to laissez faire. Trade eliminates but does not reverse the incentives to protect the resource.

Intersectoral mobility of capital. We follow Hotte et al (2005) and Copeland and Taylor (2009) and many other papers in this literature in assuming that labor is the only mobile factor. Karp (2005) shows that even in a static setting, allowing capital as well as labor to be mobile across sectors alters the factor price effects of increased resource protection. For example, a higher resource stock could increase the nominal return to both factors, altering the “factor market effect” described above, and creating an incentive to protect the resource even under trade. Thus, this extension could overturn our result.

Replacing Cobb Douglas with homothetic utility. Proposition 1, and by extension Proposition 2, also hold for general homothetic preferences, for a sufficiently large sector- M elasticity of substitution, η . Cobb Douglas preferences greatly simplify the arguments, and enable us to state the result for all $0 < \eta < \infty$, but those preferences are not necessary for the results. However, with homothetic utility and small η , the factor market effect dominates the product market effect under autarchy. In this case, a larger resource stock lowers the real return to capital under autarchy, eliminating current agents' incentives to protect the resource there.

Making indirect utility nonlinear in income. The Cobb Douglas utility function implies that indirect utility, $V(p)y$, is linear in income, where $V(p)$ is a price index and y is an agent's income. This linearity implies that the elasticity of intertemporal substitution is infinite, and leads to the simple expression of the asset price, equation 2. For a monotone increasing function G , we can replace indirect utility with $G(V(p)y)$. Karp and Rezai (2014b)

consider this extension in a closed economy one-commodity framework (where $V(p) = 1$). If, for example, $G(\cdot) = \ln(\cdot)$, intertemporal income and substitution effects cancel. In the absence of taxes, the young agent saves a constant fraction of her income, equal to her wage. This savings rule creates a linear relation between the wage and the asset price, which is independent of resource stocks. More general (and more interesting) cases lead to more complicated asset price equations, requiring numerical methods.

Endogenously changing capital stocks. We follow the tradition of this literature, where all previous papers assume that only the resource stock changes endogenously. Karp and Rezai (2014a) allow endogenous investment in capital, but rely on numerical methods, and do not consider trade.

Costly monitoring and enforcement. As described in the Introduction, we abstract from some features that are central to previous papers, in order to emphasize that our results arise even when agents have a first best means of controlling current resource harvests. The distortion occurs because they cannot control future harvests. Monitoring and enforcement costs in our setting would likely reduce agents' incentive to use a resource tax in the closed economy. If the costs are symmetric with respect to resource protection and resource depredation, the effects would likely be to reduce the absolute value of both the closed economy tax, and the open economy subsidy. Asymmetric costs would change this conjecture in obvious ways.

Minor extensions. One could imagine many other extensions, e.g. changing the growth function, changing the harvest function (so that there are decreasing returns to labor, conditional on the resource stock), or allowing imperfect property rights to capital as well as the resource stock. Bohn and Deacon (2000) show that those imperfections discourage investment (e.g. in oil extraction), and may reduce natural resource extraction.

VII. Conclusion

Many papers discuss the institutions and policies that govern natural resource use; a small literature examines the effects of trade on equilibrium resource use, either under fixed or endogenous property rights. We extend this literature, showing how endogenous resource policy depends on the trade regime when agents are selfish and forward-looking, rather than either myopic or infinitely-lived. We use an overlapping generations model, making it possible to include a market for the privately owned asset. Our results are driven by the effect of trade on this asset price, a mechanism that does not appear in infinitely lived agent models. The privately owned asset and the open access natural resource are inputs in different sectors, but policy and the resource stock influence labor allocation and thereby affect the return to capital. In each period agents coordinate on their current use of the resource, but they cannot choose their successors' policies. Trade fixes the relative prices of goods, altering equilibrium resource policy.

Our chief conclusion is that, in a closed economy, a resource tax is a best response for selfish agents, to a next-period resource tax. In an open economy, a resource subsidy is a best response for selfish agents, to a next-period resource subsidy. In both open loop and Markov perfect equilibria, the equilibrium policy is a tax in the closed economy and a subsidy in the open economy. Opening a closed economy converts a mutually beneficial policy to a mutually destructive one, harming most agents. This conclusion is useful because it illuminates a previously hidden feature of markets, not because it provides a general indictment of trade in the presence of imperfect property rights.

Our results rely on three insights, which in isolation are unremarkable, but taken together have important implications. The first insight uses the fact that the relative commodity price is endogenous in a closed economy but exogenous in a small open economy. The qualitative effect of a change in policy or the stock, on the *nominal* return to a factor, does not depend on the trade regime. However, the qualitative effect of a stock or policy change on the *real* return to a factor does depend on the trade regime. For an open economy, a

stock or policy change has the opposite qualitative effect on real returns to capital and to labor. For a closed economy, a stock or policy change has the same qualitative effect on the real returns to both factors. Consequently, trade eliminates a commonality of interests between the two factor owners that exists in the closed economy.

The second insight is that these factor market linkages cause policy and stock changes to alter the prices even of assets not used in the resource sector. Asset owners care about those price effects, regardless of their intrinsic concern for the resource stock or future generations' welfare. The asset market transfers, to agents currently alive, some of the future costs or benefits arising from changes in future resource stocks and policy. The old generation, who currently owns capital, obtains the capital gains or losses resulting from policy-induced changes. Taken together, these two insights explain why a change in the stock or the policy have different asset price effects in the two trade regimes. They therefore provide the basis for understanding why selfish agents in the closed economy have an incentive to take actions that benefit their successors. In the open economy, these same agents have an incentive to take actions that harm their successors.

The third insight is that a higher next-period stock increases the next-period tax revenue or fiscal liability. If the next period policy is a tax, and the current young generation obtains some of the tax revenue, current generations have an incentive to leave their successor a larger stock; the larger stock increases productivity in the resource sector, thereby increasing future tax revenue. Current generations therefore want to protect the resource stock using a tax. If the next period uses a subsidy, and the current young generation incurs some of the fiscal liability, current generations have an incentive to decrease the stock, using a subsidy; the lower stock decreases the next-period fiscal liability. This incentive remains even when the level of the policy responds to the stock, as in a Markov perfect equilibrium.

We also compare the political economy equilibrium to the social optimum. Regardless of the trade regime, the social planner chooses to protect the resource. The overlapping generations structure allow us to disaggregate across generations the associated aggregate

welfare gain. Again, the asset price has significant implications for the distribution of welfare across generations. The initial asset owner captures the capital gains resulting from trade. Subsequent generations may have lower welfare under trade, even in the social planner setting.

Notes

¹The ILA structure is neither necessary nor sufficient for time consistency. For example, either non-constant discounting or the presence of forward looking agents who solve investment problems that are influenced by a benevolent government with second-best policies, produce time inconsistency in an ILA setting. A perfect bequest motive (typically) produces time consistency in an OLG setting.

²Our dynamic model builds on Hassler et al. (2003), Conde-Ruiz and Galaso (2005) and Klein et al. (2008), papers that study the determination of social policy in similar OLG dynamic games. Natural resource and environmental applications of OLG models begin with Kemp and Long (1979). Subsequent contributions study sustainability under a social planner instead of a game (Howarth and Norgaard, 1992; Mourmouras, 1991; John and Pecchenino, 1994; Howarth, 1998; Bovenberg and Heijdra, 1998; Laurent-Lucchetti and Leach, 2011). These papers study only closed economies and first-best social planner policy. Karp and Rezai (2014b) study policy determination under non-commitment only for a closed economy.

³Asset markets play no role in most ILA models with endogenous capital and a linear transformation between the consumption and investment goods. That linearity and a normalization fixes the price of capital equal to 1. The endogenous price of capital is central to our results.

⁴The popular press and NGOs have documented trade-induced poaching of elephants and rhinos for over 15 years. Examples include http://www.cites.org/eng/news/pr/2013/20131202_elephant-figures.php and <https://www.worldwildlife.org/threats/illegal-wildlife-trade>.

⁵We assume that young agents can afford the asset, so the non-negativity constraint: $e_t^y \geq 0$ never binds.

⁶Extensive numerical results, described in Appendix B., show that Monotonicity and Concavity are satisfied for a wide range of parameters under *equilibrium* policies (not merely for small policies). Thus, these two assumptions are not particularly restrictive.

REFERENCES

- ABAZA, H., AND V. JHA (2002): “Integrated assessment of trade liberalization and trade-related policies,” United Nations Environmental Programme.
- ALLEN, R., AND I. KEAY (2004): “Saving the Whales: Lessons from the Extinction of the Eastern Arctic Bowhead Whale,” *Journal of economic History*, 64(2), 400–432.
- BESLEY, T. (1995): “Property rights and investment incentives: theory and evidence from Ghana?,” *Journal of Political Economy*, 103(5), (93–937).
- BOHN, H., AND R. DEACON (2000): “Ownership risk, investment, and the use of natural resources,” *American Economic Review*, 90, 526–49.
- BOVENBERG, A. L., AND B. J. HEIJDRRA (1998): “Environmental tax policy and intergenerational distribution,” *Journal of Public Economics*, 67(1), 1–24.
- BRANDER, J. A., AND M. S. TAYLOR (1997a): “International Trade and Open-Access Renewable Resources: The Small Open Economy Case,” *Canadian Journal of Economics*, 30(3), 526–52.
- (1997b): “International trade between consumer and conservationist countries,” *Resource and Energy Economics*, 19(4), 267–297.
- (1998): “Open access renewable resources: Trade and trade policy in a two-country model,” *Journal of International Economics*, 44(2), 181–209.
- BULTE, E., AND E. BARBIER (2005): “Trade and Renewable Resources in a Second Best World: An Overview,” *Environmental & Resource Economics*, 30(4), 423–463.
- BUSHNELL, J., H. CHONG, AND E. MANSUR (2013): “Profiting from regulation: evidence from the European Carbon market,” *American Economic Journal: Economic Policy*, 5(4).

CARLOS, A., AND F. LEWIS (1999): “Property rights, competition, and depletion in the eighteenth century Canadian fur trade,” *Canadian Journal of Economics*, 32(3), 705–728.

CHAY, K., AND M. GREENSTONE (2005): “Does air quality matter? Evidence from the housing market,” *Journal of Political Economy*, 113(2), 376–424.

CHICHILNISKY, G. (1994): “North-South Trade and the Global Environment,” *American Economic Review*, 84(4), 851–74.

CONDE-RUIZ, J., AND V. GALASSO (2005): “Positive arithmetic of the welfare state,” *Journal of Public Economics*, pp. 933–955.

COPELAND, B. R. (2005): “Policy Endogeneity and the Effects of Trade on the Environment,” *Agricultural and Resource Economics Review*, 34(1).

COPELAND, B. R., AND M. S. TAYLOR (2009): “Trade, Tragedy, and the Commons,” *American Economic Review*, 99(3), 725–49.

DIETZ, T., E. OSTROM, AND P. C. STERN (2003): “The Struggle to Govern the Commons,” *Science*, 302(5652), 1907–1912.

FENSKE, J. (2012): “Imachi Nkwu: trade and the commons,” CSAE Working Paper WPS/2012-19.

FERREIRA, S. (2004): “Deforestation, Property Rights, and International Trade,” *Land Economics*, 80(2), 174–193.

GERASIMCHUK, I., AND P. Y. KOH (2013): “The EU biofuels policy and palm oil: cutting subsidies or cutting rainforest,” IISD Research Report.

GORDON, H. S. (1954): “The Economic Theory of a Common-Property Resource: The Fishery,” *Journal of Political Economy*, 62, 124–142.

HARDIN, G. (1968): “The Tragedy of the Commons,” *Science*, 162(3859), 1243–1248.

HASSLER, J., J. V. RODRIGUEZ MORA, K. STORELETTEN, AND F. ZILIBOTTI (2003): “The survival of the welfare state,” *American Economic Review*, 93(1), 87–112.

HOTTE, L., N. V. LONG, AND H. TIAN (2000): “International trade with endogenous enforcement of property rights,” *Journal of Development Economics*, 62(1), 25–54.

HOWARTH, R. B. (1998): “An Overlapping Generations Model of Climate-Economy Interactions,” *Scandinavian Journal of Economics*, 100(3), 575–91.

HOWARTH, R. B., AND R. B. NORGAARD (1992): “Environmental Valuation under Sustainable Development,” *American Economic Review*, 82(2), 473–77.

JOHN, A., AND R. PECCHENINO (1994): “An Overlapping Generations Model of Growth and the Environment,” *Economic Journal*, 104(427), 1393–1410.

JUDD, K. (1998): *Numerical Methods in Economics*. MIT Press, Cambridge, Massachusetts.

KARP, L., AND A. REZAI (2014a): “Pareto-improving climate policy: the role of asset prices,” Working Paper.

——— (2014b): “The political economy of environmental policy with overlapping generations,” *International Economic Review*, p. forthcoming.

KARP, L., S. SACHETI, AND J. ZHAO (2001): “Common Ground between Free-Traders and Environmentalists,” *International Economic Review*, 42(3), 617–47.

KEMP, M. C., AND N. V. LONG (1979): “The Under-Exploitation of Natural Resources: A Model with Overlapping Generations,” *The Economic Record*, 55(3), 214–221.

KLEIN, P., P. KRUSELL, AND J. RIOS-RULL (2008): “Time-consistent public policy,” *Review of Economic Studies*, 75(3), 789–808.

KONAR, S., AND M. COHEN (2001): “Does the market value environmental performance?,” *Review of Economics and Statistics*, 83, 281–289.

LARSON, D. F., AND J. NASH (2010): “Resource Management and the Effects of Trade on Vulnerable Places and People,” World Bank Policy Research Working Paper 5258.

LAURENT-LUCCHETTI, J., AND A. LEACH (2011): “Generational welfare under a climate-change policy with induced innovation,” *Scandinavian Journal of Economics*, 113, 904–936.

LINBECK, A., AND J. WEIBULL (1987): “Balanced budget redistribution as political equilibrium,” *Public Choice*, 52, 273–297.

LINN, J. (2010): “The effect of cap and trade programs on firm profits: Evidence from the Nitrogen Oxides Budget Trading Program,” *Journal of Environmental Economics and Management*, 59(1), 571–591.

LOPEZ, R. (1998): “Agricultural Intensification, Common Property Resources and the Farm-Household,” *Environmental & Resource Economics*, 11(3), 443–458.

——— (2000): “Trade reform and environmental externalities in general equilibrium: analysis for an archetype poor tropical country,” *Environment and Development Economics*, 5(04), 377–404.

MCAUSLAND, C. (2003): “Voting for Pollution Policy: The Importance of Income Inequality and Openness to Trade,” *Journal of International Economics*, 61(2), 425–51.

——— (2008): “Trade, Politics and the Environment: Tailpipe vs. Smokestack,” *Journal of Environmental Economics and Management*, 55, 52–71.

MIRANDA, M. J., AND P. L. FACKLER (2002): *Applied Computational Economics and Finance*. MIT Press, Cambridge, Massachusetts.

MOURMOURAS, A. (1991): “Competitive Equilibria and Sustainable Growth in a Life-Cycle Model with Natural Resources,” *The Scandinavian Journal of Economics*, 93(4), 585–591.

OSTROM, E. (1990): *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge University Press.

——— (2007): “A Diagnostic Approach for Going beyond Panaceas,” *Proceedings of the National Academy of Sciences*, 104(39), 15181–15187.

OTSUKA, K., AND F. PLACE (2001): *Land Tenure and Natural Resource Management*. International Food Policy Research Institute, John Hopkins University Press.

PATTERSON, D., AND J. E. WILEN (1977): “Depletion and Diplomacy: the North Pacific Seal Hunt,” *Research in Economic History*, 2, 81–139.

PERSSON, T., AND G. TABELLIN (2000): *Political Economics - Explaining Economic Policy*. MIT Press, Cambridge.

RUTA, M., AND A. J. VENABLES (2012): “International Trade in Natural Resources: Practice and Policy,” *Annual Review of Resource Economics*, 4(1), 331–352.

TAYLOR, M. S. (2011): “Buffalo hunt: International trade and virtual extinction of the North American bison,” *American Economic Review*, 101, 3162–3195.

A Proofs and Assumption 1

Proof. (Proposition 1) Part (i) follows from the fact that a non-zero tax imposes the usual deadweight loss in current output; a 0-tax maximizes current real income. A higher stock strictly increases the feasible production set. By assumption, both sectors operate. Therefore, the higher stock increases labor productivity, increasing aggregate utility (a first order effect).

Part (ii): Open economy. The equilibrium wage is $w = p(1 - T)\gamma x$. In the open economy, p is fixed, so an increase in the tax reduces w . Equilibrium requires that labor move from sector F to sector M , increasing π , lowering L and current harvest, increasing the next period stock.

Part (ii): Closed economy. For Cobb Douglas preferences, the expenditure share of good F is α , a constant, implying

$$(A1) \quad \frac{M}{pF} = \frac{1 - \alpha}{\alpha}.$$

Using this expression and noting that $p(1 - T)\gamma x = w \implies pF = \frac{wL}{(1-T)}$, the market clearing condition (A1) is:

$$(A2) \quad \begin{aligned} \frac{1-\alpha}{\alpha(1-T)} &= \frac{M}{wL} = \frac{m(1-L)}{-Lm'(1-L)} \\ &= \frac{1}{L\beta} \left(\beta(1-L) + (1-\beta)(1-L)^{\frac{1}{\eta}} \right) \equiv z(L). \end{aligned}$$

The second equality uses the fact that $K = 1$ is fixed (eliminating the argument K in the M -sector production function, m) and the fact that labor in sector M is $1 - L$, so an increase in L decreases the amount of labor in sector M). The third equality uses the constant elasticity of substitution production function. A computation establishes

$$(A3) \quad \frac{dz}{dL} = -\frac{(1-\beta)(\eta(1-L) + L)(1-L)^{\frac{1}{\eta}-1} + \beta\eta}{L^2\beta\eta} \leq 0.$$

The inequality is strict for $\eta > 0$. Taking the differential of the market clearing condition gives $\frac{1-\alpha}{\alpha(1-T)^2}dT = \frac{dz}{dL}dL$. Rearranging and using equation (A3) gives

$$(A4) \quad \frac{dL}{dT} = -\frac{1-\alpha}{\alpha(1-T)^2} \frac{L^2\beta\eta}{(1-\beta)(\eta(1-L)+L)(1-L)^{\frac{1}{\eta}-1} + \beta\eta} < 0$$

As labor leaves sector F and enters sector M , the wage (equal to the marginal product of labor in sector M) falls, and π increases.

Part (iii) is an immediate consequence of the equilibrium condition $w = P(1-T)\gamma x$. The higher stock increases the equilibrium wage, causes labor to move to sector F , and reduces π . The result then follows from the fact that in the open economy, real returns are proportional to nominal returns.

Part (iv) The relation $\frac{1-\alpha}{\alpha(1-T)} = z(L)$ from equation (A2) implies that the equilibrium labor allocation in the closed economy depends on T , but not on the stock, x . Therefore, the higher stock leaves unchanged the nominal returns, w and π . The condition for the equilibrium wage implies $(1-T)\gamma x = \frac{w}{p}$, so the higher stock must reduce the equilibrium price. Consequently, the higher stock must increase both real returns, $p^{-\alpha}w$ and $p^{-\alpha}\pi$.

Assumption 1.iii Using $\frac{d x_{t+1}}{d L_t} < 0$, we restate the monotonicity assumption, $\frac{d x_{t+i}}{d L_t} < 0$ for $i = 1, 2, \dots, H$, as $\frac{d x_{t+1+i}}{d x_{t+1}} > 0$. This inequality holds if and only if $\frac{d x_{t+i+2}}{d x_{t+i+1}} > 0$. In the closed economy, for $\eta = 1$ and $T = 0$, the inequality is satisfied (Karp and Rezaei, 2014) for

$$1 < \varsigma < 2 \text{ with } \varsigma \equiv r + \frac{\beta(1-\alpha) + \alpha(1-\gamma)}{\beta(1-\alpha) + \alpha},$$

provided that the initial condition is “not too large” (in particular, it lies below the level at which $\bar{r}(x_t, 0) = -1$).

In the open economy, also for $\eta = 1$ and $T = 0$, the diversified equilibrium condition

$\beta(1-L)^{\beta-1} = P\gamma x$ implies $L(x) = 1 - \left(\frac{P\gamma x}{\beta}\right)^{\frac{1}{\beta-1}}$. Define

$$J = \left\{ x \left| 1 + \frac{r}{C}(1-2x) - \frac{\gamma}{1-\beta}(1-\beta L(x)) > 0 \right. \right\}$$

Using equation (4) we have

$$\frac{d x_{s+1}}{d x_s} \geq 0 \Leftrightarrow x_s \in J.$$

Assumption 1.iii is satisfied if and only if $x_0 \in J$ and $x_\infty \in J$. Using examples, it is easy to confirm that for some parameters, J is nonempty and $x_\infty \in J$.

Proof. (Lemma 1) (i) By Proposition 1.ii, the current tax lowers current harvest, increasing the next-period stock. By Assumption 1.i-iii, the higher next-period stock increases all future stocks. By Proposition 1.iii, these changes decrease future real returns to capital in the open diversified economy, and by Proposition 1.iv, they increase future real returns to capital in a closed economy. The claim then follows from equation (2).

(ii) The next period utility value of the tax revenue equals $p_{t+1}^{-\alpha} R_{t+1} = T_{t+1} [p_{t+1}^{1-\alpha} L_{t+1} \gamma x_{t+1}]$.

From Proposition 1.ii, the higher current tax decreases current labor and increases the next-period stock, for either an open or closed economy. The next period tax revenue is $R_{t+1} = T_{t+1} p_{t+1} L_{t+1} \gamma x_{t+1}$, and the utility value of next period tax revenue is $p_{t+1}^{-\alpha} T_{t+1} p_{t+1} L_{t+1} \gamma x_{t+1}$. Using the condition for equilibrium wage, $w = p(1-T)\gamma x$ we have

$$p_{t+1}^{-\alpha} R_{t+1} = T_{t+1} \left(\frac{w_{t+1}}{(1-T_{t+1})\gamma} \right)^{1-\alpha} x_{t+1}^{\alpha-1} \gamma L_{t+1} x_{t+1} = T_{t+1} g(T_{t+1}, w_{t+1}, L_{t+1}) x_{t+1}^{\alpha},$$

where we use the definition

$$g(T, w, L) \equiv \left(\frac{w}{(1-T)\gamma} \right)^{1-\alpha} \gamma L > 0.$$

The function g increases in w and L . The proof of Proposition 1.iii establishes that a higher next-period stock increases next-period wage and L in the open economy. Therefore,

$g(T_{t+1}, w_{t+1}) x_{t+1}^\alpha$ is an increasing function of the next period stock in the open economy. For the closed economy, by the proof of Proposition 1.iv, next-period w and L , and therefore g , are independent of next-period stock. Therefore, in this case also, $g(T_{t+1}, w_{t+1}) x_{t+1}^\alpha$ is an increasing function of the next-period stock.

Proof. (Lemma 2) Given Assumption 1.iv, the optimal current tax is positive if and only if

$$\left. \frac{dW_t^j(x_t, T_t)}{dT_t} \right|_{T_t=0} > 0.$$

In both the open and closed economy, the zero-tax maximizes current national income (Proposition 1.i). Consequently $\left. \frac{d(p_t^{-\alpha} Y_t)}{dT_t} \right|_{T_t=0} = 0$. This equality and equation (6) imply

$$(A5) \quad \left. \frac{dW_t^j(x_t, T_t)}{dT_t} \right|_{T_t=0} = \left[\frac{d(p_t^{-\alpha} \sigma_t)}{dT_t} + \frac{1 - \chi_{t+1}}{1 + \rho} \frac{d(p_{t+1}^{-\alpha} R_{t+1})}{dT_t} \right]_{T_t=0}.$$

In the closed economy, the first term on the right side is positive (by Lemma 1.i) and the second is non-negative if $T_{t+1} \geq 0$ (by Lemma 1.ii) Therefore, the derivative is positive if $T_{t+1} \geq 0$. Similarly, for the open economy, the first term on the right side is negative and the second term is non-positive if $T_{t+1} \leq 0$. Therefore, the derivative is negative if $T_{t+1} \leq 0$.

B Supplementary Appendices (For Online Publication)

Supplementary Appendix A. contains details of the numerical algorithm, which relies on standard methods of function approximation. Supplementary Appendix B. describes our sensitivity studies, mentioned in Section V.. Supplementary Appendix C. compares the effect of moving from a closed to an open economy, holding fixed the policy environment (BAU, MPE, and the social planner). We think that the comparison in Supplementary Appendix C. is of general interest, but apart from brief comments, we have taken it out of the paper in order to focus on our principal research questions, and in the interest of brevity.

A. MPE solution algorithm

Agents at time t take the functions $\Upsilon(x_{t+1})$ and $\sigma(x_{t+1})$ as given, but they are endogenous to the problem. We solve $\max_T W(x, T)$ using a standard dynamic programming algorithm. An arbitrary policy function, $\Upsilon^k(x_t)$, induces the real asset price, $\sigma^k(x_t, T_t)$, given by equation (8); the superscript k denotes the functional dependence of $\sigma^k(x_t, T_t)$ on the function $\Upsilon^k(x_t)$. Replacing $\sigma(x_t, T_t)$ with $\sigma^k(x_t, T_t)$ and W_t with W_t^k in the maximand, we denote

$$\Upsilon^{k+1}(x) = \arg \max_T W^k(x, T).$$

This relation is a mapping from Υ^k to Υ^{k+1} . An equilibrium Υ is a fixed point to this mapping, which we approximate using the collocation method and Chebyshev polynomials (Judd, 1998; Miranda and Fackler, 2002)

Infinite horizon models (but not finite horizon models) of this genus typically have multiple equilibria. Experiments suggest that our numerical approach always returns a unique equilibrium. An algorithm that iterates over the value function can be interpreted as the limit as the horizon goes to infinity of a finite horizon model. In view of the generic uniqueness of finite horizon models, the (apparent) uniqueness of the numerical results is not surprising.

To simplify notation, we introduce a new function, the value of the asset in units of utility (rather than in units of the numeraire good):

$$\bar{\sigma}(x_{t+1}, \Upsilon(x_{t+1})) = p^{-\alpha}(x_{t+1}, \Upsilon(x_{t+1})) \sigma(x_{t+1}, \Upsilon(x_{t+1})).$$

We approximate $\Upsilon(x_{t+1})$ and $\bar{\sigma}(x_{t+1}, \Upsilon(x_{t+1})) \equiv \Phi(x_{t+1})$ as polynomials in x_{t+1} , and find coefficients of those polynomials so that the solution to

$$\max_{T_t} P^{-\alpha}(x_t, T_t) Y(x_t, T_t) + \frac{1}{1+\rho} \{P^{-\alpha}(x_{t+1}, \Upsilon(x_{t+1}))\pi(x_{t+1}, \Upsilon(x_{t+1})) + \Phi(x_{t+1})\}$$

subject to equation (4) approximately equals $\Upsilon(x_t)$. We use Chebyshev polynomials and Chebyshev nodes. At each node, the recursion defining $\bar{\sigma}(x_{t+1}, \Upsilon(x_{t+1}))$,

$$(B1) \quad \Phi(x_t) = \frac{1}{1+\rho} \{p^{-\alpha}(x_{t+1}, \Upsilon(x_{t+1}))\pi(x_{t+1}, \Upsilon(x_{t+1})) + \Phi(x_{t+1})\}$$

and the optimality condition

$$(B2) \quad \frac{d}{dT_t} \left[P^{-\alpha}(x_t, T_t) Y(T_t) + \frac{1}{1+\rho} \Omega \right] = 0,$$

with

$$\Omega \equiv \{P^{-\alpha}(x_{t+1}, \Upsilon(x_{t+1}))\pi(\Upsilon(x_{t+1})) + \Phi(x_{t+1})\}$$

must be satisfied.

Starting with an initial guess for the coefficients of the approximations of $\Phi(\cdot)$ and $\Upsilon(\cdot)$, we evaluate the right side of equation (B1) for at each node. Using these function values, we obtain new coefficient values for the approximation of $\Phi(\cdot)$. We then use the optimality condition (B2) to find the values of $\Upsilon(\cdot)$ at each node; we use those values to update the

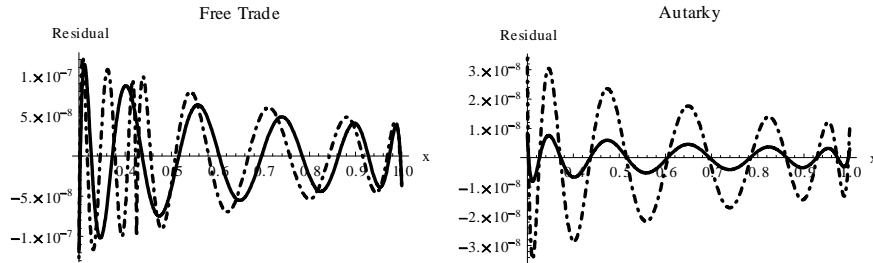


Figure 4: Approximation error for asset price function (LHS-RHS of (B1)): the MPE (solid) and the social planner's (dot-dashed) problems, the open economy (left) and closed economy (right).

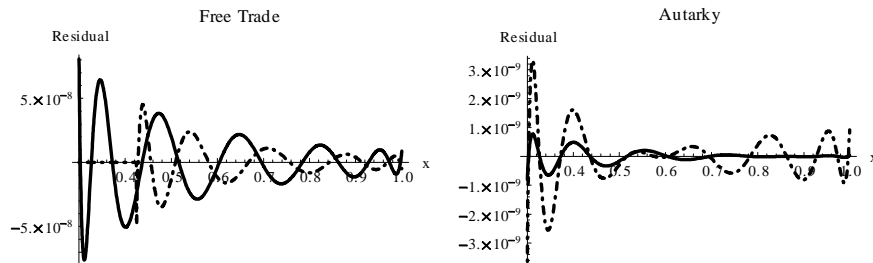


Figure 5: Approximation error for asset price function (LHS-RHS of (B2)): the MPE (solid) and the social planner's (dot-dashed) problems, the open economy (left) and closed economy (right).

coefficients for the approximation of $\Upsilon(\cdot)$. We repeat this iteration until the coefficients' difference between iterations, relative to the estimated value of the coefficient, falls below 10^{-6} . See chapter 6 of Miranda and Fackler (2002) for details.

The social planner's solution involves a prohibitive tax under free trade. We approximated the point of specialization through numerical experiments and at first limited the approximation space to the range of diversified production $x \in [0.4246, 1]$. Under a prohibitive tax, this set also contains all x_{t+1} for $x_t \in [0.3, 0.4146)$. Given the approximations of $\Phi(\cdot)$ and $\Upsilon(\cdot)$ for the set of diversified production, one can use recursion (B1) to approximate $\Phi(\cdot)$ for the range of specialized production. As $\Phi(\cdot)$ might not be smooth at $x = 0.4246$, we used separate polynomials for the ranges of diversified and specialized production.

Figures 4 and 5 graph the differences (the “residuals”) between the right and left sides of equations (B1) and (B2), respectively. These residuals equal 0 at the nodes, because we set both the degree of the polynomial and the number of nodes equal to n . We choose $n = 12$, yielding residuals are at least 6 orders of magnitudes below the solution values on the $[0.3, 1]$ interval. In the case of a social planner in the open economy, we chose $n = 10$ for $x \in [0.4246, 1]$ interval and $n = 6$ for $x \in [0.3, 0.4246]$.

Given the assumption of Cobb Douglas production in the numerical simulations, we can utilize the following equilibrium expressions for the closed economy:

$$L = \frac{1 - T}{\frac{1-\alpha}{\alpha}\beta + 1 - T}; w = \beta \left(1 + \frac{1 - T}{\frac{1-\alpha}{\alpha}\beta}\right)^{1-\beta}; p = \frac{w}{(1 - T)\gamma x} = \frac{\beta \left(1 + \frac{1 - T}{\frac{1-\alpha}{\alpha}\beta}\right)^{1-\beta}}{(1 - T)\gamma x}.$$

B. Numerical sensitivity

Corollary 2 establishes that, except for the last period, the equilibrium policy is a sequence of subsidies under trade and of taxes in the closed economy. The numerical results reported in the text show that these qualitative differences also hold in the MPE, where cannot establish the result analytically. To confirm that our numerical results (a sequence of subsidies in the open economy and of taxes in the closed economy) are not an artifact of one particular parameter set, we conduct extensive parameter sensitivity analysis. We define the following values for the model’s parameters (with bold numbers indicating the baseline value used in the text), and determine the corresponding equilibrium policy for each combination

of parameters that satisfy certain restrictions described below.

$$\alpha = \{0.1, 0.3, \mathbf{0.5}, 0.7, 0.9\}$$

$$\rho = \{0.1, \mathbf{0.41}, 0.7\}$$

$$\beta = \{0.4, \mathbf{0.5}, 0.6\}$$

$$r = \{0.1, 0.5, \mathbf{0.68}, 0.9, 1.1\}$$

$$\gamma = \{0.1, 0.3, \mathbf{0.513}, 0.7, 0.9\}$$

$$P = \{1, 2, 3, \mathbf{3.377}, 4, 6, 9\}$$

In the sensitivity runs we set $\chi = 1$ and reduce the number of collocation points to 8.

For both the open and closed economy, we include only parameters that, under BAU, lead to monotonic adjustment (the BAU x_{t+1} is an increasing function of x_t , and crosses the 45° line with slope less than 1). For the open economy, we additionally restrict parameter combinations so that at a particular value of x the BAU economy is diversified. Under specialization, equilibrium policy is indeterminate, so we do not consider that case. For lower values of x , this “diversification restriction” is more binding, so our open economy results use few combinations of parameters, the smaller is x . We used the state space $x \in [0.05, 1]$.

Given that the MPE only involves expressions in utility, the value of α has no effect on the open economy equilibrium ($P^{-\alpha}$ reduces to a scaling parameter). We hold α constant at the baseline value, $\alpha = 0.5$, and begin with $3 \times 3 \times 5 \times 5 \times 7 = 1575$ combinations of parameter values. Of these, 915 combinations lead to monotonic BAU growth paths. At $x = 0.9$, there are 813 parameter combinations that imply both monotonic BAU paths and diversification; at $x = 0.1$, there are 120 such parameter combinations (see legend of left panel in figure 6).

For the closed economy, α affects the equilibrium, but the world price parameter becomes endogenous. We therefore begin with $5 \times 3 \times 3 \times 5 \times 5 = 1125$ parameter combinations. Of these, 1065 parameter combinations lead to monotonic BAU adjustment; 780 combinations lead to both monotonic BAU adjustment and BAU steady states in the interval $[0.05, 0.95]$.

Distribution of $\Upsilon[x]$'s for $x \in [0, .1, .2, \dots, 1]$

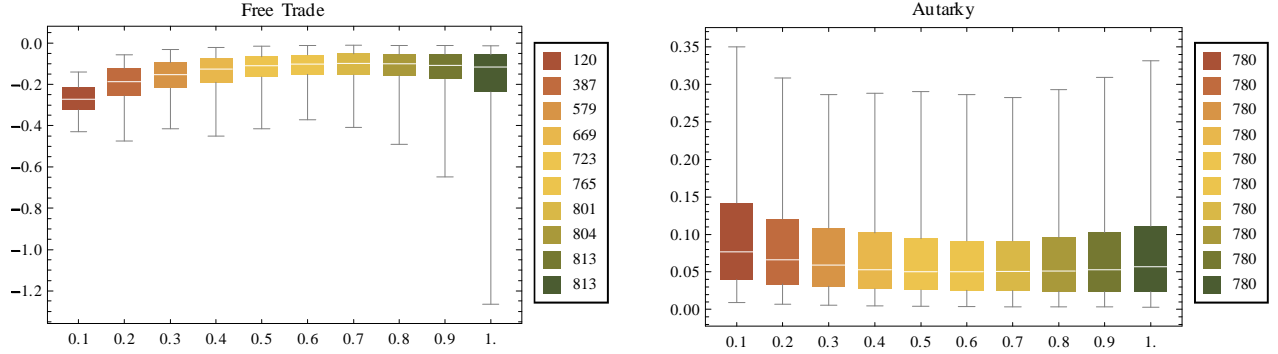


Figure 6: Parameter sensitivity of MPE: box-whisker plots of distribution of policy, T , as a function of the resource stock, x , for free trade (left panel) and autarky (right panel)

Figure 6 shows box plots for the distribution of the equilibrium policy, at different values of x . For all parameter combinations included in these plots, the policy is a subsidy for the open economy and a tax for the closed economy. The numbers at the right of each figure show the number of parameter combinations used for each value of x ; this number increases with x in the open economy (as production becomes diversified in more cases) and is constant in the closed economy. Each box contains the middle quartiles (Q2 and Q3, 25%-75%) while the lower and upper whiskers give Q1 (0%-25%) and Q4 (75%-100%). The white line in the box shows the median subsidy/tax for a given value of x . The sensitivity results summarized in Figure 6 confirm that the equilibrium in the open economy involves a subsidy, and the equilibrium in the closed economy involves a tax for a large parameter space. In summary, we do not find any parameter combinations that overturn these results; but we did not consider combinations that violate the monotonicity and diversification (under BAU) restrictions.

C. Further Discussion of Numerical Results

Figure 7 shows the welfare effect of changing the trade regime, holding fixed the policy regime: BAU, MPE, and social planner. Here we use the baseline parameters from the text, and set $\chi = 1$. The horizontal axis (labelled i) shows the number of periods from the time

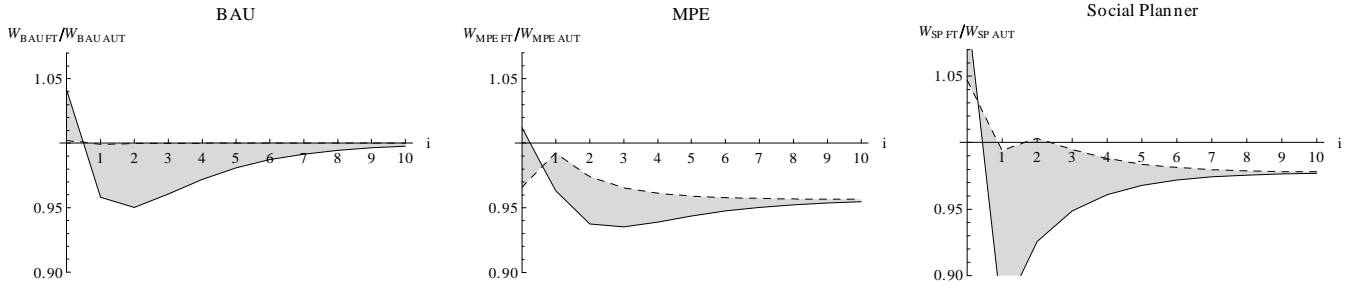


Figure 7: Welfare in the open relative to the closed economy under BAU (left), MPE (center) and social planner (right), with the initial resource stock $x_0 = 0.5$ (dashed) and $x_0 = 0.9$ (solid).

at which the closed economy opens to trade. The left panel shows the ratio of open-economy to closed economy welfare under BAU; the middle panel shows this ratio in the MPE, and the right panel shows this ratio under the social planner. As in the text, the dashed curve shows the ratio given the initial condition $x = 0.5$, and the solid curve gives the ratio at initial condition $x = 0.9$.

Under BAU, both open and closed economies have the steady states $x = 0.5$, so at this value, opening the closed economy has no effect (the welfare ratio equals 1). If the initial stock is high, current generations have higher welfare under trade. At stocks above the steady state, the domestic price is below the world market price. The higher price leads to high extraction in the current period and lower ones in subsequent ones, increasing aggregate welfare of currently living agents ($i = 0$) and lowering welfare of each future young generation.

In the MPE, all generations are worse off in the open economy, except possibly the first generation if initial stocks are large (Figure 7 middle panel). The economy reaps the standard static gains from trade, but trade reverses the incentives to protect the resource stock. The lower resource stock lowers future generations' welfare. If the initial stock is high, then the initial closed economy price is low. In this case, the standard gains from trade may be large enough that trade improves welfare for those alive in the first period. However, for

most initial stock levels, and for all future generations, the switch from resource protection to increased exploitation is more important than the standard gains from trade; here, trade lowers welfare.

Under the social planner, opening up to trade puts the economy in a first best world and necessarily increases the present discounted sum of welfare, but need not increase welfare for every generation. The right panel of Figure 7 shows that trade lowers welfare for most future generations. The trade-induced fall in future generations' welfare comes from the fact that single period utility is linear in income. With a constant commodity price, the planner has no incentive to smooth consumption. Comparison of panels *c* and *d* of Figure 1 shows that trade increases the asset price. The old generation in the first period captures all of these capital gains, which exceed 100% of the gains from trade.