

Trade and Resource Sustainability with Overlapping Generations*

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Abstract

Trade changes incentives to protect an open-access natural resource. In an OLG setting, the capital asset market transfers policy-induced future gains and 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. In a dynamic political economy, agents without bequest motives choose resource-protecting policies in both the open loop and Markov Perfect equilibria under autarchy; in the open economy agents choose policies exacerbating the open-access distortion, harming the resource. The difference arises from the interplay of the asset market and general equilibrium effects. Trade generally lowers welfare.

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1 Introduction

Societies manage their natural resources under different types of property regimes, ranging from restricted access with private property or government control, to common property and open access. Decades of research, pioneered by Ostrom (1990, 2007), challenge the view that strong property rights are needed in order to avoid the Tragedy of the Commons (Hardin, 1968; Gordon, 1954). In many cases, common property institutions successfully manage natural resources. These institutions tend to be more to be effective if the socio-ecological system changes only slowly, outsiders can be easily prevented from using the resource, and communities accept monitoring and enforcement, often using face-to-face communication. Abrupt changes, such as those arising when a closed economy opens to international trade, might erode common property management regimes, but in other cases it can increase the value of a resource, encouraging sustainable management (Copeland, 2005). We provide a novel perspective on the relation between trade and endogenous resource management in the absence of formal property rights.

Most case studies of common property resource management involve communities that consume the resources they extract. International trade, by connecting a resource such as fisheries, forests, or aquifers to a larger system, weakens or breaks the connection between extraction and local consumption, possibly complicating the governance problem (Dietz et al., 2003). Econometric studies find mixed evidence of the relation between trade and resource depletion (López, 1998, 2000; Benhin and Barbier, 2001; Ferreira, 2004).

We examine the relation between trade and endogenous resource management using a general equilibrium overlapping generations model, in which production uses a natural resource, privately owned capital, and mobile labor.¹ In the absence of any social control, there is open access to the natural resource, leading to excessive

¹Natural resource and environmental applications of OLG models begin with Kemp and Long (1979). Most subsequent contributions study sustainability and the correction of environmental externalities under a social planner instead of a political economy (game) setting (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.

exploitation. A political process enables self-interested agents to limit their own – but not their successors’ – use of the resource. Under the political economy autarchic equilibrium, agents limit resource depletion to near socially optimal levels. Trade causes these selfish agents to adopt environmentally destructive policies.

A Ricardo-Viner model enables us to trace the general equilibrium channels through which trade affects incentives to protect the natural resource. The resource sector uses a common-pool natural resource and mobile labor, and the manufacturing sector uses a privately owned asset and mobile labor. In a closed economy, the link between resource stocks and product prices gives consumers a reason to care about the resource stock. Trade breaks this link.

For both trade regimes, a higher stock of the natural resource attracts labor to the resource sector, increasing the equilibrium wage and decreasing the equilibrium return to capital. Under trade, with fixed commodity prices, nominal changes are proportional to real changes. In the closed economy, the endogenous commodity price depends on the resource stock. A higher resource stock increases the real returns to both labor and capital. Trade thus changes the relation between resource stocks and real factor returns. The real price of the privately owned asset depends on future real returns. By changing the relation between resource stocks and real returns, trade also changes the relation between resource stocks and the real price of the privately owned asset. In the closed economy, a higher resource stock increases the real price of the asset, and under trade the higher resource stock has the potential to decrease this asset price. These comparative static results are quite general. We show how they influence the equilibrium protection of the resource in a particular political economy setting.

Our key political economy assumption is that currently living agents can coordinate on their own use of the resource, but they cannot determine their successors’ policies. Agents in our setting use a resource tax/subsidy, but variations of the model could handle other policy instruments. Because agents coordinate within a period, they choose the current resource tax or subsidy to maximize their joint welfare. Their equilibrium choice depends on the effect of resource policy on asset prices. That effect depends directly on the trade regime, and also on future policies that emerge

from the political economy equilibria involving future agents. Current and future agents play a sequential-move game, with linkages arising through the overlapping generations structure, the asset price, and the resource stock. We provide analytic results for (time-consistent) open loop equilibria and numerical results for (subgame perfect) Markov equilibria. For both of these equilibria, consensus decision-making in the closed economy limits resource extraction; in the open economy the equilibrium policy is a subsidy that exacerbates the Tragedy of the Commons.

Our dynamic model builds on Hassler et al. (2003), Conde-Ruiz and Galaso (2005) and Klein et al. (2008), papers that study dynamic games in OLG settings. Related models study dynamic recursive bargaining (Sorger, 2006). We extend Karp and Rezaei (2013), which studies a closed economy equilibrium. Our paper is the first to apply game-theoretic analysis in a model of asset prices, trade, and natural resources. Recent empirical studies find significant links between environmental policy and stock prices (Konar and Cohen, 2001), house prices (Chay and Greenstone, 2005), and firm profits (Linn, 2010; Bushnell and Mansur, 2013).²

We emphasize the setting where agents have no bequest motives. For comparison, we also consider the case where people apply the same discount rate to their successors' and to their own future utility, i.e. they have a perfect bequest motive. Here, the OLG model is equivalent to the Infinitely Lived Agent (ILA) model. This agent solves a standard optimization problem, not a game. Even here, the asset market plays an important role. For example, trade increases the present discounted stream of the ILA's welfare; however, the asset market enables the generation who owns the asset at the time trade begins to capture most of these welfare gains. Opening the economy to trade can lower most future generations' welfare.

Most previous models of the relation between trade and resource use take governance institutions as given and examine the effect of trade liberalization on a static

²These empirical papers measure direct connections between the environmental outcome or policy and the asset price or profit level. The links that we study are indirect, operating only through general equilibrium (factor market) channels, and are therefore likely to be harder to measure econometrically. In addition, the environmental outcomes or policies in the empirical settings above are (plausibly) exogenous to the asset price or profit level, whereas in our setting, the policies are endogenous.

equilibrium or a sequence of static equilibria (Chichilnisky, 1994; Brander and Taylor, 1997a,b, 1998; and Karp et al., 2001).³ Hotte et al. (2005) and Copeland and Taylor (2009) are notable exceptions, in considering endogenous property rights with decision-makers who take into account the resource dynamics. Both papers consider an ILA (private resource owners in the former and a social planner in the latter) and they study the comparative statics of the steady state of the respective optimal control problems. The single decision-maker in these models chooses policies in the current and all future periods. In both settings, the potential for poaching (imperfect monitoring) causes the policy maker to inhabit a second-best world. We abstract from these admittedly important monitoring issues in order to study the effect of trade when policy emerges in a political economy setting with forward-looking agents who are unable to commit their successors to particular actions. We are interested in the transitional dynamics, not just the steady state.

In summary, we model an economy with mobile labor and two sector-specific factors, privately owned capital and a common-pool resource. For reasons outside the model, there are perfect property rights for the former and none for the latter. Protection of the resource requires that people currently living coordinate on their use of the resource stock. These people correctly anticipate, but do not control, their successors' actions. We study the effect of international commodity trade on endogenous resource governance and find that, by altering the relation between resource stocks and the price of the privately owned asset, trade significantly changes incentives to protect the resource, for reasons previously not recognized.

2 Model

We first describe the model and show that resource protection has the same qualitative effect on real returns to capital and labor in the closed economy, but opposite

³In this class of models, trade (typically) improves short run welfare but, over time, the trade-induced fall in the open-access resource stock can lower welfare. If the world price is only slightly higher than the closed economy price, then the standard gain from trade is small, but the worsening open-access problem is non-negligible. In this case, trade reduces long run aggregate welfare. Bulte and Barbier (2005) and Ruta and Venables (2013) review this literature.

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 3). Understanding those incentives helps explain the relation between the trade regime and resource management in the subgame perfect equilibrium setting (Section 4).

2.1 Fundamentals

The OLG economy consists of a manufacturing sector, M , and a resource sector, F , and, in each period, of a pair of old and young generations. Capital and labor stocks are constant, both normalized to 1. Labor is mobile across sectors, capital is specific to sector M , and the resource stock, x_t , is specific to sector F . With L_t units of labor in sector F , production equals $F_t = \gamma L_t x_t$ with $\gamma > 0$, and $M_t = m(L_t, K) = \left[\beta (1 - L_t)^{1-\frac{1}{\eta}} + (1 - \beta) K^{1-\frac{1}{\eta}} \right]^{\frac{1}{1-\frac{1}{\eta}}}$ with $0 < \beta < 1$ and $\infty > \eta > 0$. When sector M operates, the restriction $\eta < \infty$ implies that sector M employs some labor and the restriction $\eta > 0$ implies that capital is fully employed ($K = 1$) and receives positive rents. Open access eliminates rent in the resource sector. Manufacturing is the numeraire good, and p_t is the relative price of F in period t . In a closed economy, the price is a function of the resource stock, x_t , and the resource tax, T_t : $p_t = p(T_t, x_t)$. In a small open economy, p_t is a constant, P . We use p_t to denote the price in the generic case, and when no confusion results, we suppress time subscripts.

Factor returns and policy Open access results in too much labor in the resource sector. Society can manage resource use by imposing an ad-valorem tax, T_t , on production of good F (a “resource tax”). Resource-sector workers receive revenue $(1 - T_t)p_t L_t \gamma x_t$. Society returns the tax revenue, $R_t = T_t p_t L_t \gamma x_t$, in a lump sum, giving the fraction $\chi_t \in [0, 1]$ to the young generation 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.

In a diversified economy, workers are indifferent between working in either sector. An open economy might specialize in the manufacturing sector, but, because of manufacturing rents, it never specializes in the resource sector. The equilibrium

wage is $w_t = p_t(1 - T_t)\gamma x_t$ if the economy is diversified, and $w_t = m_L(1, 1)$ if the economy specializes; $p_t(1 - T_t)$ is the relative producer price of good F . Given a labor allocation, the equilibrium rental rate is $\pi_t = m_K(L_t, 1)$. The price of the manufacturing asset, capital, is σ_t .

Dynamics Agents live for two periods and have 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, $v(e, p) = p^{-\alpha} e^\alpha$, is linear in expenditures. The old agent owns the manufacturing asset, and the young agent owns labor. A young worker divides income, $w_t + \chi_t R_t$, into current consumption and saving for retirement, achieved by purchase of shares ($s_t \in [0, 1]$) 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 $e_t^o = (1 - \chi_t) R_t + s_{t-1} (\pi_t + s_t \sigma_t)$. Her 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

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

Given that the old generation's 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 $H \leq \infty$, we obtain, through repeated substitution, the price equation for capital:

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

For $t < H$, the price of capital (measured in units of good M) equals the present discounted stream of future real returns, converted to current numeraire units. If $H < \infty$, then $\sigma_H = 0$, i.e. the asset has no value in the final period.

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

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

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 in any period. 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 natural resource stock is predetermined in each period, but changes endogenously over time. The stock obeys a logistic growth function,

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

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

Given a sequence of taxes, $\{T_{t+i}\}_{i=0}^H$, a competitive equilibrium is defined by a sequence of the environmental stock, $\{x_{t+i}\}_{i=0}^H$, allocations (consumption, labor, and tax revenue) $\{c_{F,t+i}, c_{M,t+i}, L_{t+i}, R_{t+i}\}_{i=0}^H$, and prices (commodity, factor and asset prices), $\{w_{t+i}, \pi_{t+i}, \sigma_{t+i}\}_{i=0}^H$. The asset price sequence $\{\sigma_{t+i}\}_{i=0}^H$ satisfies equation (2) and the resource stock sequence satisfies equation (4). In each period: the rental rate for capital π_t equals its marginal product $m_K(L_t, 1)$; labor earns its marginal

product, and in a diversified economy, labor is indifferent between working in either sector ($m_L(L_t, 1) = w_t = p_t(1 - T_t)\gamma x_t$); consumers maximize their utility, allocating the fraction α of expenditures to the resource good; in the closed economy, product markets clear, and in the open economy trade is balanced; and the tax revenue is $R_t = T_t p_t L_t \gamma x_t$.

2.2 Comparative statics

Here we present the comparative statics of this model; we use these results below to determine the tax policies in a political economy equilibrium. Real factor returns, $p^{-\alpha}w$ or $p^{-\alpha}\pi$, equal the amount of utility that 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 in a period. Appendix A establishes:

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 , 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.*

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 reduction in this utility. An increase in the 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

the open economy, real factor returns equal nominal factor returns multiplied by the constant $P^{-\alpha}$. From the equilibrium condition $w_t = P(1 - T_t)\gamma x_t$, the higher stock increases the nominal (and real) wage, thereby decreasing the nominal (and real) return to capital. In a closed economy, a larger stock makes labor more productive in sector F , increasing the nominal wage and reducing the equilibrium price, thereby unambiguously increasing the real wage. 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 , because it increases w , but it also lowers p . For Cobb Douglas preferences, on balance the higher stock increases the real return to capital.⁴

3 Open loop Political-Economy 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. We begin with a simpler question: How does the trade regime influence agents' incentives to choose a policy in the current period, when they take as given future taxes or subsidies? That is, here we consider an *open loop* Nash equilibrium; this equilibrium is time consistent but not subgame perfect. Using the comparative statics in Proposition 1, we find that with any open loop equilibrium in the closed economy, 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. In section 4 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 $p_t = p(x_t, T_t)$. This price is a constant, $p_t = P$, in the open

⁴We can show that this relation also holds 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 are not needed for the results.

economy, and it is a function in the closed economy. The nominal value of aggregate income in period t 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 $p^{-\alpha}(x_t, T_t)Y(x_t, T_t)$. 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 optimal current revenue share and tax, therefore, 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 (see Rausser et al., 2010, for recent applications) and a probabilistic voting model (as in Lindbeck and Weibull, 1987, or Perrson 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 optimal revenue split, χ_t^* , is

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

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 .

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 essentially only creates a transfer 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 :

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

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. Hereafter, we use the function W_t rather than \tilde{W}_t .

Our goal here is to obtain intuition about the subgame perfect political economy equilibrium, where agents are fully rational in managing the resource. To achieve this goal, we put a premium on simplicity, and adopt:

Assumption 1 (i) *The taxes are constrained to lie in the interval $[-\varepsilon, \varepsilon]$ with $\varepsilon > 0$.* (ii) (**Diversification**) *For all taxes in this interval, the open economy remains diversified.* (iii) (**Monotonicity**) *For all taxes in this interval, 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 all taxes in this interval, the maximand $W_t(x_t, T_t)$ is concave in T_t .*

Large taxes might induce large changes in the stock. Assumption 1.i enables us to restrict attention to small policy-induced changes in the stock. Assumption 1.ii allows us to focus on the interesting cases, where the economy is diversified, i.e. the resource sector is active. The monotonicity assumption is the most problematic. For the closed economy, we can find parameter restrictions that guarantee monotonicity under the zero tax (“Business as Usual”, or BAU), and thus also for small ε . Analogous restrictions for the open economy involve both model parameters and the world

price, and cannot be stated in a simple (useful) manner. Assumption 1.iii enables us to circumvent this complication. Assumption 1.iv enables us to determine the sign of the optimal policy by evaluating the derivative of welfare at a zero tax.⁵ Assumption 1 means that the analytic results of this section tell us whether the equilibrium taxes are positive or negative, given that they are restricted to be small.

Our chief analytic result relies on 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, with ε small, 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 $T_{t+1} > 0$.*

Proof. See Appendix A. ■

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

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

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 $T_{t+1}^{\text{open}} \leq 0$.*

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

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

⁵Extensive numerical results, described in Appendix B.2, 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.

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

$$\left. \frac{dW_t^j(x_t, T_t)}{dT_t} \right|_{T_t=0} = \left[\frac{d(p_t^{-\alpha} \sigma_t)}{dT_t} + \frac{1 - \chi_{t+1}}{1 + \rho} \frac{d(p_{t+1}^{-\alpha} R_{t+1})}{dT_t} \right]_{T_t=0}. \quad (8)$$

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 $T_{t+1} \leq 0$. ■

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 ${}^h T \in \mathbf{T}^H$ is the tax used when there are h periods to go. (We place the superscript h to the left in order to avoid confusion with the index 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 ${}^h T \in \mathbf{T}^H$ 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 .*

Except in knife-edge cases, 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 our chief analytic result:

Proposition 2 *Under Assumption 1, with small ε and small δ , 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.

We use the function \tilde{W}_t instead of its approximation, W_t , to determine the equilibrium χ_t . Equation (5) and Proposition 2 imply

Corollary 1 *Under Assumption 1, with small ε and small δ , 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. Future policies affect the current asset value, thus affecting current welfare.

The OLNE analysis helps to show how incentives to protect the resource differ in closed and open economies. 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. The change in the asset price enables current agents to obtain some of those future benefits. In this case, the current policy increases the “intertemporal pie”, and enables those currently living to obtain some of this surplus. 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. Using a specialization of our model (with $\eta = 1$), Karp and Rezai (2013) show that 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, by Proposition 2. This fact tends to increase future young generations' welfare. However, the future taxes lower the real wage of these agents, 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 young generations' welfare. However, the future subsidies to the resource sector increase their wage, again making the welfare comparison ambiguous.

International factor mobility Introducing frictionless international factor mobility modifies but does not reverse Proposition 2. If capital is freely traded, then the world market fixes both its rental rate and price. If labor is internationally mobile, then the international labor market fixes the wage rate and, with it, capital’s rental rate and price. If both factors are freely traded, the world markets again fix factor prices. In all three cases, the first term on the right side of equation (8) equals 0 in the open economy, leaving only the second term to possibly be non-zero. However, because it is optimal to use a zero tax in the last period of the finite horizon game, backward induction implies that it is optimal to use a zero tax in every period. Thus, if opening the economy leads to free flow in commodities and either or both factor(s), agents have no incentive to use a resource policy. In this case, opening a previously closed economy eliminates the (closed economy) resource tax, replacing it with a zero tax (rather than a subsidy, as in the absence of trade in factors). Hereafter, we continue to assume that opening the economy means free trade in commodities, not in factors.

4 Markov Perfect Political-Economy 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”. Here, the only such variable is 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 allow us to compare welfare across policy and trade regimes.

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:

$$p_t^{-\alpha}(x_t, T_t) \sigma(x_t, T_t) = (1 + \rho)^{-1} \{p_{t+1}^{-\alpha}(x_{t+1}, \Upsilon(x_{t+1})) [\pi(x_{t+1}, \Upsilon(x_{t+1})) + \sigma(x_{t+1}, \Upsilon(x_{t+1})))]\}. \quad (9)$$

Equation (9) repeats the equilibrium savings condition, equation (1), showing 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 (9), 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.1.

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 (equivalently, 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 (Schneider, Traeger and Winkler, 2012). This planner has a standard (time consistent) control

problem:

$$\max_{\{T_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} (1 + \rho)^{-t} p(x_t, T_t)^{-\alpha} Y(x_t, T_t) \quad (10)$$

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

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 $\gamma = 0.513$. The productivity parameter γ equals the inverse of the amount of labor that would exhaust the resource in a single period, starting from the carrying capacity $x = 1$; with $\gamma < 1$ it is not feasible to drive the stock to extinction in a single period. We set the world price at $P = 3.377$, implying that the open and closed economy steady states are equal under BAU. System (11) collects these baseline parameter values:

$$\alpha = 0.5; \beta = 0.5; \eta = 1; \rho = 0.41; r = 0.68; \gamma = 0.513; P = 3.377. \quad (11)$$

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. The baseline results we report here are representative of those from a much larger set of parameter values reported appendix B.2.

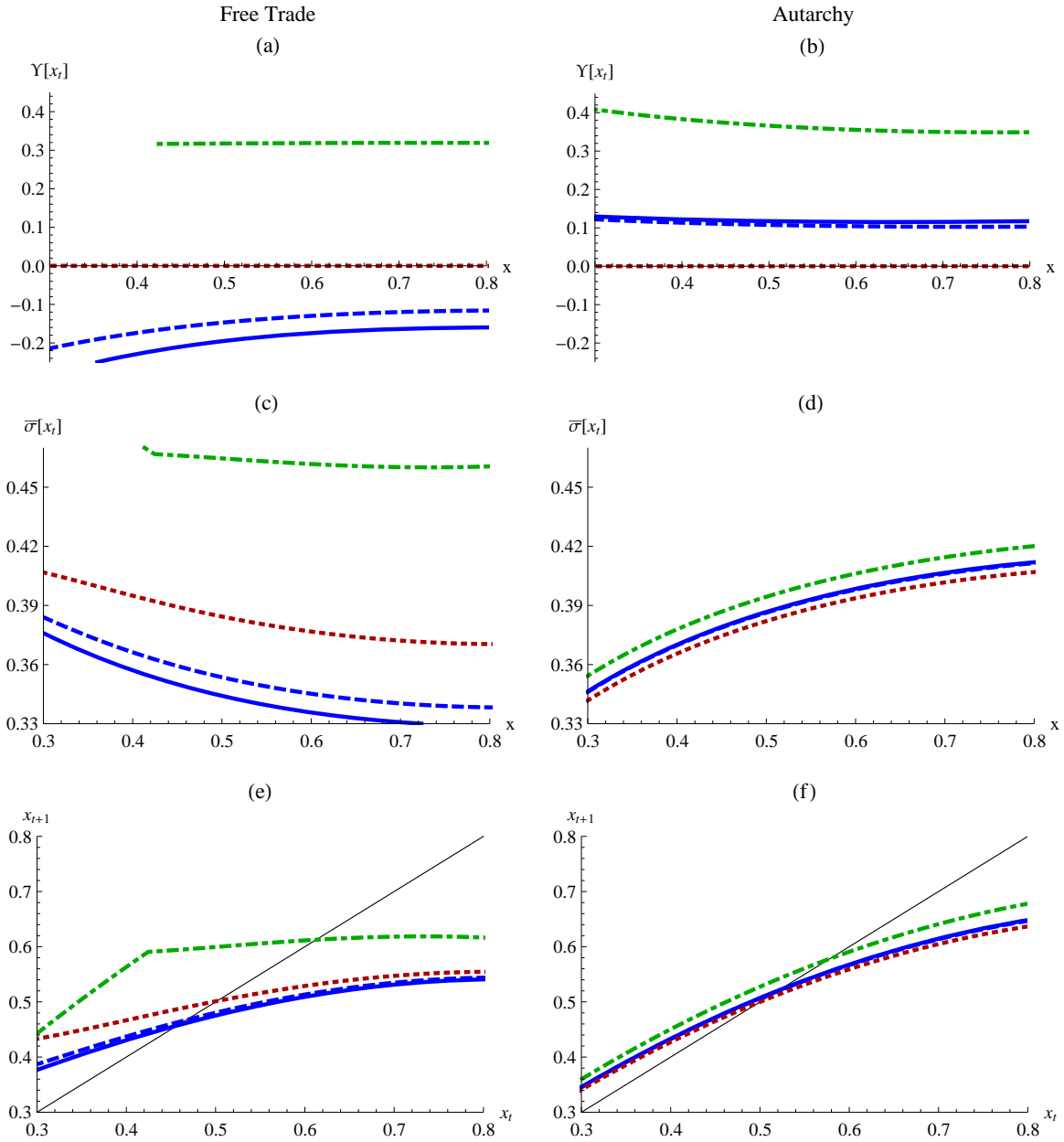


Figure 1: Left panels correspond to free trade and right panels to autarchy. Dashed graphs correspond to $\chi = 1$ and solid graphs to $\chi = 0$ in the MPE. Dotted graphs correspond to BAU and dot-dashed to social planner. The top panels show policy functions, the middle panels show the utility-denominated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

4.1 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.

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° 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 suddenly open to trade at this value of the stock, 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 fig. 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 cap-

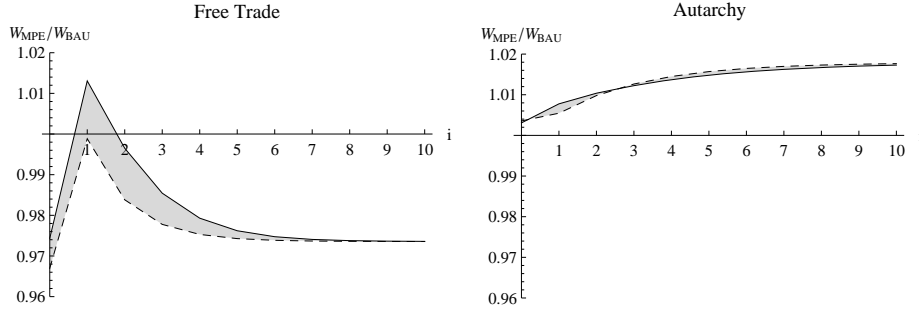


Figure 2: Welfare in MPE relative to BAU with initial resource stock $x_0 = 0.5$ (dashed) and $x_0 = 0.9$ (solid); free trade left panel and autarchy right panel, for $\chi = 1$. Period 0 shows combined lifetime welfare of old and young; subsequent periods show lifetime welfare of young.

ital loss; see the comment below 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.3 further discusses the welfare effects of trade liberalization (holding the policy regime fixed).

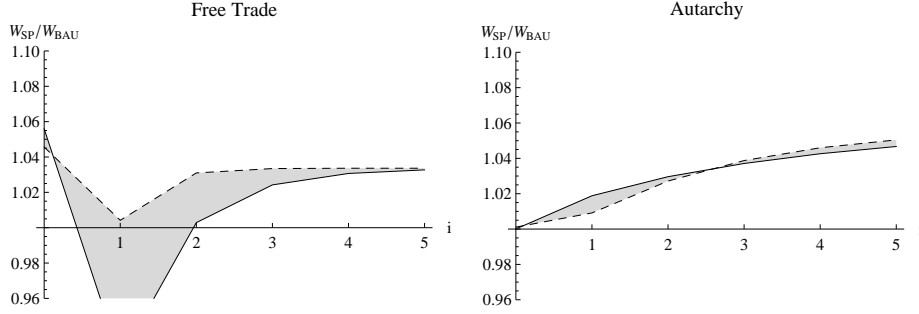


Figure 3: Welfare under the social planner relative to BAU with the initial resource stock $x_0 = 0.5$ (dashed) and $x_0 = 0.9$ (solid) for free trade (left) and autarchy (right).

4.2 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 uses a resource tax; in both trade regimes, the equilibrium stock and tax trajectories are higher under the either 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 (10), 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 only remaining distortion, and necessarily increases the planner's 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.3 contains further discussion of the welfare effects of trade liberalization.

5 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 the resource stock and policy 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 (of course) 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 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. Free factor mobility modifies but does not reverse our results. Allowing capital and/or labor to move freely, fixes the asset price and eliminates agents' incentives to use a resource policy. In this open economy, equilibrium policy is a 0 tax (instead of a subsidy) under open-loop or Markov perfection rather than a subsidy.

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 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.

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A Proofs

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

$$\frac{M}{pF} = \frac{1 - \alpha}{\alpha}. \quad (12)$$

Using this expression and noting that $p(1 - T)\gamma x = w \implies pF = \frac{wL}{(1-T)}$, the market clearing condition (12) is:

$$\begin{aligned} \frac{1-\alpha}{\alpha(1-T)} &= \frac{M}{wL} = \frac{m(1-L)}{-Lm'(1-L)} \\ &= \frac{1}{L\beta} \left(\beta(1-L) + (1-\beta)(1-L)^{\frac{1}{\eta}} \right) \equiv z(L). \end{aligned} \quad (13)$$

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

$$\frac{dz}{dL} = -\frac{(1-\beta)(\eta(1-L) + L)(1-L)^{\frac{1}{\eta}-1} + \beta\eta}{L^2\beta\eta} \leq 0. \quad (14)$$

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 (14) gives

$$\frac{dL}{dT} = -\frac{1-\alpha}{\alpha(1-T)^2} \frac{L^2\beta\eta}{(1-\beta)(\eta(1-L)+L)(1-L)^{\frac{1}{\eta}-1} + \beta\eta} < 0 \quad (15)$$

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 (13) 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 $p^{-\alpha}\pi$. ■

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. ■

B Supplementary material (Not for publication)

Appendix B.1 contains details of the numerical algorithm, which relies on standard methods of function approximation. Appendix B.2 describes our sensitivity studies, mentioned in Section 4. Appendix B.3 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 Appendix B.3 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.

B.1 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 (9); 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 $\bar{\sigma}(x_{t+1}, \Upsilon(x_{t+1}))$,

$$\Phi(x_t) = \frac{1}{1+\rho} \{p^{-\alpha}(x_{t+1}, \Upsilon(x_{t+1}))\pi(x_{t+1}, \Upsilon(x_{t+1})) + \Phi(x_{t+1})\} \quad (16)$$

and the optimality condition

$$\frac{d}{dT_t} \left[P^{-\alpha}(x_t, T_t) Y(T_t) + \frac{1}{1+\rho} \Omega \right] = 0, \quad (17)$$

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 (16) 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 (17) to find the values of $\Upsilon(\cdot)$ at each node; we use those values to update the 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

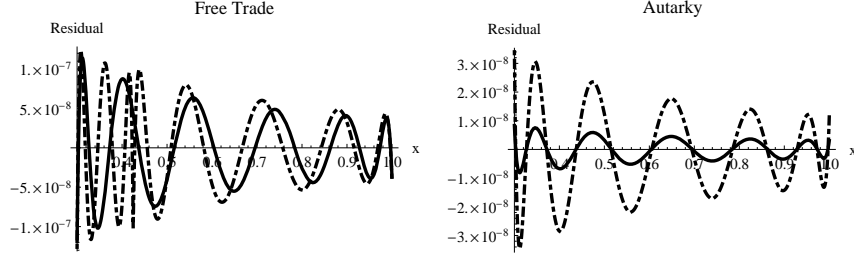


Figure 4: Approximation error for asset price function (LHS-RHS of (16)): the MPE (solid) and the social planner’s (dot-dashed) problems, the open economy (left) and closed economy (right).

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 (16) 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 (16) and (17), 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:

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

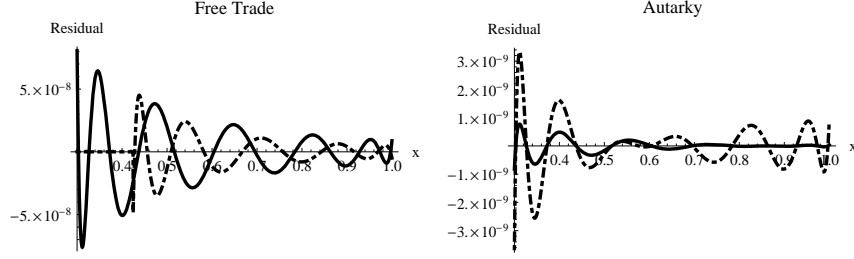


Figure 5: Approximation error for asset price function (LHS-RHS of (17)): the MPE (solid) and the social planner's (dot-dashed) problems, the open economy (left) and closed economy (right).

B.2 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.

$$\begin{aligned}
 \alpha &= \{0.1, 0.3, \mathbf{0.5}, 0.7, 0.9\} \\
 \rho &= \{0.1, \mathbf{0.41}, 0.7\} \\
 \beta &= \{0.4, \mathbf{0.5}, 0.6\} \\
 r &= \{0.1, 0.5, \mathbf{0.68}, 0.9, 1.1\} \\
 \gamma &= \{0.1, 0.3, \mathbf{0.513}, 0.7, 0.9\} \\
 P &= \{1, 2, 3, \mathbf{3.377}, 4, 6, 9\}
 \end{aligned}$$

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 $[0.05, 0.95]$.

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

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

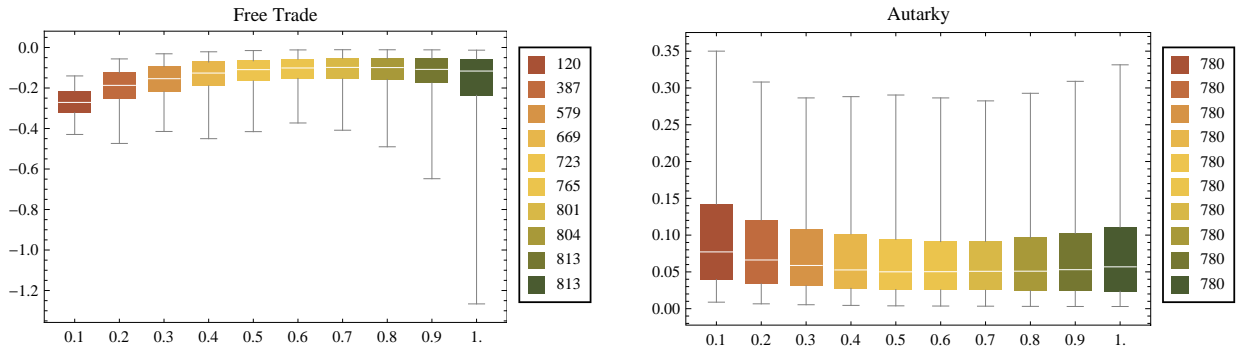


Figure 6: Parameter sensitivity of MPE: box-whisker plots of distribution of policy, T , as a function of the resource stock, x , for free trade (left panel) and autarky (right panel)

Figure 6 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.

B.3 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 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

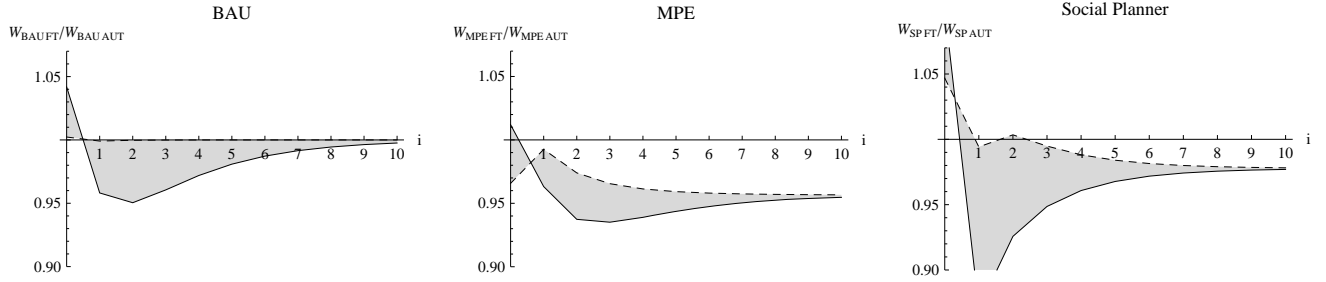


Figure 7: Welfare in the open relative to the closed economy under BAU (left), MPE (center) and social planner (right), with the initial resource stock $x_0 = 0.5$ (dashed) and $x_0 = 0.9$ (solid).

at 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 genera-

tions' 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.