Journal Of Environmental Economics And Management
September 2019, Volume 97 Pages 116-133
https://doi.org/10.1016/j.jeem.2018.04.008
https://archimer.ifremer.fr/doc/00636/74804/

Economic growth, international trade, and the depletion or conservation of renewable natural resources

Riekhof Marie-Catherine [1,*], Regnier Esther [2,3], Quaas Martin F. [3]

[1] Swiss Fed Inst Technol, CER ETH Ctr Econ Res, Zurich, Switzerland.
[2] Univ Western Brittany UBO, AMURE, Brest, France.
[3] Univ Kiel, Dept Econ, Kiel, Germany.

Corresponding author : Marie-Catherine Riekhof, email address : mcriekhof@ethz.ch

Esther.Regnier@univ-brest.fr ; quaas@economics.uni-kiel.de

Abstract :

Conservation of renewable natural resources and promotion of economic growth are both sustamable development goals. Here, we study the interdependency between economic growth, international trade, and the use of renewable natural resources under alternative institutional settings of either open access or full property rights in an endogenous growth model. We find that if the resource is depleted over time, consumption growth is reduced. Economic growth and international trade only impact resource use when the resource is harvested under full property rights. Then, widening international trade can lead countries to shift from conservation to depletion. Changes in the institutional setting of resource use in one country may have repercussions on trading partners. Our results indicate potential trade-offs between the sustainable development goals and imply that policies focusing on resource use or trade (e.g., international trade bans or certified trade) are not sufficient to prevent resource depletion.

Keywords : Economic growth, International trade, Common-pool resource, Renewable resource, Property rights, Open access, Depletion, Conservation

JEL classification : O44; Q01; F18; F64

1 Introduction

Since 1995, the world economy has grown by 2.8% p.a. on average and international trade has increased sixfold (World Bank, 2016; UNCTAD, 2015b), while the use of natural resources has come to a point where many renewable natural resources are classified as over-used (WorldBank and FAO, 2009). Different resource use regulations, trade bans and certified trade have been introduced, albeit with mixed success (Fischer, 2010). Against this background, it seems that the sustainable development goals of conservation of renewable natural resources (SDGs 14 and 15) and promotion of economic growth (SDG 8) are difficult to achieve simultaneously. Economic theory shows that optimal resource use is related to interest rates (Clark and Munro, 1975; Clark, 1990; Clark et al., 2010), and in particular resource depletion can be optimal if the interest rate is higher than the maximal reproduction rate of the resource (Clark, 1973). From a general equilibrium perspective, interest rates are highly correlated with growth rates of GDP (Acemoglu, 2008), which, in turn, are closely related to international trade (Acemoglu and Ventura, 2002).

In this study, we combine theories of renewable resource economics, international trade, and economic growth to study how economic growth and international trade of produced goods impact the depletion or conservation of renewable natural resources. We develop a general equilibrium model with endogenous growth to capture possible two-way interactions: growth may affect resource use, while resource scarcity may have repercussions on growth. The model consists of heterogeneous AK-economies in the form of Rebelo (1991) that specialize and trade in differentiated intermediate goods. Each country uses a renewable, exhaustible resource as an input in the production of a consumption good. The dynamics of the resource extraction sector are modeled according to the classical Gordon-Schaefer model (Gordon, 1954; Schaefer, 1957), where labor is the only input factor to the production function, as in Suphaphiphat et al. (2015). Renewable resources often have common-pool characteristics, possibly leading to overuse. The intrinsically dynamic nature of renewable resource use makes the management regime, i.e. the capacity to internalize dynamic stock externalities, all the more important. We therefore consider the institutional settings in the polar settings of full open access or full property rights.

We re-examine the result of optimal exhaustion of a renewable resource by Clark (1973) in a setting of endogenous growth and trade. Suphaphiphat et al. (2015) have studied this question for the first time in a general equilibrium setting with endogenous growth, but without international trade. The role of resource exploitation has also been analyzed by López et al. (2007) and Cabo et al. (2014b,a) settings with trade, but without considering the possibility of resource depletion. Our model of endogenous growth and international trade builds on Acemoglu and Ventura (2002), and extends it to include a renewable, exhaustible resources in each country (as in Suphaphiphat et al. 2015). Unlike Acemoglu and Ventura (2002) and Suphaphiphat et al. (2015)—who use log-utility, i.e. assuming an intertemporal elasticity of substitution of one—, we introduce an iso-elastic utility function that allows for weak or strong preferences for consumption smoothing over time. This flexibility matches the wide range of empirical estimates for the elasticity of intertemporal substitution, which range from 0.1 to 2 (Gruber, 2013). Allowing for an elasticity of intertemporal substitution different from one, we can study situations in which the income effect or the substitution effect dominates, which may have important effects. Bretschger and Karydas (2017) showed, for example, that the Pigouvian tax rule in a setting with exhaustible and polluting resources depends on the elasticity of intertemporal substitution. We also contribute to the literature on international trade and natural resources, which mainly uses static settings of North-South trade or small open economies with a focus on traded natural resources (see Bulte and Barbier 2005 as well as Section 2). While this literature mainly studies how trade affects welfare, the focus of our paper is on dynamic allocative effects of trade and resource use.

In contrast to most other models of international trade and resource use—which mainly focus on one country potentially exporting a natural resource—we take a broader perspective and consider a world full of trading countries. Rather than studying international trade in natural resources, we focus on trade in intermediate goods, as the bulk of traded goods globally are intermediate goods, and trade in manufacturing goods holds a dominant position over trade in natural resources and agricultural products (UNCTAD, 2015a).[1] Rather than

[1]From a world-wide perspective, the share of a harvested resource that is used domestically exceeds

studying the effect of trade on current resource prices, we thus focus on the intertemporal transmission channel of (broadening) trade on resource use in a dynamic setting. This channel is based on the idea that trade in intermediate goods impacts economic growth (Xu, 2000).

We derive three sets of results. First, we study how patterns of resource use are related to consumption growth. We find that the effect of resource exploitation on growth is neutral when the parameter setting is such that the resource stock is kept at a positive level in the long-run. When mining occurs, i.e. when the resource is depleted over time, resource scarcity slows down consumption growth. The impact from resource mining and increasing resource scarcity can be so strong as to turn consumption growth negative. The impact on capital accumulation depends on the intertemporal elasticity of substitution, i.e. whether the income or the substitution effect dominates.

The second set of results characterizes the bio-economic conditions leading to mining or conservation under the two institutional settings of open access or full property rights. Mining is more likely to occur under open access.[2] It prevails when resource productivity is low. Under full property rights, resource mining or conservation depends, among others, on economic capital productivity and the household's preferences for intertemporal substitution of consumption. If the intertemporal elasticity of substitution is low, economic growth—driven by capital productivity—makes mining more likely, as then the income effect dominates over the intertemporal substitution effect.

Our third set of results relates to the role of international trade. By inducing convergence of all countries' capital growth rates to a common rate, trade openness may influence resource

the share that is traded internationally. While seafood is highly traded (40% of production is exported as of 2012, based on `http://www.fao.org/fishery/statistics/global-commodities-production/en`), bush meat is nearly not traded internationally at all (Nasi et al., 2008). For forest products, roughly one quarter is traded internationally (FAO, 2015). If one only considers round wood, sawnwood and wood-based panels—basically excluding paper and pulp—, the share of production that is traded internationally reduces to 8%.

[2]The set of parameter values for which mining occurs under full property rights is a proper subset of the set of parameter values for which mining occurs under full property rights.

use. Reciprocally, this common rate is endogenous to the resource use in each trading country. We find that under open access, resource harvest is the same as under autarky, and trade has no consequences for resource mining or conservation. Under full property rights, widening international trade impacts resource use via changing economic growth. The direction of this impact depends on preferences and whether the income or the substitution effect dominates. For existing trade blocks, we show that a change in the institutional setting of resource use in one country can impact economic growth and thus have repercussions on resource use in all countries.

The key message of our study is that international trade does not only impact traded natural resources, but also non-traded natural resources by changing the intertemporal consumption path. We thus newly identify a link between the sustainable development goals (SDGs) of conservation of renewable natural resources and promotion of economic growth. Widening international trade may give rise to synergies or a trade-off between these SDGs, as the direction of its effect depends on preferences for intertemporal consumption smoothing and thus on whether the intertemporal income or substitution effect dominates. In the previous literature this channel has been concealed by the assumption of logarithmic utility or the focus on a situation with a constant positive resource stock level in the long run. We relax the assumption of logarithmic utility in this paper and also allow for declining resource stocks. Furthermore, we find that changes in the institutional setting of resource use in one country has external effects on other countries via trade. A policy implication of our results is that new ways to regulate renewable resources have to be explored, as, first, the 'standard' policies like trade bans or certified trade cannot protect those natural resources that are not traded. Second, improved resource regulation in one country may induce trading partners to start over-using their own natural resource, a repercussion that needs to be taken into account when designing resource policy such as rebuilding fisheries (Costello et al., 2016).

The remainder of the paper is structured as follows. Section 2 gives an overview of the literature examining the interplay between growth, trade and natural resource use. Section 3 sets up the global version of our model, and derives the general dynamic market equilibrium conditions. Section 4 focuses on the situation of a country in autarky to clearly bring out the parameter configurations leading either to mining or conservation of the renewable resource stock under each extreme management setting. Section 5 considers the full multi-country model and investigates (i) how trade drives global growth, (ii) the condition leading to either exploitation regime under perfect property rights with trade, and (iii) under which conditions resource use in one country impacts trading partners. Section 6 discusses the results and concludes.

2 A review of studies addressing economic growth, natural resource use and international trade

The present study relates to several areas of literature. Regarding the ingredients of our model, the literature on international trade, renewable resources and endogenous growth is most closely related. Here, the focus has been on how trade affects resource use in small open economies with different characteristics. (McAusland, 2005; López et al., 2007; Eliasson and Turnovsky, 2004; Nakamoto and Futagami, 2016; Cabo et al., 2014a). As an exception, Cabo et al. (2014b) use a two country set-up, with an innovating 'North' and a resource-rich 'South', focusing on the ownership of the resource (foreign monopoly, local government, many resource users that share the resource). Our paper adds to this literature by discussing the impact from trade on resource use in a model of many trading countries, which allows to examine the role of institutional spill-overs.

Potential spill-overs from resource use regulation on trading partners has been extensively studied in static frameworks, focusing on the relative abundance of the resource and changing resource prices due to trade (Brander and Taylor, 1997a; Hannesson, 2000; Brander and Taylor, 1998; Emami and Johnston, 2000; Chichilnisky, 1994; Brander and Taylor, 1997b; Karp et al., 2001, 2003).[3] Our study adds to this literature in a complementary way. We focus on the impacts from changes in the intertemporal consumption profile on resource use, excluding mechanisms that work through the resource price.

[3]See Bulte and Barbier (2005) and Fischer (2010) for overviews.

In contrast to the above mentioned models, we consider trade in intermediate products. With this set-up, we are closer to Bogmans (2015) and Benarroch and Weder (2006), who examine pollution in models with trade in intermediate products. Bogmans (2015), for example, shows in a static model that environmental policy can impact global pollution through the trade in intermediate products. This hints towards an additional mechanism through which trade could impact renewable resources. We leave this for future research.[4]

Our analysis also contributes to the discussion on resource use and growth. One could say it 'bridges' the literature on non-renewable, exhaustible resources with declining resource stocks and on renewable, exhaustible resource with constant resource stocks in the long-run (Bovenberg and Smulders, 1996). If resources are non-renewable, there is the concern that long-run growth may not be possible e.g. with respect to 'peak oil'. This question has been studied in the framework of exogenous growth (Dasgupta and Heal, 1974; Solow, 1974) and also in frameworks of endogenous growth (Acemoglu et al., 2012). In a sense, a renewable resource can also turn into a non-renewable resource if it is exhausted. As Suphaphiphat et al. (2015), we allow for both cases—conservation and exhaustion—and derive conditions for either the one or the other to prevail. As discussed in the literature on the 'resource curse', natural resources may (or may not) themselves represent an obstacle to development (Sachs and Warner, 1999; Gylfason, 2001; Papyrakis and Gerlagh, 2007; Brunnschweiler, 2008).[5]

Our results related to the preferences for consumption smoothing also expand the existing literature on renewable resource use and growth. Bovenberg and Smulders (1996) include an elasticity of intertemporal substitution assumed to be smaller than one, but focus on a constant resource stock in the long-run. Eliasson and Turnovsky (2004) also include a utility function that allows the elasticity of intertemporal substitution not to equal one, but

[4]For a literature overview on pollution and trade, see Copeland and Taylor (2004) and Cherniwchan et al. (2017).

[5]In our model, no resource curse occurs. A more productive resource can only increase the growth rate. This is in line with the empirical evidence provided by Brunnschweiler (2008), who uses a new measures of resource endowment and finds a positive relationship between natural resource abundance and economic growth.

focus on logarithmic utility for the transitional dynamics and on a constant resource stock in steady state. Bretschger and Karydas (2017), in turn, explicitly discuss both, an elasticity smaller and larger than one in a setting with non-renewable resources and pollution. They find that whether the Pigouvian tax rule starts off above or below its long-run value depends on the elasticity of intertemporal substitution.

3 A world full of countries with natural resources

We consider a dynamic model of J trading countries. All countries have the same economic structure, although technological parameters may differ across economies. The production structure of the economy is very similar as in Acemoglu and Ventura (2002) and Acemoglu (2008), where economies grow endogenously and freely trade differentiated intermediate goods. We extend their model by including a renewable, exhaustible natural resource, as in Suphaphiphat et al. (2015). The resource can be harvested under two different institutional settings: open access or full property rights.

Each country has four sectors of production: 1. The production of the consumption good uses labor, capital, intermediate goods and resource harvest. 2. The investment good is produced by means of capital and intermediate goods. 3. Intermediate goods are produced from capital only. 4. the resource is harvested from a renewable but exhaustible stock using labor only. Each county is inhabited by a representative household who supplies labor, owns assets—either directly or by owning firms—, rents capital to firms and derives utility from consuming the consumption good. All markets are competitive.

As discussed in Rebelo (1991), a capital good that is produced without contribution of non-cumulative factors—like labor or the natural resource—can generate endogenous growth. The investment good, for which all inputs are produced by capital only, is such a capital good.

In terms of notation, time t is assumed to be continuous. Latin letters denote variables which all may change over time; Greek letters are used to denote time invariant parameters of the model. Each country and all quantities and prices referring to this country are indexed by $j \in 1, ..., J$. We omit the index whenever no confusion arises.

3.1 Preferences and production technologies

We describe the structure of one country that is representative for all countries. The country uses capital to produce a continuum of intermediate products $x(t,\nu)$ indexed by $\nu \in [0,\mu]$, where $\mu > 0$ denotes the overall mass of intermediates produced in this country. As Acemoglu and Ventura (2002), we assume that μ is fixed. Countries with a higher μ are able to produce more varieties, they are technologically more advanced. One unit of capital produces one unit of the intermediate good. Countries trade in intermediate goods only, all other goods are non-tradable, and production factors (labor, capital, and the natural resource) are immobile. We adopt the Armington assumption that the intermediates are differentiated according to origin,[6] and use $N = \sum_j \mu_j$ to denote the overall mass of intermediates available.

Natural resource harvest $H(t)$, labor $L^C(t)$, capital $K^C(t)$, and a total mass N of intermediate products with individual quantity $x^C(t,\nu)$ are used to produce the consumption good $C(t)$. The production function is

$$C(t) = \chi\, H(t)^{\alpha}\, L^C(t)^{\frac{\alpha}{\beta}-\alpha}\, K^C(t)^{\gamma} \left(\int_0^N x^C(t,\nu)^{\frac{\varepsilon-1}{\varepsilon}}\, d\nu \right)^{\frac{\tau\,\varepsilon}{\varepsilon-1}}, \tag{1}$$

with $\gamma, \beta, \alpha, \tau > 0$, $\gamma + \frac{\alpha}{\beta} + \tau = 1$, and $\varepsilon > 1$.[7] The parameter χ scales production.

The investment good $I(t)$ is produced from capital and the composite of intermediates. Let the superscript I denote that inputs are used to produce the investment good. Production is according to

$$I(t) = \zeta^{-1}\, \chi\, K^I(t)^{1-\tau} \left(\int_0^N x^I(t,\nu)^{\frac{\varepsilon-1}{\varepsilon}}\, d\nu \right)^{\frac{\tau\,\varepsilon}{\varepsilon-1}}, \tag{2}$$

where $\zeta^{-1} > 0$ is a productivity parameter.

[6] Acemoglu and Ventura (2002) provide a micro foundation for this assumption.

[7] We use $\frac{\alpha}{\beta} - \alpha$ to denote the expenditure share for labor, because this will save notation later on by generating simple expressions for labor allocation.

The formulation of resource growth and harvesting closely follows the model of Suphaphiphat et al. (2015). The resource stock $S(t)$ grows logistically according to

$$\dot{S}(t) = \eta\, S(t) \left(1 - \frac{S(t)}{\overline{S}}\right) - H(t), \tag{3}$$

with the Schaefer production function

$$H(t) = \psi\, L^H(t)\, S(t). \tag{4}$$

Here, $\eta > 0$ is the intrinsic growth rate, $\overline{S} > 0$ is carrying capacity, i.e. the equilibrium resource stock size in the absence of harvesting, $\psi > 0$ is the 'catchability' coefficient measuring the efficiency of resource harvesting, and $L^H(t)$ is labor used for harvesting. We choose units of measurement for labor and the resource stock such that $\psi = \overline{S} = 1$.

Households own the assets and have preferences over consumption described by

$$\int_0^\infty e^{-\rho t}\, \frac{C(t)^{1-\vartheta}}{1-\vartheta}\, dt, \tag{5}$$

where $\rho > 0$ is the utility discount rate and $\vartheta > 0$ the inverse of the elasticity of intertemporal substitution, representing the preference for intertemporal consumption smoothing. At time $t = 0$, the representative household is endowed with one unit of labor, $K(0) > 0$ units of capital and an initial resource stock of $S(0) > 0$. We assume that the initial capital stock is small enough for the household to save a positive amount.

The budget constraint of the representative household is

$$\underbrace{p^I(t)\, \dot{K}(t)}_{\text{savings}} + \underbrace{p^C(t)\, C(t)}_{\text{consumption}} = Y(t) = \underbrace{r(t)\, K(t)}_{\text{capital income}} + \underbrace{w(t)\, L^C(t)}_{\text{wage income}} + \underbrace{q(t)\, H(t)}_{\substack{\text{income from}\\ \text{resource harvesting}}}, \tag{6}$$

where $p^I(t)$ denotes the price of the investment good, $p^C(t)$ the price of the consumption good, $r(t)$ the rental rate of capital, $w(t)$ the wage rate and $q(t)$ the price of resource input. In (6) we ignore capital depreciation to economize on notation. Since there is no trade in assets, income $Y(t)$ must equal consumption plus saving. The change in the capital stock $\dot{K}(t)$ equals investments $I(t)$.

3.2 Optimal production choices

Using $p(t)$ to denote the price of intermediates, we have

$$p(t,\nu) = r(t) \quad \text{for all } \nu \in [0,\mu]. \tag{7}$$

As one unit of capital produces one unit of the intermediate good, and as firms are perfectly competitive, the value of the marginal intermediate product is simply the output price and equal to the factor price, i.e. the rental rate of capital (as stated in Equation (7)).

Profit maximization in production of the consumption good leads to the conditions

$$q(t)\, H(t) = \alpha\, p^C(t)\, C(t), \tag{8a}$$

$$w(t)\, L^C(t) = \left(\frac{\alpha}{\beta} - \alpha\right) p^C(t)\, C(t), \tag{8b}$$

$$r(t)\, K^C(t) = \gamma\, p^C(t)\, C(t), \tag{8c}$$

$$p_j(t)\, x_j(t,\nu_j)^{\frac{1}{\varepsilon}} = \frac{\tau\, p^C(t)\, C(t)}{\int_0^N x^C(t,\nu)^{\frac{\varepsilon-1}{\varepsilon}}\, d\nu}. \tag{8d}$$

Let the price index of intermediates be the numeraire,

$$\sum_j \mu_j\, r_j^{1-\varepsilon} = 1.$$

As pointed out in Acemoglu and Ventura (2002), this choice of numeraire implies that $p_j(t)$ is the terms of trade of country j. It is the price of exports relative to imports, assuming that countries export practically all of their produced intermediates to import the ideal basket of intermediate inputs. Re-arrange (8d) to obtain

$$p_j(t)^{1-\varepsilon} = x^C(t,\nu)^{-\frac{1-\varepsilon}{\varepsilon}} \left(\frac{\tau\, p^C(t)\, C(t)}{\int_0^N x^C(t,\nu)^{\frac{\varepsilon-1}{\varepsilon}}\, d\nu}\right)^{1-\varepsilon}. \tag{9}$$

Integrating over the set of varieties available in country j, and using that $\sum_j \mu_j\, r_j(t)^{1-\varepsilon} = 1$ leads to

$$1 = \left(\int_0^N x^C(t,\nu)^{\frac{\varepsilon-1}{\varepsilon}}\, d\nu\right)^{\varepsilon} \left(\tau\, p^C(t)\, C(t)\right)^{1-\varepsilon}. \tag{10}$$

In combination with (8d), we obtain the demand for one variety of the intermediate products for the production of the consumption good,

$$x_j^C(t,\nu) = \tau\, p^C(t)\, C(t)\, p_j(t)^{-\varepsilon}. \tag{11}$$

The demand for each variety of the intermediate products is an iso-elastic downward-sloping function of its price, and linearly increasing with the value of consumption output.

We can also use (10) and (8c) to re-write (1) as

$$C(t) = \chi\, H(t)^{\alpha}\, L^C(t)^{\frac{\alpha}{\beta}-\alpha}\, K^C(t)^{\gamma+\tau}\, \left(r(t)\,\frac{\tau}{\gamma}\right)^{\tau}. \tag{12}$$

Profit maximization in the investment goods sector leads to the conditions

$$\begin{aligned} r(t)\, K^I(t) &= (1-\tau)\, p^I(t)\, I(t), \\ p(t,\nu)\, x^I(t,\nu) &= \tau\, \frac{x^I(t,\nu)^{\frac{\varepsilon-1}{\varepsilon}}}{\int_0^N x^I(t,\nu)^{\frac{\varepsilon-1}{\varepsilon}}\, d\nu}\, p^I(t)\, I(t). \end{aligned} \tag{13}$$

Following a line of argument similar to the one above, we obtain the demand for one variety of the intermediate products for the production of the investment good,

$$x_j^I(t,\nu) = \tau\, p_j^I(t)\, I_j(t)\, p(t,\nu)^{-\varepsilon}. \tag{14}$$

The demand for each variety of the intermediate product in investment good production is an iso-elastic downward-sloping function of its price, and linearly increasing with the value of output of the investment goods sector. This resembles demand for intermediate productsm in consumption good production. Also, combining (2) and (13) with

$$1 = \left(\int_0^N x^I(t,\nu)^{\frac{\varepsilon-1}{\varepsilon}}\, d\nu\right)^{\frac{\varepsilon}{1-\varepsilon}} \tau\, p^I(t)\, I(t)$$

and choosing units such that $\chi = \tau^{-\tau}(1-\tau)^{1-\tau}$ yields

$$p^I(t) = \zeta\, r(t)^{1-\tau}. \tag{15}$$

The price of the investment good increases with the rental rate of capital at a decreasing rate.

3.3 The household's optimal choices

As households are homogeneous and population is constant and normalized to one in each country, the households of each country can be described by a representative consumer. If the resource is under private property, the representative household maximizes (5) subject to the budget constraint (6), as well as resource dynamics (3), harvesting technology (4), and $L^C(t) + L^H(t) = 1$ for all t. We introduce the labor share used in resource harvesting ℓ and superscript fp to denote that it is the full property rights solution.

In the following we do not explicitly write out the time dependency of variables. The current-value Hamiltonian can be written as

$$\mathcal{H}^{fp} = \frac{C^{1-\vartheta}}{1-\vartheta} + \frac{\lambda}{p^I} \left(r\,K + w\,(1-\ell^{fp}) + q\,\ell^{fp}\,S - p^C\,C + \pi\,\left(\eta\,S\,(1-S) - \ell^{fp}\,S\right)\right). \quad (16)$$

The multiplier of the resource constraint, $\lambda\,\pi/p^I$, is written in such a way that π is the shadow price of the resource in monetary terms. First-order conditions for optimization over C, ℓ, and K, are given in Appendix A.

3.3.1 Optimal investment into the capital and the resource stock

The first-order conditions lead to the following equations that determine the optimal investment in produced capital and the natural resource stock. For the produced capital stock,

$$\underbrace{\frac{r}{p^I}}_{\substack{\text{marginal capital}\\ \text{productivity}}} + \underbrace{\hat{p}^I - \hat{p}^C}_{\text{capital gains}} = \underbrace{\rho + \vartheta\,\hat{C}.}_{\substack{\text{social}\\ \text{discount rate}}} \quad (17a)$$

The social discount rate resembles the standard Keynes-Ramsey rule. Define $\bar{r} = r/p^I$, as the marginal capital productivity based on $\frac{\partial \dot{K}}{\partial K} = \frac{I}{K} = \frac{r}{p_I}$, and using (6). Also, $\bar{r} = r/p^I = \zeta^{-1}\,r^\tau$ according to (15). Using (8c) in growth rates, Condition (17a) can also be written as

$$\hat{K}^C + (\vartheta - 1)\,\hat{C} + \tau\hat{r} = \bar{r} - \rho. \quad (17b)$$

For the optimal intertemporal allocation of the resource stock, we obtain a similar condition:

$$\overbrace{\underbrace{\eta\,(1-2\,S)}_{\substack{\text{marginal resource}\\ \text{productivity}}} + \underbrace{\hat{\pi}-\hat{p}^C}_{\substack{\text{natural}\\ \text{capital gains}}} + \underbrace{\frac{w\,\ell^{fp}}{\pi\,S}}_{\text{'stock effect'}}}^{\text{own interest rate of natural resource}} = \underbrace{\rho+\vartheta\,\hat{C}}_{\substack{\text{social}\\ \text{discount rate}}} \tag{17c}$$

Here, $\pi = q - \frac{w}{S}$ from the first order condition of labor (in the Appendix) is to be interpreted as the marginal resource rent. Condition (17c) is a generalization of the well-known condition for optimal renewable resource use (Clark, 1990). The stock of the resource should be invested, such that the social discount rate equals the own rate of interest of the natural resource, which is composed of marginal resource productivity plus natural capital gains plus the 'stock effect'. The marginal resource productivity and natural capital gains are analogous as the corresponding terms in the optimality condition for investment into produced capital.[8]

In addition, the 'stock effect' measures the value of a marginal increase of the resource stock size in terms of reduced harvesting costs, which come about as harvesting costs decrease with the size of the resource stock.

The difference between the setting with open access to the resource and the case with full property rights over the resource stock is that under open access, the representative household ignores the effect of harvest on the stock development of the resource. We introduce the superscript *oa* to denote that it is the open access solution. The current-value Hamiltonian can thus be written as

$$\mathcal{H}^{oa} = \frac{C^{1-\vartheta}}{1-\vartheta} + \frac{\lambda}{p^I}\,\left(r\,K + w\,(1-\ell^{oa}) + q\,\ell^{oa}\,S - p^C\,C\right). \tag{18}$$

From the first-order conditions of optimization over C, ℓ, and K, we derive that the condition for the optimal allocation of produced capital when the resource is harvested under open access is formally identical to (17a), although the values of the variables will be different in general. The labor allocation, however, is determined by the condition that the marginal resource rent is zero, i.e. $q = w/S$.

[8] Similar to the marginal capital productivity, we term $\frac{\partial \dot{S}}{\partial S} = \eta\,(1-2\,S)$ for $H=0$ 'marginal resource productivity'.

3.3.2 Labor allocation and resource harvesting

Economic growth may affect resource harvesting through three different channels. It affects (i) demand for resource harvest, as captured by the resource price q, (ii) the opportunity costs of harvesting effort, as captured by the wage rate w, and (iii) the social discount rate $\rho + \vartheta \hat{C}$.

Under open access, the social discount rate does not affect the harvesting decision. Given the assumption of a Cobb-Douglas production function for consumption goods production, we further find that the effects (i) and (ii) cancel out, such that labor allocation is constant in open access. Using (8b) and (8c) in the condition $q = w/S$, we find

$$\ell^{oa} = \beta. \tag{19}$$

Labor allocation between consumption good production and resource harvesting only depends on β, which is part of the partial production elasticities in consumption good production. It is independent of parameters that describe the resource productivity.

We now consider the outcome under full property rights. Unlike in open access, labor allocation is not constant. Using $\pi = q - w/\, S$, (8a), (8b), (19), and (4), we find

$$\frac{\pi\, S}{p_C\, C} = \frac{\alpha}{1-\ell} \left(\frac{1}{\ell} - \frac{1}{\ell^{oa}} \right). \tag{20}$$

The right-hand side of this equation describes the opportunity costs of shifting a marginal unit of the resource stock to the production of consumption goods. For $\ell \to \ell^{oa}$, these opportunity costs are zero, which directly follows from the definition of open access. For $\ell \to 0$, these costs approach infinity, as the marginal product of resource input into production of the consumption goods approaches infinity under dwindling resource input. For the optimal labor allocation, the marginal opportunity cost of allocating more labor in the production of consumption goods should equal the marginal benefits, which are captured by the value of the increased resource stock size on the left-hand side of Condition (20). With full property rights, the household is able to capture the resource rents.

Lemma 1 states how labor allocation under full property rights compares to open access.

Lemma 1. *The representative household with full property rights allocates more labor to the consumption sector and less labor to resource harvesting compared to open access,*

$$\ell^{fp} < \ell^{oa}. \tag{21}$$

Proof of Lemma 1.
This follows directly from Equation (20), under the Condition $\pi > 0$. To verify that $\pi > 0$ is the case, suppose $\pi < 0$. Using the first-order Condition (43) from Appendix A, it follows that

$$\frac{\frac{d}{dt}\left(e^{-\rho\, t}\frac{\lambda(t)\,\pi(t)\,S(t)}{p^I}\right)}{e^{-\rho\, t}\frac{\lambda(t)\,\pi(t)\,S(t)}{p^I}} = -\rho + \hat{\lambda} + \hat{\pi} + \hat{S} - \hat{p}^I$$
$$= -\frac{q\,\ell}{\pi} - \eta\,(1 - 2\,S) + \ell + \hat{S} = -\frac{q\,\ell}{\pi} + \eta\,S + \ell.$$

For $\pi < 0$, the present value of the resource stock, $e^{-\rho\, t}\lambda\,\pi\,S\,p^I$, thus grows at a positive rate, which is in contradiction to the transversality condition $e^{-\rho\, t}\,\lambda\,\pi\,S/p^I \xrightarrow{t\to\infty} 0$. □

3.4 Market equilibrium under autarky and with trade

For most markets, we already included market clearing in our discussion of optimality conditions to economize on notation.

Under autarky, the capital market is the only market in which we have not imposed a condition. Walras' law ensures, however, that the capital market is also in equilibrium when all other markets clear.

Under trade, we have not yet imposed market clearing conditions for the capital market and for the intermediate goods market. Making use of Walras law again, we only impose the trade balance to ensure equilibrium on the market for intermediates. Using (11) and (14), the trade balance for county j implies

$$\overbrace{\sum_{i=0}^{J} \mu_j \, r_j^{1-\varepsilon} \left(\tau \, p_i^C \, C_i + \tau \, p_i^I \, \dot{K}_i\right)}^{\text{value of exports}} = \overbrace{\sum_{i=0}^{J} \mu_i \, r_i^{1-\varepsilon} \left(\tau \, p_j^C \, C_j + \tau \, p_j^I \, \dot{K}_j\right)}^{\text{value of imports}}$$

$$\mu_j \, r_j^{1-\varepsilon} \sum_{i=0}^{J} \left(p_i^C \, C_i + p_i^I \, I_i\right) = \left(p_j^C \, C_j + p_j^I \, I_j\right) \sum_{i=0}^{J} \mu_i \, r_i^{1-\varepsilon} = p_j^C \, C_j + p_j^I \, I_j.$$

Writing these equations in incomes, we obtain

$$\mu_j \, r_j^{1-\varepsilon} \, Y_g = Y_j, \tag{22}$$

where $Y_g = \sum_{j=1}^{J} Y_j$ is global income.

Equation (22) shows that a country's share in world income Y_j/Y_g is related to the mass of intermediate products μ_j a country is able to produce. Countries that are able to produce more intermediate goods have a higher share in world income. Before we consider international trade, we consider the situation of a country in autarky.

4 Growth and the conservation or depletion of renewable natural resources under autarky

We model autarky by setting $N = \mu$. The numeraire reduces to $\mu \, r^{1-\varepsilon} = 1 \Leftrightarrow r = \mu^{\frac{1}{\varepsilon-1}}$ and (15) becomes

$$\bar{r} = \frac{r}{p^I} = \zeta^{-1} \, \mu^{\frac{\tau}{\varepsilon-1}}. \tag{23}$$

The marginal productivity of capital is constant. It is increasing in the income share of intermediate products τ and decreasing in the elasticity of substitution between intermediate goods ϵ.

4.1 Economic dynamics under autarky

At the country level, the evolution of the economy over time can be characterized by three to four differential equations, depending on whether the natural resource is harvested under open access or full property rights. Then,[9]

$$\hat{S}(t) = \eta\,(1 - S) - \ell(t), \tag{24a}$$

$$\hat{K}(t) = \bar{r}\left(1 - \frac{\gamma + \tau}{\gamma}\frac{K^C(t)}{K(t)}\right), \tag{24b}$$

$$\hat{K}^C(t) = \frac{\bar{r} - \rho - (\vartheta - 1)\left(\alpha(\hat{S}(t) + \hat{\ell}(t)) + \left(\frac{\alpha}{\beta} - \alpha\right)\dot{\ell}(t)/(1 - \ell(t))\right)}{1 + (\vartheta - 1)(\gamma + \tau)}. \tag{24c}$$

Labor allocation depends on the institutional setting of resource use. Equation (19) gives the labor allocation under open access. Equation (20), with $p^C\,C = r\,K^C/\gamma$ from (8c), gives the labor allocation under full property rights. Equation (20) in growth rates gives the development of the shadow price of the resource in monetary terms. Equation (24c) shows how economic dynamics under autarky depend on the elasticity of intertemporal substitution $1/\vartheta$. For $\vartheta = 1$, the last term in the numerator vanishes. For $\vartheta \neq 1$, the interrelations depend on ϑ being smaller or larger than one.

To see the role of the intertemporal elasticity of substitution in (24c), suppose the depletion rate of the resource stock $\hat{S}$ increases, e.g. because of a shift in the regulatory regime. Resource use is moved to the present. With the Cobb-Douglas production function of the consumption good, the present demand for capital K^C also increases, leading to an increase in the rental rate of capital r. Households use capital markets to allocate consumption over time. A higher rental rate of capital makes future consumption relatively cheaper, motivating households to shift consumption to the future. This is an intertemporal substitution effect. At the same time, a higher rental rate of capital increases the income of the households, leading to more consumption opportunities over all times. This is the income effect. For the intertemporal elasticity of substitution $1/\vartheta = 1$, both effects cancel, and a change in the growth rate of the resource stock has no impact on $\hat{K}^C$. For $\vartheta > 1$, the substitution effect dominates: households shift consumption to the future and consume less today. Accordingly, they need less capital in consumption good production today, but more tomorrow, i.e. they allocated more capital towards the investment good to increase the overall capital

[9]With (24a) based on (3) and (4), (24b) based on (6), (8a), (8b), (8c) and (15), and (24c) based on (17b), (12) in growth rates using (4) and using that r is constant, see (23).

stock. The absolute increase in $\hat{S}$—a higher depletion rate—increases $\hat{K}^C$. One could say that capital and the resource are turned into substitutes in terms of investment. The natural resource stock is depleted faster, while human-made capital is accumulated faster.

This interpretation can also be applied when the resource is harvested under open access: the increase in the depletion rate of the resource stock $\hat{S}$ may be caused by a shift from full property rights to open access. The resource stock can no longer serve as investment the same way it did before. Then, for $\vartheta > 1$, the substitution effect dominates and investment in the other available asset—the capital stock—is increased.

For $\vartheta < 1$, the income effect dominates. With a higher rental rate of capital, consumers want to consume more today. Capital and resource investments are turned into complements. The amounts of both inputs in consumption good production are increased, while investment in both stocks is reduced, resulting into a lower $\hat{K}^C$.

4.2 Growth dynamics and conservation or depletion of the resource stock in steady state

We are interested in the long-run development of the economy and its resource use. In what follows, we will concentrate on a steady state, i.e. a development of the economy where all growth rates are constant. Then, labor allocation must be constant in both institutional settings of resource use. Furthermore, capital used in consumption good production and in investment good production grow at the same rate as the total capital stock. We introduce the superscript $*$ to denote the steady state. We use (24c) and (17b) to obtain the following long-run growth rate for consumption in open access and in the full property rights case:

$$\hat{C}^* = \frac{\alpha}{1 + (\gamma + \tau)(\vartheta - 1)} \hat{S}^* + \frac{\gamma + \tau}{1 + (\gamma + \tau)(\vartheta - 1)} (\bar{r} - \rho) . \tag{25}$$

In particular, the consumption growth rate depends on the growth rate of the resource stock, which may not be the same in both institutional settings of resource use. As the denominator in (25) is always positive, the value of ϑ impacts the growth of consumption, but not whether it is positive or negative.

We now define two concepts that play an important role in the interpretation of the steady-state results, before we turn to the two institutional settings of resource use. The concepts refer to the long-run use of the resource.

Definition 1. *[Resource conservation]*

'Resource conservation' refers to a harvesting sector with $\hat{S}^* = 0$ *and* $S^* > 0$ *in steady state.*

Definition 2. *[Resource mining]*

'Resource mining' refers to a harvesting sector with $\hat{S}^* < 0$ *and* $S^* \to 0$ *in steady state.*

Resource mining implies that the resource stock is asymptotically exhausted over time, while resource conservation refers to a situation in which the resource stock converges towards a positive level in the long-run. To distinguish between situations with resource conservation and mining, we introduce the subscripts c and m, respectively. As these concepts relate to the steady state, the $*$ is dropped when c or m are used.

4.2.1 Resource mining or conservation in open access

The following Proposition gives conditions for resource mining and conservation to occur in open access. The case $\hat{S}^* > 0$ is impossible in the long-run, as the resource stock and its regeneration capacity are bounded.

Proposition 1. *[Resource use in open access]*

The resource is mined in open access if $\eta < \beta$*, with* $\hat{S}^{oa}_m = \eta - \beta < 0$ *and* $S^{oa}_m \to 0$*. The resource is conserved in open access if* $\eta > \beta$*, with* $\hat{S}^{oa}_m = 0$ *and* $S^{oa}_m = 1 - \frac{\beta}{\eta}$*.*

Proof. The proposition directly follows from using (19) and (4) in (3). □

Proposition 1 shows that there is resource mining and the resource stock approaches zero in the long-run if the intrinsic growth rate of the resource, η, is smaller than the harvesting rate, $\ell^{oa} = \beta$. When the reverse is true, $\eta > \beta = \ell^{oa}$, a strictly positive amount of the resource stock is sustained in the long-run, i.e. the resource is conserved. In open access, the long-run resource stock is only affected by resource productivity (η) and by the income shares in (1), but not by preference parameters. For $\eta = \beta$, $\hat{S}^* = S^* = 0$.

4.2.2 Resource mining and conservation under full property rights

We now turn to results under full property rights. The condition for shifting from conservation to the mining regime of the renewable resource in the full property rights steady-state differs from that derived in Proposition 1 for open access. The condition is developed in the following and summarized in Proposition 2 below.

With constant labor allocation, it follows from (20) that $\hat{\pi} - \hat{p}^C = \hat{C} - \hat{S}$. Using this, (8b), and (20) in (17c) leads to

$$\frac{(1-\ell^{oa})\,\ell^{fp}}{\ell^{oa}-\ell^{fp}}\,\ell^{fp} = \rho + (\vartheta - 1)\,\hat{C} + \eta\,S^* = \frac{\rho + (\vartheta-1)\,(\gamma+\tau)\,\bar{r} + (\vartheta-1)\,\alpha\,\hat{S}}{1+(\vartheta-1)\,(\gamma+\tau)} + \eta\,S^*. \tag{26}$$

The left-hand side (LHS) of (26) captures the 'stock effect'.[10] It is positive and upward-sloping in ℓ^{fp} from zero—shifting labor away from resource harvesting has no benefit—to $+\infty$ for $\ell^{fp} \to \ell^{oa}$—shifting labor away from resource harvesting yields a very high rate of return in terms of a stock effect. It is the upward-sloping curve in Figure 1. This figure illustrates the labor allocation in the full property rights steady state. The horizontal axis depicts the labor share allocated to resource harvesting, and the vertical axis is in terms of (interest) rates per year.

The right-hand side (RHS) of (26) captures the social discount rate, natural capital gains and marginal resource productivity (cf. Equation 17c) as functions of labor, but written in terms of the capital interest (the alternative investment) net of the marginal stock growth. This net interest rate depends on the long-run development of the resource stock. Hence it differs for optimal conservation and mining. The conservation case is characterized by a constant resource stock $\dot{S}^*_c = 0$ with $S^*_c = 1 - \ell^*_c/\eta$ and holds for $\ell^*_c < \eta$. The mining case is characterized by a declining resource stock $\hat{S}^*_m = \eta - \ell^*_m$ and holds for $\ell^*_m > \eta$. This

[10] Equation (43) in the Appendix shows the transformation from the LHS of (17c) to the LHS of (26).

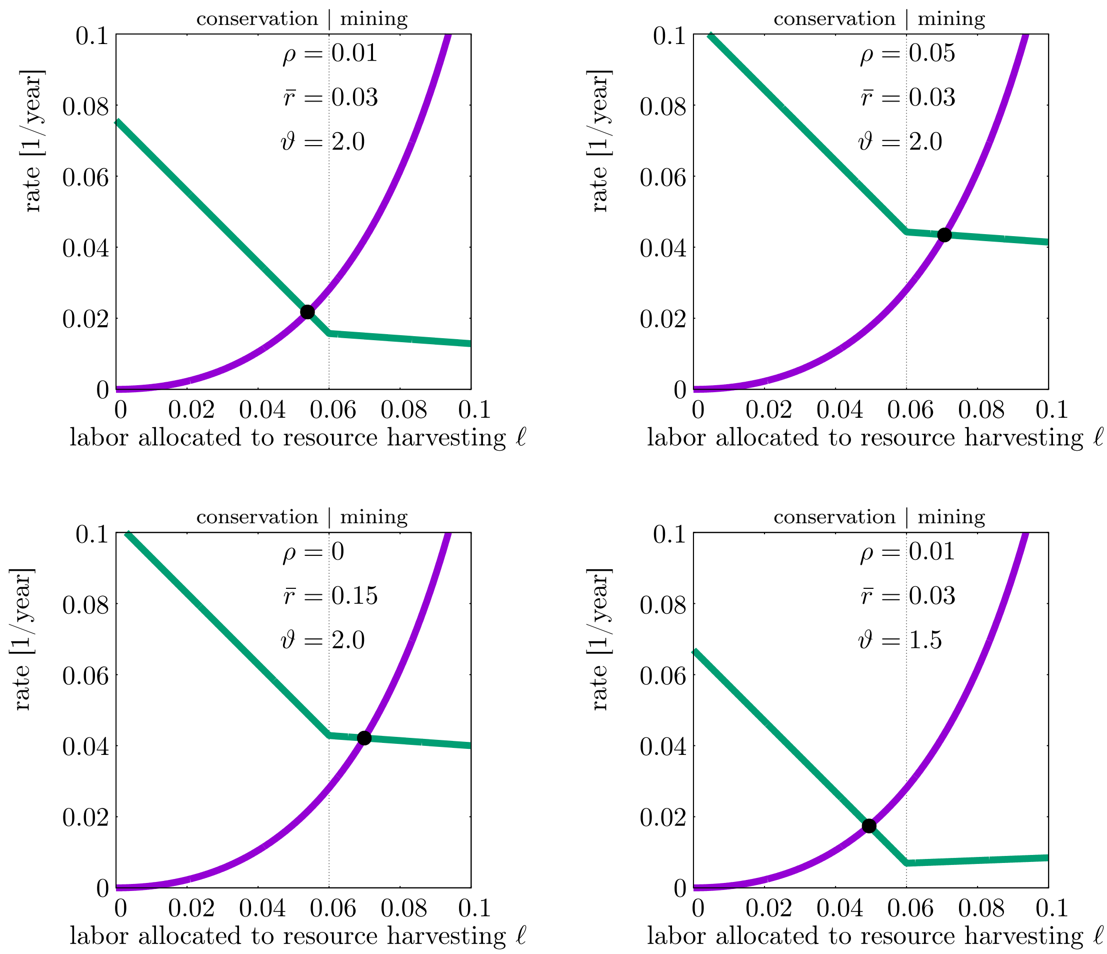

Figure 1: Illustration of labor allocation to the resource sector in the full property right steady state, using the specification $\alpha = 0.1$, $\beta = 1/6$, $\gamma + \tau = 0.4$, $\eta = 0.06$; other parameter values as specified in the graphs. Vertical lines separate the "conservation" and "mining" regimes; dots indicate the optimal choice.

case ultimately implies $S_m^* \to 0$. The representative household with full property rights acts as if choosing the case which generates the higher net rate of return on capital. Plugging respective values of $\hat{S}$ and S^* into (26) and reorganizing, we can compactly write (26) for both cases as

$$\frac{(1-\ell^{oa})\,\ell^{fp}}{\ell^{oa}-\ell^{fp}}\,\ell^{fp} = \frac{\rho + (\vartheta-1)\,(\gamma+\tau)\,\bar{r}}{1+(\vartheta-1)\,(\gamma+\tau)} + \max\left\{\underbrace{\left(\eta-\ell^{fp}\right)}_{\text{conservation}},\ \underbrace{\frac{(\vartheta-1)\,\alpha}{1+(\vartheta-1)\,(\gamma+\tau)}\left(\eta-\ell^{fp}\right)}_{\text{mining}}\right\}. \quad (27)$$

Both cases—conservation and mining—are depicted as the downward-sloping curve in Figure 1. The kink indicates a labor input $\ell^* = \eta$. While for $\ell^* < \eta$, the 'conservation' case applies, the 'mining' case holds for $\ell^* > \eta$. The intersection of the LHS—the stock effect—and the maximum of the RHS defines the optimal labor allocation under full property rights in steady state, and indicates whether conservation regime or mining regime prevails in steady state.

Proposition 2 gives the conditions for mining or conservation to occur in the case of full property rights given $\gamma + \tau > \alpha$, which we assume to hold for the rest of the paper. This condition can be related to the feasibility conditions of long-run positive consumption in the case of exhaustible resources. For a Cobb-Douglas production function without technical change, consumption is bounded away from zero if the income share of capital is higher than the income share of the resource (Dasgupta and Heal, 1979). The corresponding condition for our model is $\gamma + \tau > \alpha$.

Proposition 2. *[Resource use under full property rights]*

Assuming $\gamma + \tau > \alpha$, resource mining occurs under full property rights if $\ell^{oa} > \eta$ and $\rho > \Omega$ with

$$\Omega \equiv (1 + (\vartheta - 1)(\gamma + \tau)) \frac{(1 - \ell^{oa})\,\eta}{\ell^{oa} - \eta}\,\eta - (\vartheta - 1)(\gamma + \tau)\,\bar{r}. \tag{28}$$

Otherwise, the resource is conserved.

Proof of Proposition 2.

Either conservation or mining is optimal, depending on which of the two terms on the RHS of (27) is larger. The two are equal if and only if $\ell^* = \eta$. The slope of the RHS of (27) in ℓ^* is smaller in absolute value for the mining case than for the conservation case if $1 + (\vartheta - 1)(\gamma + \tau - \alpha) > 0$, which holds due to the assumption that $\gamma + \tau > \alpha$.

Whether $\ell^* < \eta$ or $\ell^* > \eta$ is optimal depends on the point of intersection between the LHS and the RHS of (27). The boundary case is when $\ell^* = \eta$ is optimal, i.e. when $\ell^* = \eta$

solves (27). This case results from a parameter combination characterized by

$$\frac{(1-\ell^{oa})\,\eta}{\ell^{oa}-\eta}\eta = \frac{\rho + (\vartheta - 1)\,(\gamma+\tau)\,\bar{r}}{1+(\vartheta-1)\,(\gamma+\tau)}$$
$$\Leftrightarrow \quad \rho = \Omega \equiv (1+(\vartheta-1)\,(\gamma+\tau))\,\frac{(1-\ell^{oa})\,\eta}{\ell^{oa}-\eta}\eta - (\vartheta-1)\,(\gamma+\tau)\,\bar{r}. \quad (29)$$

This equation only has a solution if $\beta > \eta$, i.e. if mining occurs in the open-access setting. Thus, we obtain the following conditions:

$$\begin{aligned} &\text{if } \beta < \eta \text{ or } \rho < \Omega \quad \text{conservation is optimal,} \\ &\text{if } \beta > \eta \text{ and } \rho > \Omega \quad \text{mining is optimal.} \end{aligned} \quad (30)$$

□

As stated in Proposition 2, the mining case can only arise if $\beta > \eta$. Thus, a necessary condition for mining to be optimal in the full property rights case is that open access—with $\ell^{oa} = \beta$—would result in mining. Put it differently, it can never be optimal for the representative household with full property rights to mine the resource if the resource were not mined under open access conditions. Clearly, a sufficiently large discount rate is also required for optimal mining.

In the following, we study the dependence of the critical value Ω for the discount rate on other parameter values. For $\vartheta = 1$, the result is particularly simple. Mining is optimal if the discount rate ρ is larger than the stock effect at $\ell^* = \eta$.

For $\vartheta < 1$, mining is optimal if the discount rate ρ is larger than a convex combination of the stock effect and the marginal return to capital, $\bar{r}$, with weighting factor $(1-\vartheta)\,(\gamma+\tau)$.

For $\vartheta > 1$, it may happen that mining is optimal for any positive discount rate. This is the case if the rental rate of capital is high enough,

$$\bar{r} = \frac{r^{\tau}}{\zeta} \geq \frac{1+(\vartheta-1)\,(\gamma+\tau)}{(\vartheta-1)\,(\gamma+\tau)}\,\frac{(1-\ell^{oa})\,\eta}{\ell^{oa}-\eta}\eta. \quad (31)$$

The intuition is that $\vartheta > 1$ implies that the substitution effect dominates, turning capital and the harvested resource into substitutes in terms of investment behavior. If the return to capital is sufficiently high, and investments into the resource stock and the capital stock are substitutes, it may turn out to be optimal to only invest in capital. In steady state, the resource input is low in absolute terms, but the capital input is high.

4.2.3 Consumption growth and resource use

It follows from (25) that the consumption growth rates are the same for open access and for a representative household with full property rights if resource conservation prevails in both cases. In that case, the consumption growth rate is not affected by parameters describing natural resource dynamics. The growth rate $\hat{C}^*$ is positive if $\bar{r} > \rho$, i.e. if the marginal capital productivity is larger than the discount rate. With conservation, the economy turns into a standard AK-economy.

If mining prevails,

$$\hat{C}^* = \frac{\alpha}{1 + (\gamma + \tau)(\vartheta - 1)} (\eta - \ell) + \frac{\gamma + \tau}{1 + (\gamma + \tau)(\vartheta - 1)} (\bar{r} - \rho), \tag{32}$$

with $\ell = \ell^{oa} = \beta$ in open access and $\ell = \ell^* < \ell^{oa}$ (cf. Lemma 1) under full property rights. Consumption growth rates differ between the two cases, as the growth of the resource stock depends on labor allocated to resource harvesting, which is higher or equal in open access compared to a representative household with full property rights. Again, a positive consumption growth rate is only possible if $\bar{r} > \rho$. Other than under resource conservation, the consumption growth rate is dragged down by resource mining. This can lead to a negative consumption growth rate:

$$\hat{C}^*_m < 0 \quad \Leftrightarrow \quad \ell > \eta + \frac{\gamma + \tau}{\alpha} (\bar{r} - \rho). \tag{33}$$

In particular, a negative growth rate can result if the discount rate ρ is large, the resource's intrinsic growth rate η is small, or if the productivity of capital accumulation $\bar{r}$ is small.

The following proposition summarizes how the steady state consumption growth rate of the economy is affected by resource harvesting, comparing open access to a representative household with full property rights.

Proposition 3. *[Consumption growth and resource use]* *(i) For $\beta < \eta$, resource conservation occurs under open access and under full property rights. Consumption growth rates are identical in both cases and independent from the productivity of the resource.*

(ii) If the resource is mined, consumption growth is reduced.

(iii) For $\beta > \eta$, consumption growth rates are lower in open access than with full property rights and may even turn negative due to resource mining.

Proof. (i) For $\beta < \eta$, the resource is conserved independent from the institutional setting (cf. Proposition 2). (ii) follows from $\hat{S}_m < 0$. (iii) For $\beta > \eta$, the resource is mined under open access, while it may be either mined or conserved under full property rights, depending on ρ and Ω. If the resource is mined under open access but not under full property rights, the growth rate will be higher under full property rights. If the resource is mined in both cases, the growth rate of the economy is still higher under full property rights, as less labor is allocated towards resource mining. Consumption growth turns negative under open access if the resource is mined and resource harvesting is very efficient according to (33). □

Proposition 3 shows that when natural resources are used under full property rights, consumption growth is never smaller than in a situation with resources under open access. When the resource is productive enough that conservation is optimal, the institutional setting of resource use is irrelevant for consumption growth.

5 Growth and the conservation or depletion of renewable natural resources under trade

We allow that productivities of capital accumulation (ζ_j), the mass of intermediates (μ_j), the coefficients of the final goods production function (α_j, β_j, γ_j, τ_j), and the resource growth rate η_j to differ between the countries $j = 1, \dots, J$.[11] The share of intermediate

[11] Also, carrying capacity $\overline{S}_j$ and and harvesting function (ψ_j) may differ, but in the current set-up, they are normalized to one.

products τ_j is usually interpreted as a measure of openness (Acemoglu and Ventura, 2002). We also allow for the case that institutional setting of resource use differs across countries, with some countries harvesting their resources under open access conditions, while others have full property rights. In addition, we allow for the discount factor ρ_j to differ between countries, but assume the preference of consumption smoothing over time, ϑ, is the same in all countries, to avoid tedious case distinctions.

The dynamic system can still be described by the equations stated in Section 4.1 for each country, but the determination of the rental rates of capital is more complicated, as the countries' rental rates of capital are interdependent. In what follows, we will concentrate on a steady state, i.e. a state with constant growth rates and constant rental rates of capital. Then, labor allocation must be constant in both institutional settings of resource use. Furthermore, capital used in consumption good production and in investment good production grows at the same rate as the total capital stock.

As rental rates of capital r_j are constant in steady state, it follows from (22) that all incomes grow at the same rate. Because local capital stocks grow at the same rate as local income, all capital stocks also grow at the same rate. Using g to denote the common growth rate of capital stocks, we obtain from (17b) that

$$r_j^\tau = \zeta_j \, (g + (\vartheta - 1) \, \hat{C}_j^* + \rho_j). \tag{34}$$

Using this and the fact that the consumption growth rates equal $\hat{C}_j^* = \alpha_j \, \hat{S}_j^* + (\gamma_j + \tau_j) \, g$, i.e.

$$r_j^\tau = \zeta_j \, (g + (\vartheta - 1) \, (\alpha_j \, \hat{S}_j^* + (\gamma_j + \tau_j)) + \rho_j) \tag{35}$$

in the equation for the price index of the numeraire, the common capital growth rate g is implicitly given by

$$\sum_{j=1}^{J} \mu_j \, \Big(\zeta_j \, ((1 + (\vartheta - 1) \, (\gamma_j + \tau_j)) \, g + (\vartheta - 1) \, \alpha_j \, \hat{S}_j^* + \rho_j) \Big)^{\frac{1-\varepsilon}{\tau}} = 1. \tag{36}$$

If all countries conserve their resources, the model turns into an AK-model with trade, as in Acemoglu and Ventura (2002): Equation (36) directly determines the common growth rate g as a function of parameter values.

In our analysis of growth and the conservation or depletion of renewable natural resources under trade, we proceed in two steps. First, we analyze how widening international trade affects the use of natural resources. We define 'widening international trade' as including an extra trading partner, such that $J \rightarrow J+1$ and the mass of intermediates N increases. This includes the case of opening up to trade from one to two trading partners. We discuss the impacts from moving from autarky to trade for symmetric countries in Appendix C. Once we know the impact of trade on resource use, we proceed to discuss the overall impact of widening trade for a country. Second, we study how a change in the institutional setting of resource use in of one country affects resource use and growth for the trading partners.

5.1 Resource mining or conservation under trade

Widening trade increases the mass of available intermediate products and changes the demand for the individual intermediate product. This impacts the local rental rates of capital. Intertemporal income and substitution effects occur, which may impact the pattern of resource use. In the following, we first discuss what happens in the long-run when the resource is harvested under open access before we turn to the discussion of the full property rights case.

In countries with open access conditions, the labor allocation that determines resource use is independent from the trading regime. We have $\ell_j^{oa} = \beta_j$ for all countries j where the resource is harvested under open access conditions. In these countries, the resource is mined (or conserved) in steady state, depending on whether β_j is larger (or smaller) than η_j.

The situation is different for countries with full property rights. As widening the number of trading partners affects the common growth rate (see Equation (36)), there are repercussions on resource use in countries with full property rights.

Following a line of argument similar to the one for the autarky case, we find that labor ℓ_j^{fp} allocated to resource harvesting in steady state in country j is determined by

$$\frac{(1-\ell_j^{oa})\,\ell_j^{fp}}{\ell^{oa_j}-\ell_j^{fp}}\,\ell_j^{fp} = \rho_j + (\vartheta-1)\,(\gamma_j+\tau_j)\,g + \max\left\{\underbrace{\eta_j - \phi\,\ell_j^{fp}}_{\text{conservation}},\underbrace{(\vartheta-1)\,\alpha_j\,(\eta_j-\phi_j\,\ell_j^{fp})}_{\text{mining}}\right\}. \quad (37)$$

The steady state is determined jointly by Condition (37) for all countries j with full property rights and Equation (36). Either conservation or mining is optimal, depending on which of the two terms on the RHS of (37) is larger in steady state. The two are equal if and only if $\ell_j^* = \eta_j$ for country j. This value of ℓ_j^* solves (37) for country j if

$$\rho_j = \bar{\Omega}_j(g) \equiv \frac{(1 - \ell_j^{oa})\, \eta_j}{\ell_j^{oa} - \eta_j}\, \eta_j - (\vartheta - 1)\,(\gamma_j + \tau_j)\, g. \tag{38}$$

This equation has a solution only if $\beta_j > \eta_j$, i.e. if mining occurs in the open-access setting. Thus, we obtain the following conditions

$$\begin{aligned} &\text{for all countries with } \beta_j < \eta_j \text{ or } \rho_j < \bar{\Omega}_j(g) \quad \text{conservation is optimal} \\ &\text{for all countries with } \beta > \eta_j \text{ and } \rho_j > \bar{\Omega}_j(g) \quad \text{mining is optimal.} \end{aligned} \tag{39}$$

For countries in the conservation regime, there is no feedback of the labor allocation and resulting resource use on the common steady-state growth rate g. For countries in the mining regime, however, an increase in ℓ_j^* decreases the rate of resource depletion, $d\hat{S}_j^*/d\ell_j^* < 0$. This affects the growth rate g.

By (36), we have $\partial g/\partial \left((\vartheta - 1)\, \hat{S}_j^* \right) < 0$.[12]

The results on resource use under trade are summarized in the following proposition.

Proposition 4. *[Trade and resource use]*

(i) For countries with open access conditions, trade has no influence on resource use.

(ii) Widening international trade in a steady state where no country with full property rights initially mines the resource favors mining if $\vartheta > 1$, and favors conservation if $\vartheta < 1$.

Proof. (i) The result follows from $\ell_j^{oa} = \alpha_j/(\alpha_j + \beta_j)$.

(ii) If no country with full property rights mines the resource, widening international trade unambiguously increases the common growth rate g (cf. Condition 36). An increasing g decreases the left-hand side of (38) if $\vartheta > 1$, and increases the left-hand side of (38) if $\vartheta < 1$. □

[12] For this reason, Condition (37) holds although g depends on whether the country mines or conserves its resource.

Some remarks on the results summarized in Proposition 4 are in order. First, under the given assumptions on production technologies, we find that when the resource is used under open access, opening up for trade with intermediate goods has an unambiguously positive effect. It does not influence resource extraction and enhances capital accumulation. This is in contrast to the case where the resource good is traded directly, as trade may decrease long-run welfare if the world market price of the resource is larger than the domestic price in autarky (Brander and Taylor, 1997a). Under full property rights, trade can have an impact based on the intertemporal mechanism. In the described set-up, widening trade increases the common growth rate and thus the rental rate of capital (see Equation (35)). With $\vartheta > 1$, the substitution effect dominates, and capital and the resource become substitutes in terms of investment. With the increased rental rate of capital, investment into the capital stock is increased. It substitutes for investment into the resource stock — more of the resource is used presently in consumption goods production, and less is left for future uses. Mining becomes more likely.

5.2 The institutional setting of resource use impacts resource use and economic growth of trading partners

We now turn to the question that basically initiated the literature on renewable resource use and trade. Changing the institutional setting of resource use in one country may impact resource use in that country. If the change in the institutional setting impacts local resource use, it may also impact resource use in other countries.

Proposition 5. *[The institutional setting of resource use and economic growth of trading partners]*

Consider a country j in an open-access mining regime that shifts towards private property rights. When all other countries operate either under open access or in the conservation regime under full property rights, the switch of country j leads the common growth rate to increase if $\vartheta < 1$, and to decrease if $\vartheta > 1$.

Proof. See the Appendix B. □

Proposition 5 shows that the development of one country, in terms of improved property rights, has external effects on other countries. This is a pecuniary exernality, as it comes about due to the change in terms of trade, and trade balance requires all countries to grow at the same rate in steady state. When the substitution effect dominates, i.e. for $\vartheta > 1$, the shift towards full property rights decreases the common growth rate. he reason is as follows. With the introduction of property rights, the resource stock turns into an investment good, leading to a lower depletion rate and reduced resource use. With $\vartheta > 1$, the substitution effect dominates and investments into to resource and capital turn into substitutes. The 'investment' into the resource is increased and less of it is used in consumption good production. Accordingly, capital is shifted from investment good production to consumption good production. Capital accumulation in this one country slows down. This has repercussion on the trading partners, as less intermediate goods are available from the country that changed the property right regime. The result is that the common growth rate slows down. Although this is a pecuniary externality it has welfare consequences for the other countries. This is particularly evident for a country j where households have a very low time preference rate $\rho_j \approx 0$. Welfare in this country only depends on the long-run development of the economy, i.e., on the steady state consumption growth rate g. Welfare in this country thus decreases with the other country's switch to private property rights if $\vartheta > 1$ and increases if $\vartheta < 1$.

The change in the growth rate may have repercussions on resource use for countries with full property rights. As we assumed countries have the same ϑ, the potential feedback effect goes in the same direction for all these countries. If these other countries are mining their resources under open access, this process may even turn positive consumption growth rates into negative growth rates. The effect is particularly pronounced if the country that improves property rights is 'big' in the sense that it contributes a large mass μ_j of intermediate products to the world market. All these effects are reversed when preferences for intertemporal consumption smoothing are weak, $\vartheta < 1$. Proposition 5 offers an explanation why there is international effort to regulate the resources in other countries, but it also explains why this effort may be limited in some situations.

If a country considers the growth rate of consumption to be more relevant than the growth rates of income g, the country may have an incentive to introduce full property rights even when $\vartheta > 1$ and, following Proposition 5, the common growth rate is reduced. Consider

$$\hat{C}_j^* = \alpha_j \hat{S}_j^* + (\gamma_j + \beta_j)g.$$

With the introduction of private property rights, $\hat{S}_j$ decreases in absolute terms. Then, the growth rate of consumption may still increase, although g decreases.

Proposition 6 states results for the situation when one country switches from full property rights to open access.

Proposition 6. *[The institutional setting of resource use and resource use of trading partners]*

Consider a steady state where all countries with full property rights are in the conservation regime. If a country with full property rights and $\beta_j > \eta_j$ shifts towards open access, this favors mining in all countries with full property rights.

Proof. Country j will switch to the mining regime in open-access. This will cause an increase of $(\vartheta - 1)\, g$ and thus a decrease of the right-hand side of (38) (see Proof of Proposition 5 for $dg/d\hat{S}_j$). Thus, this switch favors mining in all countries with full property rights. □

Proposition 6 shows that a change in the institutional setting of resource use in one country, leading to resource mining in that country, can spill over to other countries that are connected via trade. Whether the trading partners do start mining their resource depends on their characteristics, captured by the parameter values. They allocate more capital to the investment sector and use the resource as substitute. Whether they actually start mining depends on the exact parameter configuration. For $\vartheta < 1$, the reasoning is analogously in the opposite direction.

6 Discussion and conclusion

We have studied the impact of economic growth and international trade on resource conservation and depletion. We also examined under which conditions resource use has repercussions on economic growth and to what extent the institutional setting of resource use matters.. Our study shifts the focus compared to previous models on resource use and international trade in the sense that the natural resource is not traded in our set up. We use our dynamic general equilibrium setting to focus on a novel, intertemporal mechanism that also affects the optimal conservation or depletion of renewable resources. The impact of the mechanism depends on the households' preferences for consumption smoothing and may turn capital and the resource into substitutes or complements concerning investment and consumption good production. Thereby, the mechanism relates to the composition effect—a change in the share of the resource in national income—discussed in the literature (Copeland and Taylor, 2004). It may interact with the technique effect, while it works independently from the scale effect. The intertemporal mechanism would also be at work if a resource was traded and managed under full property rights. The dynamic effects of trade on resource use would add to the standard effects of comparative advantage and specialization that are studied in static models. For open access, we show that the intertemporal mechanism does not matter (as might have been expected), and thus neither re-inforces nor offsets other channels.

In line with resource-economic theory, we show that under open access, agents allocate labor to exploit the resource without considering the consequences for long-run economic development. Labor allocation to the resource only depends on production elasticities, it is independent of preferences and resource productivity. Resource conservation only prevails when the resource is sufficiently productive. Besides, if conservation prevails under open access, it also prevails under full property rights. In this case, consumption growth rates are the same under both institutional settings. When mining occurs, the negative drag on consumption growth is stronger under open access, as more labor is used in resource harvesting. The decision to mine or conserve the resource under full property rights is further driven by the preference for intertemporal consumption smoothing and the utility discount rate, as well as capital productivity. Specifically, we have shown that a strong preferen ce for consumption smoothing gives incentives to deplete the resource stock to maintain consumption while accumulating capital. In a context of international trade, trade balance drives convergence in capital growth between trading partners. Widening international trade mechanically increases income growth through the larger variety of intermediate goods available for production, assuming the impact on resource depletion is sufficiently small. For countries with open access to the natural resource, trade has no impact on the decision to mine or conserve the resource. However, under full property rights, harvest regimes across a trade block become conditional on the exploitation regime others adopt since mining impacts the common capital growth, the direction being dependent on preferences for consumption smoothing. We have restricted our analysis to the case where countries share the same consumption smoothing preferences, but relaxing this assumption, our model set up offers the possibility to investigate an even wider range of cases.

Our results show that changes in the institutional setting of resource use in one country may have external effects on other countries via trade. Under international trade, the introduction of full property rights may lead to higher or lower economic growth for all trading partners. Even if this is a pecuniary externality, that comes about due to terms of trade effects, it has welfare consequences in the other countries. These possible negative welfare effects on trading partners may explain overall low progress on international resource conservation. Our results also show that international trade impacts resource conservation or depletion of natural resources. If widening trade leads to an overall increase in the growth rate of capital, it makes mining more likely for weak intertemporal substitution. These two results show how international trade may have conflicting impacts on the achievement of the sustainable development goals.

The case of India's forest policy is one example that can be interpreted in the light of our findings. Obviously, India is a growing economy that is trading in intermediate products. It implemented policies to increase forest cover (see Foster and Rosenzweig (2003) for a description of the data). Based on our new mechanisms, one could say that this decision is driven by low preferences for intertemporal consumption smoothing that turned natural resource (i.e. forest) and capital investments into complements.

In our analysis, we focused on resources that are locally used and show that international trade nevertheless impacts resource use by changing economic growth. Harvesting the resource only depends on labor. As a next step, one could include directed technical change and examine which type of innovation policies aggravate or relief the pressure on the local resource. Another way forward would be to combine our intertemporal mechanisms with the static effects from changing resource prices due to trade.

Finally, we largely abstract from the welfare effects of trade in our paper. A full analysis of the welfare effects of trade, taking into account the new mechanism discovered in this paper, would be an important next step of research.

References

Acemoglu, D., 2008. Introduction to modern economic growth. Princeton University Press, Princeton, New Jersey, USA.

Acemoglu, D., Aghion, P., Bursztyn, L., Hemous, D., 2012. The environment and directed technical change. American Economic Review 102 (1), 131–166.

Acemoglu, D., Ventura, J., 2002. The world income distribution. Quarterly Journal of Economics 117 (2), 659–694.

Benarroch, M., Weder, R., 2006. Intra-industry trade in intermediate products, pollution and internationally increasing returns. Journal of Environmental Economics and Management 52 (3), 675–689.

Bogmans, C., 2015. Can the terms of trade externality outweigh free-riding? the role of vertical linkages. Journal of International Economics 95 (1).

Bovenberg, A. L., Smulders, S. A., 1996. Transitional impacts of environmental policy in an endogenous growth model. International Economic Review 37 (4), 861–893.

Brander, J. A., Taylor, M. S., 1997a. International trade and open-access renewable resources: The small open economy case. Canadian Journal of Economics 30 (3), 526–552.

Brander, J. A., Taylor, M. S., 1997b. International trade between consumer and conservationist countries. Resource and Energy Economics 19 (4), 267–297.

Brander, J. A., Taylor, M. S., 1998. The simple economics of easter island: A ricardo-malthus model of renewable resource use. American Economic Review 88 (1), 119–138.

Bretschger, L., Karydas, C., 2017. Optimum growth and carbon policies with lags in the climate system. Environmental and Resource Economics 57 (2), 1–26.

Brunnschweiler, C. N., 2008. Cursing the blessings? Natural resource abundance, institutions, and economic growth. World Development 36 (3), 399–419.

Bulte, E. H., Barbier, E. B., 2005. Trade and renewable resources in a second best world: An overview. Environmental and Resource Economics 30 (4), 423–463.

Cabo, F., Martín-Herrán, G., Martínez-García, M., 2014a. On the effect of resource exploitation on growth: Domestic innovation vs. technological diffusion through trade. In: Moser, E., Semmler, W., Tragler, G., Veliov, V. M. (Eds.), Dynamic optimization in environmental economics. Vol. 15 of Dynamic Modeling and Econometrics in Economics and Finance. Springer, pp. 243–264.

Cabo, F., Martín-Herrán, G., Martínez-García, M., 2014b. Property rights for natural resources and sustainable growth in a two-country trade model. Decisions in Economics and Finance 37 (1), 99–123.

Cherniwchan, J., Copeland, B. R., Taylor, M. S., 2017. Trade and the environment: New methods, measurements, and results. Annual Review of Economics 9 (1), 59–85.

Chichilnisky, G., 1994. North-south trade and the global environment. American Economic Review 84 (4), 851–874.

Clark, C. W., 1973. Profit maximization and the extinction of animal species. Journal of Political Economy 81 (4), 950–961.

Clark, C. W., 1990. Mathematical bioeconomics, 2nd Edition. Wiley, New York.

Clark, C. W., Munro, G. R., 1975. The economics of fishing and modern capital theory: A simplified approach. Journal of Environmental Economics and Management 2, 92–106.

Clark, C. W., Munro, G. R., Sumaila, U. R., 2010. Limits to the privatization of fishery resources. Land Economics 86 (2), 209–218.

Copeland, B. R., Taylor, M. S., 2004. Trade, growth, and the environment. Journal of Economic Literature 42 (1), 7–71.

Costello, C., Ovando, D., Clavelle, T., Strauss, C. K., Hilborn, R., Melnychuk, M. C., Branch, T. A., Gaines, S. D., Szuwalski, C. S., Cabral, R. B., Rader, D. N., Leland, A., 2016. Global fishery prospects under contrasting management regimes. Proceedings of the National Academy of Sciences 113 (18), 5125–5129.

Dasgupta, P. S., Heal, G., 1974. The optimal depletion of exhaustible resources. Review of Economic Studies 41, 3 – 28.

Dasgupta, P. S., Heal, G. M., 1979. Economic Theory and Exhaustible Resources. Cambridge University Press, Oxford, Great Britain.

Eliasson, L., Turnovsky, S. J., 2004. Renewable resources in an endogenously growing economy: balanced growth and transitional dynamics. Journal of Environmental Economics and Management 48 (3), 1018 – 1049.

Emami, A., Johnston, R. S., 2000. Unilateral resource management in a two-country general equilibrium model of trade in a renewable fishery resource. American Journal of Agricultural Economics 82 (1), 161–172.

FAO, 2015. 2015 global forest products facts and figures. http://www.fao.org/3/a-i6669e.pdf, accessed: 2017 May 11.

Fischer, C., 2010. Does trade help or hinder the conservation of natural resources? Review of Environmental Economics and Policy 4 (1), 103–121.

Foster, A. D., Rosenzweig, M. R., 2003. Economic growth and the rise of forests. Quarterly Journal of Economics 118 (2), 601–637.

Gordon, H. S., 1954. The economic theory of a common-property resource: The fishery. Journal of Political Economy 62, 124–142.

Gruber, J., 2013. A tax-based estimate of the elasticity of intertemporal substitution. Quarterly Journal of Finance 03 (01), 1350001.

Gylfason, T., 2001. Natural resources, education, and economic development. European Economic Review 45 (4-6), 847–859.

Hannesson, G., 2000. Renewable resources and the gains from trade. Canadian journal of economics 33 (1), 122–132.

Karp, L., Sacheti, S., Zhao, J., 2001. Common ground between free-traders and environmentalists. International Economic Review 42 (3), 617–648.

Karp, L., Zhao, J., Sacheti, S., 2003. The long-run effects of environmental reform in open economies. Journal of Environmental Economics and Management 45 (2), 246–264.

López, R. E., Anríquez, G., Gulati, S., 2007. Structural change and sustainable development. Journal of Environmental Economics and Management 53 (3), 307 – 322.

McAusland, C., 2005. Learning by doing in the presence of an open access renewable resource: is growth sustainable? Natural Resource Modeling 18 (1), 41–68.

Nakamoto, Y., Futagami, K., 2016. Dynamic analysis of a renewable resource in a small open economy: The role of environmental policies for the environment. Environmental and Resource Economics 64 (3), 373–399.

Nasi, R., Brown, D., Wilkie, D., Bennett, E., Tutin, C., van Tol, G., Christophersen, T., 2008. Conservation and use of wildlife-based resources: the bushmeat crisis. Secretariat of the Convention on Biological.

Papyrakis, E., Gerlagh, R., May 2007. Resource abundance and economic growth in the United States. European Economic Review 51 (4), 1011–1039.

Rebelo, S., 1991. Long-run policy analysis and long-run growth. Journal of Political Economy 99 (3), 500–521.

Sachs, J. D., Warner, A. M., 1999. The big rush, natural resource booms and growth. Journal of Development Economics 59, 43–76.

Schaefer, M. B., 1957. Some considerations of population dynamics and economics in relation to the management of the commercial marine fisheries. Journal of the Fisheries Board of Canada 14 (5), 669–681.

Solow, R. M., 1974. The economics of resources or the resources of economics. American Economic Review 64 (2), 1–14.

Suphaphiphat, N., Peretto, P. F., Valente, S., 2015. Endogenous growth and property rights over renewable resources. European Economic Review 76, 125–151.

UNCTAD, 2015a. Key statistics and trends in international trade 2014. UNITED NATIONS, New York and Geneva.

UNCTAD, 2015b. Key statistics and trends in international trade 2015. Tech. rep., UNCTAD.

World Bank, 2016. World bank data. http://data.worldbank.org/indicator [Accessed: 29.09.2016].

WorldBank, FAO, 2009. The sunken billions : The economic justification for fisheries reform. Tech. rep., World Bank.

Xu, B., 2000. Multinational enterprises, technology diffusion, and host country productivity growth. Journal of Development Economics 62 (2), 477–493.

Appendix

A First-order conditions for the representative household's dynamic optimization problem

$$
\begin{aligned}
C^{-\vartheta} &= \frac{\lambda}{p^I}\, p^C & (40)\\
w + \pi\, S &= q\, S \\
\pi = q - \frac{w}{S} &= \alpha\,\frac{p^C\,C}{\ell^{fp}\,S} - \beta\,\frac{p^C\,C}{S\,(1-\ell^{fp})} \\
&= \frac{p^C\,C}{S}\left(\frac{\alpha}{\ell^{fp}} - \frac{\beta}{1-\ell^{fp}}\right) \\
\frac{\pi\,S}{p^C\,C} &= \frac{\alpha}{1-\ell^{fp}}\left(\frac{1}{\ell^{fp}} - \frac{1}{\ell^{oa}}\right) = \frac{\alpha}{1-\ell^{fp}}\,\frac{\ell^{oa}-\ell^{fp}}{\ell^{fp}\,\ell^{oa}} & (41)\\
\frac{r}{p^I} &= \rho - \hat{\lambda} \overset{(40)}{=} \rho + \vartheta\,\hat{C} + \hat{p}^C - \hat{p}^I & (42)
\end{aligned}
$$

and in addition there is the condition for the optimal intertemporal allocation of the resource stock,

$$
\begin{aligned}
\frac{\lambda}{p^I}\left(q\,\ell^{fp} + \pi\left(\eta\,(1-2\,S) - \ell^{fp}\right)\right) &= \rho\,\frac{\lambda\,\pi}{p^I} - \frac{\lambda\,\pi}{p^I}\left(\hat{\pi} + \hat{\lambda} - \hat{p}^I\right) \\
\frac{q}{\pi}\,\ell^{fp} + \eta\,(1-2\,S) - \ell^{fp} &= \rho - \hat{\pi} - \hat{\lambda} + \hat{p}^I & (43)\\
\frac{q}{\pi}\,\ell^{fp} + \eta\,(1-2\,S) - \ell^{fp} &= \rho - \hat{\pi} + \vartheta\,\hat{C} + \hat{p}^C - \hat{p}^I + \hat{p}^I \\
\frac{w\ell^{fp}}{\pi\,S} + \eta\,(1-2\,S) + \hat{\pi} - \hat{p}^C &= \rho + \vartheta\,\hat{C} \\
\frac{\beta\,\frac{p^C\,C}{1-\ell^{fp}}\,\ell^{fp}}{p^C\,C\,\frac{\alpha}{1-\ell^{fp}}\,\frac{\ell^{oa}-\ell^{fp}}{\ell^{fp}\,\ell^{oa}}} + \eta\,(1-2\,S) + \hat{\pi} - \hat{p}^C &= \rho + \vartheta\,\hat{C} \\
\frac{\beta\,\ell^{fp}}{\alpha\,\frac{\ell^{oa}-\ell^{fp}}{\ell^{fp}\,\ell^{oa}}} + \eta\,(1-2\,S) + \hat{\pi} - \hat{p}^C &= \rho + \vartheta\,\hat{C} \\
\frac{\alpha\,\frac{1-\ell^{oa}}{\ell^{oa}}\,\ell^{fp}}{\alpha\left(\frac{1}{\ell^{fp}} - \frac{1}{\ell^{oa}}\right)} + \eta\,(1-2\,S) + \hat{\pi} - \hat{p}^C &= \rho + \vartheta\,\hat{C} \\
\frac{(1-\ell^{oa})\,\ell^{fp}}{\ell^{oa}-\ell^{fp}}\,\ell^{fp} + \eta\,(1-2\,S) + \hat{\pi} - \hat{p}^C &= \rho + \vartheta\,\hat{C}
\end{aligned}
$$

with the transversality conditions

$$e^{-\rho\,t}\,\lambda\,\pi\,S/p^I \xrightarrow{t\to\infty} 0$$

and

$$e^{-\rho\,t}\,\lambda\,K \xrightarrow{t\to\infty} 0.$$

B Proof of Proposition 5

The change from open-access mining to private property reduces the labor share allocated towards harvesting (see Lemma 1.). The lower share of labor allocated towards harvesting leads to an increase in $\hat{S}_j$ (note that $\hat{S}_j < 0$, so in absolute terms, it decreases). All other countries do not change their behavior. Next, consider how a change in the growth rate of one resource stock impacts the growth rate of all economies, using the Implicit Function Theorem on (36):

$$\frac{dg}{d\hat{S}_j} = \tag{44}$$

$$-\frac{\mu_j \frac{1-\varepsilon}{\tau}\left(\zeta_j\left(\left(1+(\vartheta-1)\left(\gamma_j+\tau_j\right)\right)g+(\vartheta-1)\,\alpha_j\,\hat{S}_j+\rho_j\right)\right)^{\frac{1-\varepsilon}{\tau}-1}(\vartheta-1)\alpha}{\sum_{j=1}^{J}\mu_j\,\frac{1-\varepsilon}{\tau}\left(\zeta_j\left(\left(1+(\vartheta-1)\left(\gamma_j+\tau_j\right)\right)g+(\vartheta-1)\,\alpha_j\,\hat{S}_j+\rho_j\right)\right)^{\frac{1-\varepsilon}{\tau}-1}(1+(\vartheta-1)(\gamma+\tau))} \tag{45}$$

To stay within real numbers, $\zeta_j\left(\left(1+(\vartheta-1)\left(\gamma_j+\tau_j\right)\right)g+(\vartheta-1)\,\alpha_j\,\hat{S}_j+\rho_j\right) > 0$.

If $\vartheta > 1$, $\frac{dg}{d\hat{S}_j} < 0$.

If $\vartheta < 1$, The condition $\vartheta < 1$ implies $-1 < (\vartheta - 1) < 0$. Also,

$$1 + (\vartheta - 1)(\gamma + \tau) < 0 \tag{46}$$

$$\Leftrightarrow (\vartheta - 1) < \frac{-1}{\gamma + \tau}, \tag{47}$$

cannot hold because because $\gamma + \tau < 1$ and $-1/(\gamma + \tau) < -1$. Thus,

$$1 + (\vartheta - 1)(\gamma + \tau) > 0$$

and $\frac{dg}{d\hat{S}_j} > 0$.

C Trade with symmetric countries

Consider the case of symmetric countries. We lose a lot in terms of management spill-overs, but it allows solving for g explicitly. Assume n identical countries. Then, from (36) we obtain

$$g = \frac{n^{\frac{\tau}{\varepsilon-1}}\mu^{\frac{\tau}{\varepsilon-1}}\frac{1}{\zeta} - (\vartheta - 1)\,\alpha\,\hat{S}^{*} - \rho}{1 + (\vartheta - 1)\,(\gamma + \tau)}.$$

We now compare this capital growth rate g under trade to the steady state capital growth rate without trade. As all local capital stocks grow at the same rate, based on (24c) and using (23), we have

$$\hat{K}^* = \frac{\overbrace{\mu^{\frac{\tau}{\epsilon-1}}\frac{1}{\zeta}}^{\bar{r}} - (\vartheta-1)\,\alpha\,\hat{S}^* - \rho}{1+(\vartheta-1)\,(\gamma+\tau)}.$$

Thus, if $\hat{S}^*$ was identical with and without trade—as e.g. under open access—, the growth rate of capital (and also of consumption) would be higher with trade (note that $\varepsilon > 1$.) Accordingly, under open access, the growth rate of the economy is higher with trade, independent of resource conservation or depletion. Also, when countries are more open—represented by a higher τ—, a higher growth rate g prevails.

Now consider impact on the rental rate of capital,

$$\begin{aligned} r^{\tau} =& \zeta(g + (\vartheta-1)(\alpha\hat{S} + (\gamma+\tau)g) + \rho) \\ =& \zeta((n^{\frac{\tau}{\varepsilon-1}}\mu^{\frac{\tau}{\varepsilon-1}}\frac{1}{\zeta} - (\vartheta-1)\,\alpha\,\hat{S}^* - \rho) + (\vartheta-1)\alpha\hat{S} + \rho) \\ =& n^{\frac{\tau}{\varepsilon-1}}\mu^{\frac{\tau}{\varepsilon-1}} \\ r =& (n\mu)^{\frac{1}{\varepsilon-1}} \end{aligned}$$

For identical countries, trade increases the rental rate of capital (under autarky: $r = \mu^{\frac{1}{\varepsilon-1}}$).