Supply-side climate policy using capital income taxes: A game-theoretic model of OECD and OPEC

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Abstract

When exhaustible fossil fuel resources are both scarce and cheap to extract, attempts to curtail related externalities by conventional demand-side measures may perversely accelerate depletion. An unconventional approach to limiting carbon emissions, which may avoid this 'Green Paradox', is explored: taxation of the financial returns to sovereign wealth investments held by resource-rich countries. A differential game model of a general equilibrium Dasgupta-Heal-Solow-Stiglitz economy is set up, with decisions on capital accumulation and resource use made jointly. When the resource owner has no opportunities to use the resource domestically, differential capital income taxation can be used to attain the efficient outcome. The possibility to develop a domestic production industry limits the effectiveness of policy based on capital income taxes, as capital is allocated inefficiently. The welfare implications of implementing such suboptimal policies are studied.

Keywords: non-renewable resources, fossil fuels, climate change, green paradox, OPEC
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1 Introduction

According to the 'Green Paradox' (Sinn [2008]), supply-side responses may render demand-side policies to curtail the use of exhaustible, polluting resources ineffective. Worse, such policies may perversely accelerate the depletion of such resources and hence aggravate the resulting pollution problem. A rational owner of a stock of an exhaustible resource will plan a depletion schedule such that profits cannot be increased by shifting extraction across time: along an optimal schedule, the marginal net revenues gained from selling the resource must be constant, in present value terms, at all moments. Policies which affect demand, and so the marginal net revenues, differently across time will result in the resource owner changing her depletion plans accordingly. In particular, policies perceived to cut future demand by more than present demand will increase present depletion rates. The resource owner foresees that the resource will fetch a lower price in the future, and seeks to sell more of the resource now.

In the context of climate change, such unintended policy consequences would ceratinly matter. The use of exhaustible fossil fuel resources produces carbon dioxide (CO_2), which traps infrared radiation in the Earth's atmosphere, resulting in a radiative imbalance that causes a mean warming of the Earth's climate, and consequent more detailed changes in the climate. CO_2 is a stock pollutant with very low rates of removal from the subsystem composed of the atmosphere, the biosphere and the surface ocean. An increase the rate of build-up of atmospheric concentrations could plausibly accelerate climate change. This would adversely affect welfare. Firstly, bringing forward the impacts would increase their cost in present-value terms. Secondly, it is likely that the severity of these impacts depends on the rate of climate change, as this affects the cost of adaptation.

Furthermore, an extreme version of the Green Paradox argues that demand-side policies may not be able to limit the cumulative depletion of the resource—that the cumulative supply may be perfectly inelastic. This depends on the costs of extracting the resource and the characteristics of potential substitutes (van der Ploeg and Withagen [2010]). Were marginal climate impacts to rise severely above some threshold level, an optimal policy would seek to leave some fossil fuels unused forever. For example, Allen et al. [2009] have argued that we should aim to emit no more than a trillion tonnes of carbon altogether if we want to have a reasonable chance of remaining below the $2\circ$C threshold.

Thus, climate policy has to take into account such supply-side responses. Notice that the conventional 'first-best' climate policy instrument—a price on carbon equal to the social cost—would imply depressing future relative to present-day demand, and thus could end up bringing climate change forward.

The Green Paradox is predicated on the Hotelling exhaustible resource model. According to this model, the resource owner chooses a depletion schedule which eliminates opportunities for intertemporal arbitrage. In particular, along an optimal schedule, at every moment, return to the marginal unit of the resource should be equal whether the resource is left in the ground, unextracted, or instead extracted and sold, with the revenues invested. The respective rates of return are the rate of appreciation of the unit price of the resource, and the rate of return on financian investments. According to the well-known Hotelling Rule, these two must be equated for a depletion plan to be optimal.

It has been suggested that this relationship between the rate of return on investments and resource depletion could be utilised to develop alternative climate policy instruments—namely, taxes on capital income, i.e. altering the effective rate of return on financial assets (Sinn [2008]). If resource owners can be identified, and if they are essentially reliant on financial markets for saving opportunities, then such taxes would alter the effective rate of return on investments they face. Such a policy would be most readily interpreted in an international context, in which countries which are reliant on fossil fuel wealth and uncooperative in terms of climate policy could be easily identified, and capital income taxes imposed to incentivise efficient depletion choices. Such a policy may also have various other benefits. Taxing returns to foreign investors may be politically more palatable than imposition of carbon taxes. The taxes would also, in themselves, have a positive fiscal effect on the countries which are the recipients of investment. However, several drawbacks, specific to the proposed policy instruments, also exist. The instruments would likely be toxic in terms of foreign, climate and geopolitics. They would be unlikely to foster a cooperative atmosphere in which to conduct climate negotiations. Secondly, there could be substantial distributional effects which might turn out to be ethically indefensible. The effectiveness of such instruments also relies on the lack of alternative investment opportunities. Were these present—in terms of non-resource rich economies that chose to remain outside the policy regime, and thus would offer better investment opportunities—or in terms of developing the local productive sectors, the effectiveness of the policy could be blunted. Potentially, in the latter case, there could be alternative benefits in terms of reducing the dependence of said economies on resource revenues, considering all the difficulties that such reliance can bring.

Finally, the proposed policy, if not applied to domestic fossil fuel owners, would be limited in scope. Coal, the most abundant and one of the dirtiest of fossil fuels, is geographically widely distributed. Hence, targeting owners of coal stocks could be very difficult.

In what follows, I will sketch a general equilibrium, long-term model of the world economy (a version of the so-called Dasgupta-Heal-Solow-Stiglitz economy). Thus, the model fits into a tradition of modelling economic growth when an essential factor input is exhaustible. The global economy is divided into two countries, one of which owns the entire resource stock, with the other one focusing on producing goods. This model will be augmented with a stock externality tied to the use of the exhaustible resource, to consider how such an externality affects what should be considered as optimal growth.

The present study belongs to a line of literature on sustainable resource use and capital accumulation, beginning with Stiglitz [1974] and Dasgupta and Heal [1974]. A decentralised, differential game model was developed by Chiarella [1980]. Other authors have since furthered the analysis of the centralised model, including Pezzey and Withagen [1998].

Two papers are particularly relevant to the present study. Groth and Schou [2006] develop an endogenous growth model, with growth driven by positive externalities to investment. They study the effects of constant taxes on capital gains and on interest income, as well as time-varying taxes on use of the resource, on long-run growth rates. Daubanes and Grimaud [2009] develop a two-region endogenous growth model, with growth driven by an explicitly modelled research sector, to consider taxation of a polluting resource both from a globally optimal viewpoint, and in a decentralised equilibrium. This paper presently features a simple two-region Ramsey-Cass-Koopmans growth model, and uses it to study the effect of time-varying capital income taxes on the depletion schedule of the polluting resource. The present model should be considered a precursor to more realistic models in the same vein.

The paper is divided into 5 parts. In Section 2, I set up the basic model and consider the benchmark cases of a decentralised equilibrium in the absence of climate policy, and of the global optimum. In Section 3.2, I first consider the case in which the resource exporter has no opportunities to invest in its domestic production sector, and show that the efficient outcome can be attained by appropriate capital income taxes. I then consider the outcome if such taxes are mandated without regard for the possibility that the resource exporter may take its investments elsewhere. In Section 4, an equilibrium in open-loop strategies is developed, when the objective of climate policy is not to maximise global welfare, but welfare of the oil-importing countries. Section 5 concludes.

2 Model setup

Consider a differential game between two players, called Country E (exporter) and Country I (importer). Country I imports fossil fuels, used as a factor of production. Both players represent a bloc of small countries, and their decisions represent individual choices made by a continuum of consumers. Hence, all prices are taken as given, except the resource price, which is determined jointly by Country E consumers. Decisions on the resource price are made taking into account effects on global demand and on the profitability of domestic firms. I interchangeably refer to a country and its representative consumer.

Country E owns a stock of the fossil fuel resource $S(t)$, with the initial amount S_0 given[2]. The resource can be extracted costlessly and sold to Country I. Alternatively, the resource can be sold to domestic producers. An international secondary market in the resource exists, eliminating any price differentials. Net revenues, from resource sales, interest on savings, and wage income can be either spent on consumer goods, or invested in asset markets. The stock of financial assets is denoted by A.

In addition to the resource, the other factors used in production are physical capital K and labour L. Production technologies are identical across the two countries, up to a multiplicative Hicks-neutral TFP factor. The production sector manufactures a homogeneous good, which can be either consumed immediately or used in investment. Negative investment is allowed, i.e. capital can be consumed. Physical capital does not depreciate. It is instantaneously mobile, and can be immediately and costlessly transported from one country to the other. Hence, in the absence of taxes or subsidies on capital income, the marginal product of capital is always equalised between the two countries. Introducing such taxes drives a wedge between the rate of return on invested funds, and the marginal product of capital. We thus denote *effective* rates of return that investors face by by r_E^e and r_I^e. Labour endowments are immobile and constant. In both countries, the production sector is perfectly competitive.

The assumption of perfect capital mobility is made for simplicity, but it is justified as the present model should be considered as one of long-run dynamics. With imperfect capital mobility, a policy change (change in capital income taxation) would result in initial transition dynamics to the new equilibrium path. As these will not add particularly interesting insights, I abstract from them to focus on the equilibrium path. The tax applies to negative investment, i.e. borrowings, too, in which case it is a subsidy on interest payments. Alternatively, negative net investment implies Country I investors owning Country E capital stocks; returns on such investments are, effectively, subsidised. Negative tax rates imply subsidies to capital income and taxes on interest payments.

A discrete change in the tax rate causes an immediate adjustment in the allocation of capital between the two countries, and related changes in resource allocation, so as to equate the post-tax rate of return to capital and the oil price on world markets.

Consumption of the resource produces a pollutant: carbon dioxide. The induced climate change reduces the welfare of representative consumers. The

[2]Variables are denoted by the Roman and time-invariant parameters by the Greek alphabet (with the exception of costate variables, denoted by μ and λ). For clarity, the dependence of variables on time t is not explicitly denoted.

severity of these impacts depends on G, the accumulated stock of greenhouse gases in the atmosphere. This stock does not decay: the carbon emissions due to the burning of fossil fuels remain in the atmosphere forever.

We now turn to the choices the players face. Country E chooses consumption $C_E(t)$ and the resource price $p(t)$ to maximise a utilitarian welfare function. The resource price is measured in units of the consumption good, which is used as the numeraire. Country E observes the demand curve for the resource; equivalently, it could observe inverse demand and set the extraction rate.

Country E's problem is

$$\max_{C_E,p} \int_0^\infty \exp(-\rho t)\Big(L_E u(\frac{C_E}{L_E}) - L_E D_E(G)\Big)\,\mathrm{d}t \tag{1a}$$

$$s.t. \quad \dot{A} = r_I^e A_I + r_E A_E + pR(p) + \pi_E - C_E \tag{1b}$$

$$\dot{S} = -R \tag{1c}$$

$$\dot{G} = R + \frac{\mathrm{d}\tilde{G}}{\mathrm{d}t}, \quad G(0) = G_0 \tag{1d}$$

$$S(0) = S_0, \quad S(t) \geq 0 \quad \forall t \tag{1e}$$

$$A(0) = A_0 \tag{1f}$$

$$\pi_E = F_E(K_E, R_E, L_E) - r_E K_E - pR_E \tag{1g}$$

Savings held abroad and domestically equal total assets: $A = A_E + A_I$. Given C_E, saving is determined by the budget constraint. The objective is to maximise the discounted stream of felicity from per-capita consumption $u(\frac{C_E}{L_E})$ and (per-capita) costs of climate change $D_E(G)$. L_E is Country E's share of world population, with total population normalised to one. ρ denotes the discount rate.

We assume that climate change impacts on welfare are strictly convex in the stock of greenhouse gases, and bounded over $G \in [G_0, \overline{G}]$ where $\overline{G}$ denotes the maximum possible stock accumulable. The stock of greenhouse gases changes according to (1d), with $\tilde{G}$ denoting an exogenous time profile of concentrations due to other sources, such as burning coal to generate power. The stock is monotonically increasing, so that drawdown of carbon dioxide into the deep ocean and eventually the Earth's crust, or efforts to accelerate these processes by carbon capture and storage, are ignored.

$R(p)$ gives the aggregate demand for the resource. r_E^e is the rate of return on financial assets, and r_E the marginal product of capital employed domestically. Finally, (1g) gives domestic wage income, or production less factor payments. The production function $F(K, R, L)$ is assumed jointly concave and homogeneous of degree one.

Turn now to Country I. The representative consumer has an identical felicity function to that of the Country E consumer, and is also affected by climate change damages. The consumer also owns capital employed by domestic firms, denoted by B. The problem is then to solve

$$\max_{C_I} \int_0^\infty \exp(-\rho t)\big(L_I u(\frac{C_I}{L_I}) - L_I D_I(G)\big)\,\mathrm{d}t \tag{2a}$$

$$s.t. \quad \dot{B} = r_I^e B_I + r_{I,E}^e B_E + \pi_I + T - C_I \tag{2b}$$

$$B(0) = B_0 \tag{2c}$$

$$\pi_I = F_I(K_I, R_I, L_I) - r_I K_I - pR_I \tag{2d}$$

and the equations governing the greenhouse gas stock (1d). r_I and $r_{I,E}$ indicate the effective (post-tax) rates of return Country I investors face on domestic and foreign investments, respectively. T represents net tax revenues collected using the capital income taxes (these may amount to a net subsidy). All other variables are analogous to those defined in Country E's problem and similar assumptions are made regarding convexity or concavity.

Global goods markets clear at all points in time (the subscript W is used to denote aggregate values), and the returns on financial assets must equal the return on capital assets:

$$\dot{K} = F_W - C_W \tag{3}$$

$$r_E = r_E^e, \quad r_I^e = r_{I,E}^e \tag{4}$$

By Walras' Law, the financial market then also clears, so that $K = A + B$.

I now simplify the analysis by assuming specific functional forms for the production, felicity, and damage functions. The production function is Cobb-Douglas, with decreasing returns to scale in capital and the resource jointly:

$$F_i = \Omega_i K_i^\alpha R_i^\beta L_i^{1-\alpha-\beta}, \qquad \alpha + \beta < 1, \qquad i \in \{I, E\} \tag{5}$$

where Ω_i represents technological progress. Both countries' resource demand curves exhibit constant price elasticity, and so does aggregate demand:

$$R_i = \left(\frac{\Omega_i \beta K_i^\alpha L_i^{1-\alpha-\beta}}{p}\right)^{\frac{1}{1-\beta}}, \qquad \epsilon \equiv \frac{\partial R}{\partial p}\frac{p}{R} = -\frac{1}{1-\beta} \tag{6}$$

The above implies Country E takes into account the effect its resource supply choices have on the current global rental rate of capital. I could equally assume that it takes the rate of return as given, in which case the (still constant) elasticity would be different.

The allocation of Country E capital and of the resource between the two markets is uniquely determined and will satisfy

$$\frac{K_I}{K_E} = \left(\frac{r_E^e}{r_I}\right)^{\frac{1-\beta}{1-\alpha-\beta}} \left(\frac{\Omega_I}{\Omega_E}\right)^{\frac{1}{1-\alpha-\beta}} \frac{L_I}{L_E} \tag{7}$$

$$\frac{R_I}{R_E} = \frac{r_I}{r_E^e}\frac{K_I}{K_E} \tag{8}$$

In the absence of taxes, as the technology is homothetic, resource and capital are employed in the same ratio by both countries. The introduction of capital income taxation shifts capital out of Country I, more than proportionately to the share of the capital income that is taxed away. It also shifts the resource towards Country I. As a result, production is shared between the two countries according to

$$\frac{F_I}{F_E} = \Big(\frac{r_E^e}{r_I}\Big)^{\frac{\alpha}{1-\alpha-\beta}}\Big(\frac{\Omega_I}{\Omega_E}\Big)^{\frac{1}{1-\alpha-\beta}}\frac{L_I}{L_E} \tag{9}$$

I also specify the felicity function to have the isoelastic form:

$$u(C) = \begin{cases} \frac{C^{1-\frac{1}{\sigma}}}{1-\frac{1}{\sigma}} & \text{for } \sigma \neq 1, \\ \log C & \text{for } \sigma = 1 \end{cases} \tag{10}$$

Finally, I specify the marginal pollution impacts to have a constant elasticity with respect to the pollution stock:

$$D(G) = \xi G^{\theta} \tag{11}$$

2.1 Equilibrium without climate policy

I consider the decentralised equilibrium of the model in open-loop strategies. Under these strategies, both players commit, at time $t = 0$, to the entire time path their control variables. These paths are determined by optimising, taking the other player's control variables as given. In equilibrium, both players' expectations are correct. We thus have two dynamic optimisation problems, and necessary conditions for an optimum are obtained using Pontryagin's Maximum Principle.

Country E's Hamiltonian is

$$\begin{aligned} \mathscr{H}_E = &L_E u\big(\frac{C_E}{L_E}\big) - L_E D_E(G) + \mu_A\big(rA + pR(p) + \pi_E - C_E\big) \\ &- \mu_{S,E}R + \mu_{G,E}\big(R + \tilde{G}(t)\big) \end{aligned} \tag{12}$$

where μ_A, $\mu_{S,E}$ and $\mu_{G,E}$ denote the costate variables. The maximised Hamiltonian is concave in the state variables, and by the Arrow Sufficiency Theorem, a unique optimum to the problem exists. Note that I am implicitly assuming that neither country recognises the relationship between its stock of financial assets and the aggregate capital stock, and thus the scale of production. This is motivated by the assumption that investment decisions are made by individual (small) investors).

We will denote growth rates of variables by hats[3]. The first-order conditions and the equations of motion of the costate variables are

$$u'(\frac{C_E}{L_E}) = \mu_A \tag{13a}$$

$$p(1-\frac{1}{|\epsilon|})(1-\frac{\partial R_E}{\partial R})\mu_A = \mu_{S,E} - \mu_{G,E} \tag{13b}$$

$$\hat{\mu}_A = (\rho - r), \quad \hat{\mu}_{U,E} = \rho - d_E, \quad d_E \equiv \frac{L_E D'_E(G)}{\mu_{U,E}} \tag{13c}$$

where we have defined $\mu_{U,E} \equiv \mu_{S,E} - \mu_{G,E}$, or the welfare benefit of retaining the marginal unit of oil underground, rather than in the atmosphere. This benefit arises from being able to the use the unit later, plus avoiding the marginal climate impacts.

Recall that ϵ is the price elasticity of fossil fuel demand. (13b) shows that the marginal benefit (to the resource owner) of pumping out an extra unit of oil and selling it, taking into account both its market power and the positive effect on the profits of domestic firms, must equal the marginal welfare cost of transferring the unit of carbon from underground to the atmosphere. From these, we obtain straightforwardly the Ramsey Rule and the Hotelling Rule:

$$\hat{C_E} = \sigma(r^e_E - \rho) \tag{14}$$

$$\hat{p} = r^e_E - d_E + (\hat{R} - \hat{R}_I) \tag{15}$$

Note that the standard Hotelling rule is augmented by consideration of climate change impacts and of the impacts on domestic manufacturing industry. It will never be optimal to extract the entire stock in finite time, as the marginal product of the resource goes to infinity as use tends to zero.

Finally, an optimal solution has to satisfy the transversality conditions:

$$\lim_{t\to\infty} \exp(-\rho t)\mu_A A = 0 \tag{16a}$$

$$\lim_{t\to\infty} \exp(-\rho t)\mu_{S,E} S = 0 \tag{16b}$$

$$\lim_{t\to\infty} \exp(-\rho t)\mu_{G,E} G = 0 \tag{16c}$$

As μ_S is strictly positive and grows at the rate ρ, (16b) implies $S \to 0$. μ_G is bounded, as is G, and so the third condition is automatically satisfied. Because of the bounded marginal damages and discounting at a strictly positive rate, and the unbounded marginal product of the resource and marginal utility of consumption, it will be optimal to (asymptotically) use up the entire stock. Consideration of (16a) is deferred until later, when dealing with particular instances of the model.

[3] I.e. $\hat{X} \equiv \frac{\frac{dX}{dt}}{X}$.

Turning to Country I, recall that the only decision variable is consumption (also determining investment). The Hamiltonian for its problem is

$$\mathscr{H}_I = L_I u\Big(\frac{C_I}{L_I}\Big) - L_I D_I(G) + \mu_B\big(r_I^e B + \pi_I + T - C_I\big) \tag{17}$$

We have simply omitted the equation of motion for G: as this depends on factors taken as given by the consumer, Country I cannot affect greenhouse gas emission and they do not enter the solution. The maximised Hamiltonian is jointly concave in the state variable B. The first-order condition for consumption, the equation of motion for the costate and the transversality condition are

$$u'\Big(\frac{C_I}{L_I}\Big) = \mu_B \tag{18a}$$

$$\hat{\mu}_B = \rho - r_I^e \tag{18b}$$

$$\lim_{t\to\infty} \exp(-\rho t)\mu_B B = 0 \tag{18c}$$

From (18a) we derive the Ramsey Rule for Country I:

$$\hat{C_I} = \sigma(r_I^e - \rho) \tag{19}$$

We now obtain the growth rate of aggregate consumption:

$$\hat{C_W} = \frac{C_I}{C_W}\hat{C}_I + \frac{C_E}{C_W}\hat{C}_E = \sigma(\frac{C_I}{C_W}r_I^e + \frac{C_E}{C_W}r_E^e - \rho) \tag{20}$$

In the absence of taxes, effective rates of return faced by two consumers equal the respective marginal products of capital, and so each other. Then, both countries just consume a fixed share of aggregate consumption.

3 Global optimum and optimal climate policy

Consider now the globally optimal outcome. We assume there exists a social planner who cares equally about the welfare of all people, and thus maximise the sum of the two welfare functions above. Solving as above, it is straightforward to obtain the key results. Firstly, capital and the resource are allocated so that their marginal products are equal across the two countries. Secondly, consumption is allocated so as to achieve equal *per capita* consumption everywhere.

The other optimality conditions include the Ramsey Rule and the Hotelling Rule:

$$\hat{C_W} = \sigma(r - \rho) \tag{21}$$

$$\hat{p} = r - d_W, \quad d_W \equiv \frac{L_I D_I'(G) + L_E D_E'(G)}{\mu_{S,W} - \mu_{G,W}} \tag{22}$$

where r and p stand for the marginal products of capital and the resource. μ_U has the same interpretation as before, but seen from the perspective of a social planner maximising global welfare. The slope of the Hotelling price path is attenuated only by global concerns over resource availability (μ_S) and climate change (aggregate marginal damages and μ_G). For a given level of greenhouse gas concentrations, the planner's Hotelling price path is shallower than the decentralised path—broadly implying conservation of the resource—when Country E makes up a lower fraction of the total population, reflecting the public bad nature of greenhouse gas emission. General statements are impossible to make as the entire trajectory of the system differs between the two solutions, and we leave further investigation for numerical experiments.

Consider now Country I setting up a climate regulator, which has the mandate to use capital income taxes (on capital invested in Country I, or by Country I residents in Country E) to implement climate policy. Say $\frac{q_I}{r_I}$ and $\frac{q_E}{r_I}$ percent of the capital income (interest payments) is taxed away (subsidised). Investors face the effective interest rates

$$r_I^e = r_I - q_I, \quad r_E^e = r_I - q_E \tag{23}$$

Any net revenues collected by the regulator will be paid back, lump-sum, to citizens of Country I. These taxes alter the resource owners' optimal depletion schedule; they affect aggregate investment incentives; and they affect the composition of where to produce. Finally, they will have a distributional impact. I will now develop two particular instances of the model to investigate these effects.

3.1 Very small resource exporter

I now want to consider the case in which the resource exporting country is very small. Then, as the resource revenues are divided between very few people, the welfare effect of these revenues is much greater than the related climate change impacts. Using an extreme case to fix ideas, I assume $D_E(G) \equiv 0$. Secondly, as the supply of the fixed factor (labour) is very low, Country E has little opportunity to produce goods domestically. Again, I choose the extreme case of there being no production technology in Country E ($\Omega_E = 0$). Country E can only sell the resource to Country I and it takes no account of the induced climate change. Under such a scenario, the Hotelling rule is just

$$\hat{p} = r_E^e$$

The solution to the problem turns out to be identical to that of maximising global utility from consumption, under a social planner who does not care about the externality. This is intuitive: under open-loop strategies, Country I takes the resource depletion path as given. As Country E does not care about pollution, and as climate change impacts enter welfare additively, i.e. without interacting with production or consumption, optimal choices are not altered. As resource demand has constant price elasticity, the optimal price path set by a monopolist coincides with the equilibrium price path in a competitive market. In the absence of externalities, the First Fundamental Theorem of Welfare Economics tells us that a decentralised outcome achieves the social optimum. Climate change impacts only act to reduce Country I's welfare; under open-loop strategies, Country I passively accepts this. The equilibrium outcome is thus identical to that in a particular case of the model employed by Chiarella [1980].

Consider first the case without taxes. The only steady state in levels is the degenerate one in which all variables equal zero. Following the example of Stiglitz [1974] and later authors (e.g. Chiarella [1980]; Pezzey and Withagen [1998] for the centralised problem without an externality), I instead rewrite the system in terms of the consumption-capital ratio, the output-capital ratio, and Country E's shares of the aggregate capital stock and consumption:

$$\begin{aligned} x &\equiv \frac{C_W}{K} \equiv \frac{C_E + C_I}{K} \\ y &\equiv \frac{F}{K} \\ z &\equiv \frac{A}{K} \\ s_C &\equiv \frac{C_I}{C_W} \end{aligned} \tag{24}$$

Now, the economy follows the system

$$\hat{x} = x - (1 - \sigma\alpha)y - \rho\sigma \tag{25a}$$

$$\hat{y} = \frac{1 - \alpha - \beta}{1 - \beta} x - (1 - \alpha)y \tag{25b}$$

$$\hat{z} = x - (1 - \alpha)y + \frac{\beta y - (1 - s_C)x}{z} \tag{25c}$$

$$\tag{25d}$$

The subsystem (x, y) in (25) is independent of the rest of the system. Figure 1 illustrates the phase diagram in (x, y)-space. The loci of points for which $\hat{x} = 0$ are given by $y = \frac{x - \rho\sigma}{1 - \sigma\alpha}$; of those for which $\hat{y} = 0$ are given by $y = \frac{1-\alpha-\beta}{(1-\alpha)(1-\beta)} x$). Following Stiglitz [1974], the following proposition obtains:

Proposition 1. As $t \to \infty$, the decentralised open-loop equilibrium of the

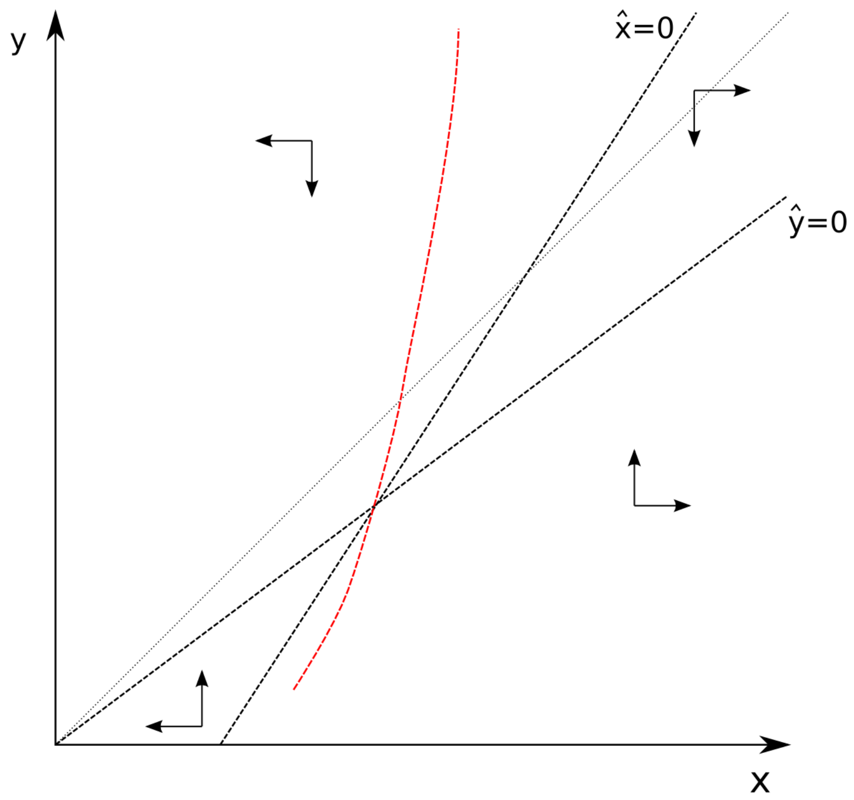

Figure 1: Phase diagram for the decentralised equilibrium. The black dashed lines indicate the loci of points for which $\hat{y} = 0$ or $\hat{x} = 0$. With no externality, the economy will start on the saddle-path (*red dashed line*) and head to the steady state (see Proposition 1). Initial stocks of capital and the resource determine the starting point of the economy.

economy will tend to a steady state in the variables (x, y, z), given by

$$x_\infty = \frac{(1-\beta)(1-\alpha)}{\alpha(1-\alpha-\beta\frac{1-\sigma}{\sigma})}\rho$$
$$y_\infty = \frac{1-\alpha-\beta}{\alpha(1-\alpha-\beta\frac{1-\sigma}{\sigma})}\rho$$
$$z_\infty = \frac{(1-s_{C,\infty})x_\infty - \beta y_\infty}{x_\infty-(1-\alpha)y_\infty}$$

where $s_{C,\infty}$ is determined by

$$A(0) + p(0)S_0 = \int_0^\infty \exp(-rt)(1-s_{C,\infty})C_W(t)\,\mathrm{d}t$$

See Appendix A for proof. The system is saddle-path stable. The initial point $\big(x(0), y(0)\big)$ is determined by the relative abundance of the factors of production in the economy. Higher S_0, given K_0, implies the economy initially has higher output-capital and consumption-capital ratios. To see this, consider the economy for which the equilibrium solution will begin (and remain) exactly at the steady state. A marginal increase in S_0 means $R(0)$, and so $F(0)$, should be increased so as not to (asymptotically) leave any resource in the ground. The new initial state features a higher output-capital and consumption-capital ratio forever. Part of the increased initial output is invested to build higher future capital stocks.

Now consider the global optimum for the above economy. We define the proportional growth rate of the pollutant stock

$$m \equiv \frac{R}{G} \tag{26}$$

The system now behaves according to

$$\hat{x} = x - (1 - \sigma\alpha)y - \sigma\rho \tag{27a}$$

$$\hat{y} = \frac{1 - \alpha - \beta}{1 - \beta}x - (1 - \alpha)y + \frac{\beta}{1 - \beta}d_W \tag{27b}$$

$$\hat{m} = -\frac{\alpha}{1 - \beta}x + \frac{1}{1 - \beta}d_W - m \tag{27c}$$

$$\hat{d}_W = (\theta - 1)m - \rho + d_W \tag{27d}$$

Note that the rates of growth of x and y are identical to the decentralised case, except for an additive term $\frac{\beta}{1-\beta} \geq 0$ in the growth rate $\hat{y}$. For $\xi > 0$, $d_W > 0$ for $t > 0$, and, further, $\lim_{t\to\infty} d_W(t) = 0$: in the very long run, as almost the entire stock of the resource has been used up, the marginal damages are very much smaller than the social benefits arising from having an extra unit of the resource to use in production.

Note that if $G_0 = 0$, then $d_W(0) = 0$; that is, the additive term is initially zero, as well as asymptotically approaching zero. If the system approaches the steady state from above and to the right, it can be shown that the time path of d_W is single-peaked.

For any given pair (x, y), the rate of change of x is equal for both the centralised and the decentralised outcome, but $\hat{y}$ is higher under the social optimum. Thus, under the social optimum, the trajectories will 'bend' upwards. Thus, certainly any solution which would start on the saddle-path for the decentralised outcome will not be optimal as it will bend off the saddle-path, never bend back, and hence head towards $x = 0$. An optimal solution will traverse a path located to the right of the decentralised saddle-path; these paths will converge as $t \to \infty$ (Figure 2). An equilibrium may even feature the optimal trajectory initially moving up 'behind' the loci of points $\hat{y} = 0$, then moving back towards the steady state from above (Figure 3).

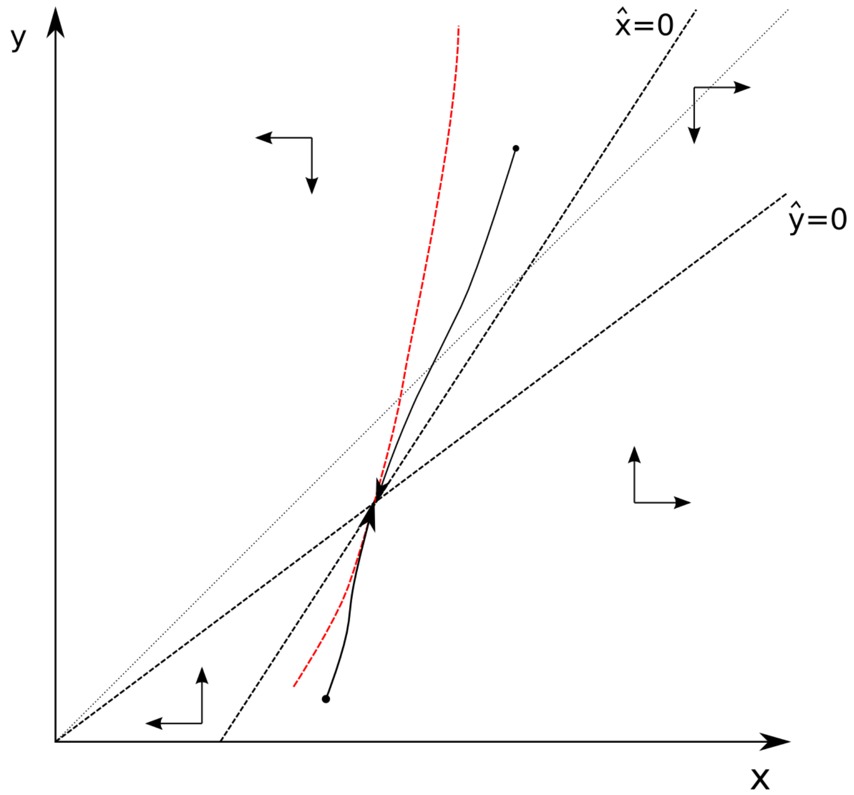

Figure 2: Phase diagram for the global optimum. When an externality is present, the loci of points such that $\hat{y} = 0$ will initially rise and become steeper, until eventually falling down again. The optimal saddle-path will start from a point to the right of the no-externality saddle-path (*red dashed line*) but approach the same steady state. See Figure 1 for construction of the graph.

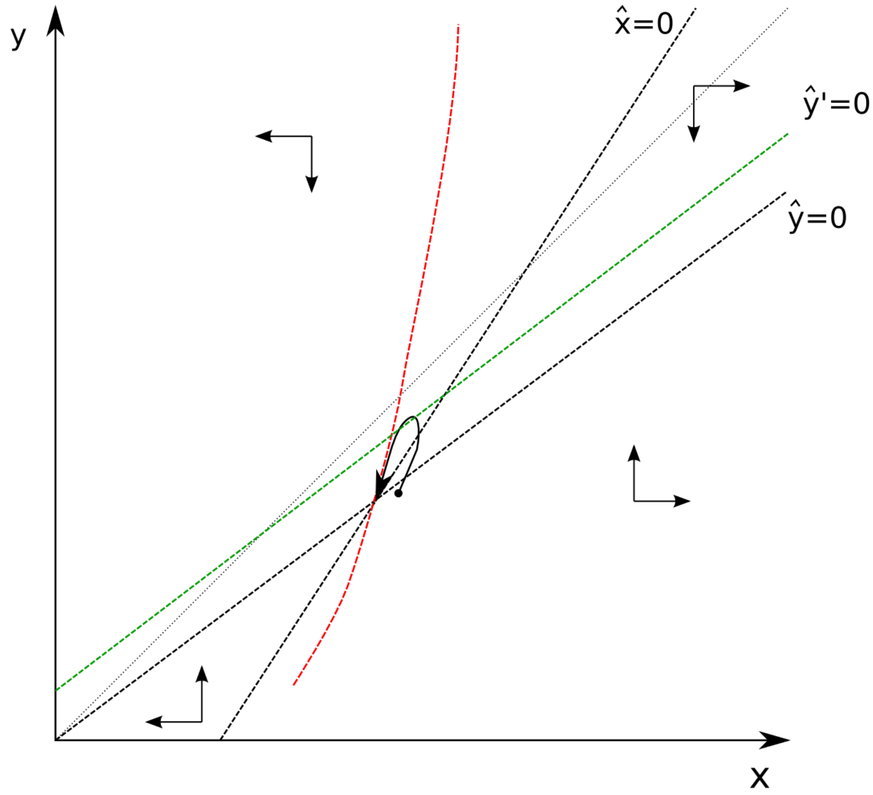

Figure 3: Phase diagram for the global optimum. It is possible for the economy to follow a non-monotonic path in x and y when the externality is present. The loci of points $\hat{y} = 0$ shifts up with d_W; as $t \to \infty$, the line converges to the corresponding one for the case of decentralised equilibrium without taxes. See Figure 1 for construction of the graph.

3.2 Optimal policy

Consider now setting up the proposed regulator. We want to consider whether the proposed tax instruments are sufficient for obtaining the efficient outcome, i.e. an equilibrium in which aggregate consumption, investment and resource use mirror those required for the global optimum. This outcome will not be fully optimal, unless international transfers are used to balance consumption levels between the two countries. However, such transfers would be required even in the absence of the externality[4].

After the regulator commits to the time paths of the capital income taxes, the countries will face effective interest rates $r_I^e = r_I - q_I$, $r_E^e = r_I - q_E$. As Country E has no productive industry, all production will remain within Country I. The countries now face modified Ramsey Rules and Hotelling Rule

$$\hat{C}_E = r_I - q_E - \rho, \qquad \hat{C}_I = r_I - q_I - \rho,$$

and the Hotelling rule

$$\hat{p} = r_I - q_E$$

From the Ramsey rules, we obtain the rate of change of aggregate consumption:

$$\begin{aligned} \hat{C}_W &= \frac{\dot{C}_E + \dot{C}_I}{C_E + C_I} \\ &= \frac{C_E}{C_E + C_I}\hat{C}_E + \frac{C_I}{C_E + C_I}\hat{C}_I \\ &= (1 - s_C)\hat{C}_E + s_C\hat{C}_I \\ &= r - \rho - (1 - s_C)q_E^e - s_C q_I^e \end{aligned} \tag{28}$$

The taxes which will yield the globally optimal outcome can now be determined:

Proposition 2. Under the decentralised equilibrium in open-loop strategies, a climate regulator can obtain the globally optimal aggregate outcome by setting taxes on capital income

$$q_E = d_W, \qquad q_I = -\frac{1 - s_C}{s_C} q_I$$

with the net tax proceeds distributed in a lump-sum fashion. With international lump-sum transfers to equate consumption between Country E and Country I, the global optimum obtains.

Proof. Immediate from equating (3.2) and (28) with (22) and (21), respectively. □

[4]Obviously, we may get, by fluke, an outcome for one of the cases which actually achieves the global optimum, if the two countries' initial wealth levels just happen to be equal.

It is clear that, in order to achieve the globally optimal trajectory, the tax on assets must equal the rate of depreciation of the *social* shadow value of retaining the resource underground, d_W. Then the resource is depleted in an optimal fashion, balancing the increase in the marginal product of oil with the marginal product of capital and the resulting stream of climate damages. However, such a tax will deter investment by Country E. Correcting one distortion—the externality—has led to a second one! Hence, Country I financial returns are subsidised, proportionally to q_E, in order to spur the required extra investment. This clearly has a distributional effect and so lump-sum transfers are required to correct for the transfers, or to achieve consumption parity, if this is desired.

Proposition 3. When climate damages are strictly convex, the optimal time path of the tax on Country E assets will satisfy

$$q_E \in [0, \rho), \qquad \lim_{t\to\infty} q_E(t) = 0$$

Proof. $\lim_{t\to\infty} d_W(t) = 0$ has already been established, and so the corresponding value for $q_E(t)$ as well. Clearly $d_W \geq 0$ holds always. Note that

$$d_W \equiv \frac{L_I D_I'(G)}{\mu_{S,W} - \mu_{G,W}}$$

As the pollution stock is non-decreasing and marginal damages are convex, the costate for the pollution stock equals

$$\begin{aligned}
\mu_{G,W}(t) &= \int_t^\infty \exp\Big(- \rho(s-t) D'\big(G(s)\big)\Big)\,\mathrm{d}s \\
&< \int_t^\infty \exp\Big(- \rho(s-t) D'\big(G(t)\big)\Big)\,\mathrm{d}s \\
&= \frac{D'\big(G(t)\big)}{\rho}
\end{aligned}$$

as resource extraction does not end in finite time, so that $\dot{G} > 0$ for all t. Furthermore, clearly $\mu_{S,W} > 0$. The upper bound on q_E follows. □

Characterising the path of the optimal capital income tax in more detail is convoluted. While under particular initial parameter combinations it is possible to say, for example, that the tax peaks only once, more general claims remain work in progress. So do numerical solutions.

At least some of the revenues required to subsidise domestic investment can be collected from the tax on foreign sovereign wealth investments, reducing the need to collect extra revenues in a lump-sum fashion. No lump-sum taxes at all need to be collected when $z > 1 - s_C$; i.e. when Country E's share of total global asset stock exceeds their share of aggregate consumption.

An exploratory numerical solution, for an arbitrary set of parameter values, is illustrated in Figure 4. The solution behaves according to conventional intuition, i.e. the externality causes depletion of the resource to be postponed. Capital stocks are also built up more slowly. In the long run, consumption and capital stocks are higher than in the case with no climate policy. Proper numerical solutions remain work in progress, and an algorithm is considered in Appendix C.

Note that the capital income tax on Country E rises sharply, lowering the effective rate of return early on. The net rate of return stays positive throughout, i.e. the capital itself is not taxed.

Several features of the proposed policy instrument suggest the instrument might be politically an easier task to implement than a carbon price which yields the globally optimal outcome. Firstly, the tax is not levied on Country I voters. If these voters are boundedly rational, this may be a political selling point in itself. Secondly, the net fiscal effect on Country I is positive. Even after accounting for the corrective subsidies to domestic capital income, there may be no need to raise additional lump-sum revenues.

Should the capital income tax be perceived as a politically more feasible instrument, it also gains credibility. As the described supply-side responses to climate policy depend crucially on expectations of future policy, this may be the most important factor when comparing the effectiveness of various instruments.

Other factors suggest against using taxation of capital income as an instrument of climate policy. Firstly, the distributional impacts would be substantial. Substantial aid flows (not linked to oil revenues) would be required to offset these. The present model does not consider diversification of resource-rich economies. While this could have desirable effects, as the detrimental effects of relying on resource wealth are well documented, it might blunt the effectiveness of the policy instrument. Alternatively, replacing a flow of revenues from selling a natural resource with a flow of aid revenue would also dampen any benefits due to diversification.

Taxation of capital income might also be perceived, in the international arena, as aggressive behaviour and there could well be substantial geopolitical implications. It would hardly foster a cooperative atmosphere for climate negotiations. Thirdly, the present model presumes perfect cooperation in tackling climate change (i.e. within the 'climate bloc' denoted Country I). This may be the shakiest assumption, as substantial incentives would exist for individual members of the bloc to act as secret bankers to the resource-rich economies. Such financial dealings could be difficult to monitor. On the other hand, as the present model is best interpreted as describing the evolution of entire economies over decades, the flight of sovereign wealth investments into particular countries or region would likely be observable to some degree.

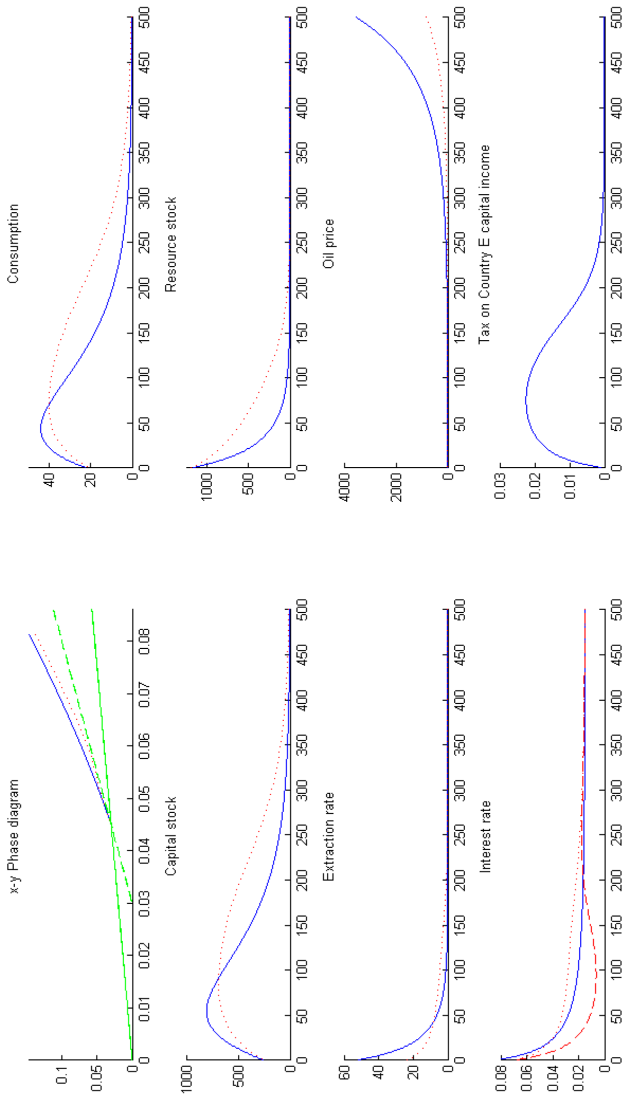

Figure 4: An exploratory numerical solution, comparing the decentralised outcome (*solid blue line*) with the globally optimal outcome (*dashed red line*). Parameters are arbitrary ($\alpha = .5$; $\beta = .25$; $\rho = .03$; $\theta = 2$; $\xi = .01$; $S_0 = 1200$; $K_0 = 250$; $G_0 = 0$). The optimal solution has lower depletion and consumption rates at $t = 0$. The effective rate of return Country E faces under optimal climate policy is indicated by the red dashed line.

3.3 Resource exporter with diversification opportunities

The simplified model of a very small resource exporter ignored the possibility that resource exporting countries may respond to a capital income tax by expanding their domestic productive opportunities. Were this a possibility, the effectiveness of the proposed instrument—in terms of delaying the accumulation of greenhouse gases—could be dulled.

Suppose that Country E actually does have a productive technology, but that it still comprises a relatively small fraction of global population (say 5 percent). Now, in the absence of taxes, (7) determines the optimal share of capital across the two countries. Due to the homothetic technoogy, the resource is efficiently allocated (by the market) in the same proportions.

With the introduction of capital income taxes, some capital is shifted out of Country I. From (7), it is clear that this effect may be quite pronounced, depending on the parameter values. Define the shares of Country I capital, output and resource use:

$$s_K \equiv \frac{K_I}{K_W}, \quad s_F \equiv \frac{F_I}{F_W}, \quad s_R \equiv \frac{R_I}{R_W}$$

A marginal unit of capital will be allocated between the two countries according to the current shares of capital, and we its contribution to aggregate output—'global marginal product of capital'—is

$$r_W = s_K r_I + (1 - s_K) r_E = r_I - (1 - s_K) q_E \tag{29}$$

In general, the entire trajectory of the economy will again shift due to the changes in future production, consumption, *et cetera.* Given this new trajectory, the tax instruments can be calibrated so that an efficient path of resource use is obtained, and so that the aggregate Ramsey Rule is satisfied given the aggregate rate of return to capital. However, there is clearly a cost in terms of lowering the path of aggregate output.

Notice that the capital income taxes cannot be set so that the rate of appreciation of the marginal product of the resource equals the global marginal product of capital, as $r_E^e = r_W + s_K q_E$. Suppose, instead, that the climate regulator is set up with the explicit objective of setting taxes according to Proposition 2. What, then, is the equilibrium outcome? In particular, how seriously will the resulting shift in aggregate output impact the resulting depletion schedule, and welfare more generally?

We express the resulting system in terms of aggregate (global) output-capital and consumption-capital ratios. Noting that $r_I = \frac{s_F}{s_K} \alpha y_W$, $r_E^e =$

$r_I - q_E$, and $q_E = d_W$, the system now behaves according to

$$\hat{x}_W = x_W - (1 - \sigma\alpha\frac{s_K}{s_F})y_W - \sigma\rho \tag{30a}$$

$$\begin{aligned}\hat{y}_W = &\frac{1-\alpha-\beta}{1-\beta}x_W - (1-\alpha)y_W \\ &- \frac{\beta}{1-\beta}\frac{s_K}{1-s_K}(r_W - r_I) + \frac{\alpha}{1-\alpha-\beta}(s_F - s_K)(\hat{r}^e_E - \hat{r}_I)\end{aligned} \tag{30b}$$

$$\hat{s}_K = (1-s_K)\frac{1-\beta}{1-\alpha-\beta}\frac{q_E}{r_I - q_E}(\hat{r}_I - \hat{r}^e_E) \tag{30c}$$

$$\hat{s}_F = (1-s_F)\frac{\alpha}{1-\alpha-\beta}\frac{q_E}{r_I - q_E}(\hat{r}_I - \hat{r}^e_E) \tag{30d}$$

$$\hat{s}_C = \frac{1-s_C}{s_C}\sigma q_E \tag{30e}$$

$$\hat{d}_W = (\theta - 1)m - \rho + d_W \tag{30f}$$

$$\begin{aligned}\hat{m} = &-\frac{\alpha}{1-\beta}x_W + \frac{\alpha}{1-\beta}\Big(1 - \frac{s_K}{s_F}\Big)y_W \\ &+ \frac{1}{1-\beta}q_E + \frac{\alpha}{1-\beta}\Big(s_R + (1-s_R)\frac{s_K}{1-s_K}\Big)\hat{s}_K - m\end{aligned} \tag{30g}$$

By arguments used previously, we know that the optimal tax will tend to zero as $t \to \infty$. Thus, the rates of return converge in the long run, and so we have $s_K \to s_F$.

Proposition 4. With $\Omega_E > 0$, as $t \to \infty$, the decentralised open-loop equilibrium of the economy will tend to a steady state in the variables (x, y, z), given by

$$\begin{aligned} x_\infty &= \frac{(1-\beta)(1-\alpha)}{\alpha(1-\alpha-\beta\frac{1-\sigma}{\sigma})}\rho \\ y_\infty &= \frac{1-\alpha-\beta}{\alpha(1-\alpha-\beta\frac{1-\sigma}{\sigma})}\rho \\ z_{\infty,\mathrm{PROD}} &= \frac{(1-s_{C,\infty})x_\infty - \beta y_\infty + (1-\alpha-\beta)(1-s_{F,\infty})y_\infty}{x_\infty - (1-\alpha)y_\infty} \end{aligned}$$

with $s_C(t)$ determined by the budget constraint:

$$A(0) + p(0)S_0 = \int_0^\infty \exp(-rt)(1 - s_{C,\infty}(t))C_W(t)\,\mathrm{d}t$$

For proof, see Appendix B. We note that the steady state is identical to the case in which Country E has no productive technology, except that the steady state share of assets Country E rise proportionally to Country E's output share in the absence of taxes. Thus, better productive opportunities imply Country E will eventually own a higher proportion of aggregate assets.

Notice, also, that the above steady state does not consider the actual scale of the economy, which will be reduced due to the inefficient allocation of capital.

Numerical solutions are required for further analysis of the system. Using reverse shooting methods, these should be feasible, but presently remain work in progress (see Appendix C). Another interesting extension would be to allow the regulator to move first, acting as a Stackelberg leader, and maximising global welfare.

4 Selfish climate policy

I now turn to a different question: what if Country I sets up an institution which is not politically strong enough to set optimal policy, but rather acts in the interests of its patron country? I again consider an open-loop equilibrium. For simplicity, suppose that the institution will not meddle with domestic interest rates, but is given the limited remit to determine taxes on Country E financial returns.

Now, Country E's problem is as it was in Section 3.2, including the amended budget constraint. Country I has a single new instrument, and so its problem is

$$\begin{aligned} &\max_{C_I, q_A} \int_0^\infty \exp(-\rho t)\big(u(C_I) - D(G)\big)\,\mathrm{d}t \\ &s.t. \quad \dot{B} = rB + F - rK - pR + q_A A - C_I \end{aligned} \tag{31}$$

and the other, usual conditions. For the problem to be well-formed, the tax rate has to have bounds. As an example, we limit $q \in [0, r]$: effectively, Country E's assets are never confiscated, but the tax rather only affects the interest income.

Country E's Hamiltonian is

$$\mathscr{H}_E = u(C_E) + \mu_A\big(rA + pR - \tilde{q}_A A - C_E\big) - \mu_S R \tag{32}$$

where $\tilde{q}$ denotes E's beliefs over I's action, the tax rate. First-order conditions, equations of motion and the Ramsey and Hotelling Rules are as in the previous section, as are the transversality conditions. Again, the Arrow Sufficiency Theorem guarantees any solution satisfying the necessary conditions is the global optimum.

The Hamiltonian for Country I's problem is

$$\mathscr{H}_I = u(C_I) - D(G) + \mu_B\big(rB + F - rK - \tilde{p}R + q_A A - C_I\big) + \mu_G R \tag{33}$$

The first-order condition for consumption is as previously. The Hamiltonian is linear in the tax rate q. Hence, optimal taxation is given by

$$q_A = \begin{cases} 0 & \text{if} \quad \mu_B A < 0 \\ r & \text{if} \quad \mu_B A > 0 \end{cases} \tag{34}$$

with the optimal taxation rate indeterminate (clearly it has no effect) when $\mu_B A = 0$. The equations of motion for the costates are as in Section 2.1, as are the Ramsey Rule and the transversality conditions.

As μ_B can be interpreted as the shadow value of relaxing Country I's intertemporal budget constraint, I will assume it is greater than zero. Hence, Country I will set the maximum possible tax on E's financial returns when Country E has a positive stock of assets; when Country E is a net borrower, the rate of interest on its liabilities will equal the market rate (as negative tax rates have been ruled out by assumption). I will assume that Country E initially holds positive assets: $A(0) = A_0 > 0$. Then, an optimal solution will have $q_A(0) = r$.

In an open-loop equilibrium, Country I takes the depletion schedule of the resource as a given. Hence, in the maximisation problem, when setting the tax, it only directly considers the effect of the tax on its intertemporal budget constraint, rather than explicitly tackling the Green Paradox. Given the depletion schedule, at any time Country E would be earning positive returns, it is always optimal to tax them away. Even so, taxation of financial returns affects the equilibrium depletion schedule, as will soon be made clear.

In equilibrium, beliefs are correct. There are now two regimes to study: Regime 1, in which $A < 0$ and $q_A = 0$; and Regime 2, in which $A > 0$ and $q_A = r$. In Regime 1, the economy clearly behaves as the decentralised system in Section 2.1 did (albeit it will, in general, be on a different trajectory, having entered Regime 1 at some general point (x', y')). In particular, along any final section of the optimal path for which $q = 0$, the system will approach the same steady state, along the same possible trajectories as in the previous case: if, for some final phase of the equilibrium path $t \geq t'$, $q_A(t) = 0$, then the equilibrium behaviour along this path will maximise aggregate welfare from consumption.

Under the second regime, $q = r$, and so $r_{\text{eff}} = 0$. Now, working as before, the behaviour of the system can be summarised in

$$\hat{x} = x - (1 - \alpha(1 - v))y - \rho \tag{35a}$$

$$\hat{y} = \frac{1 - \alpha - \beta}{1 - \beta}(y - x) \tag{35b}$$

$$\hat{z} = x - y + \frac{\beta y - vx}{z} \tag{35c}$$

$$\hat{w} = \frac{\alpha}{1 - \beta}(y - x) + w \tag{35d}$$

$$\hat{v} = -\alpha(1 - v)y \tag{35e}$$

where I have used $\hat{p} = 0$, and $\hat{C}_W = \frac{\dot{C}_E + \dot{C}_I}{C_E + C_I} = -\rho + (1 - v)r$.

Now, the subsystem (x, y, v) can be solved independently. Under the regime $q = r$, Country E's share of world consumption v decreases monotonically, ignoring the trivial and unstable steady state in which Country E

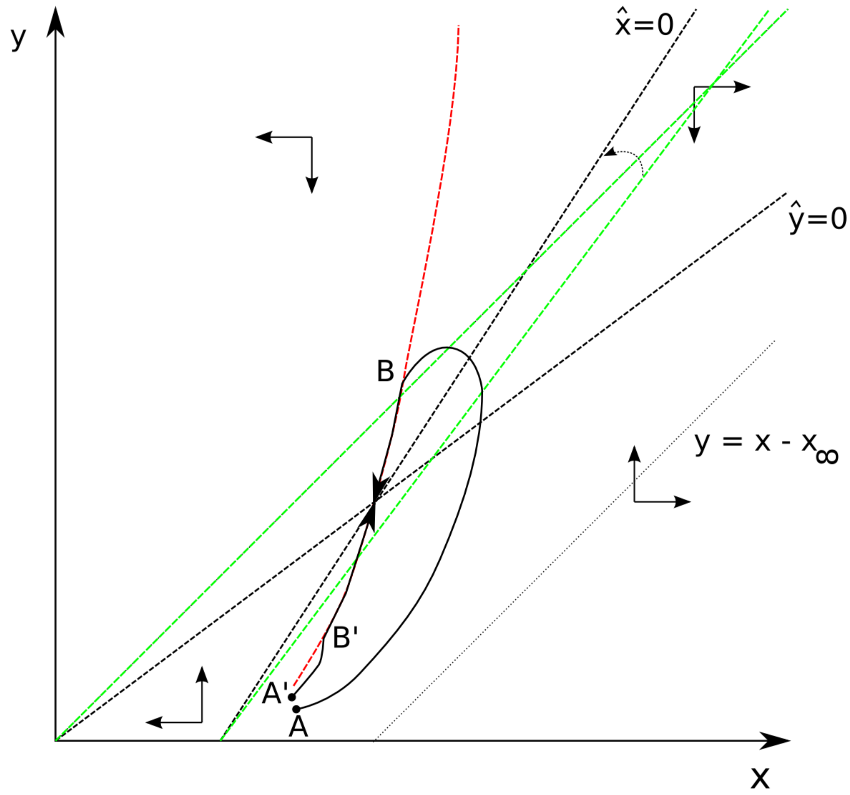

Figure 5: Equilibrium behaviour under selfish climate policy; two illustrated trajectories. Graph construction as in Figure **??**; also illustrated are the loci $\hat{x} = 0$, $\hat{y} = 0$ (*green dashed lines*); the loci of $\hat{y} = 0$ is the 45-degree line through the origin. The economy starts at A (A') in the regime $q_A = r$. The line $\hat{x} = 0$ pivots up as v falls. The economy will eventually switch to Regime 1 ($q_A = 0$), at point B or B') at which assets become negative, and approach the steady state given in Proposition 1. Actual behaviour of the system depends on parameter values and initial asset and resource stocks. Under equilibrium strategies, the system will never stray to the right of the line $y = x - x_{\infty,q_A=0}$.

accounts for the entire world consumption. Thus, if there is a steady state under the second regime, v tends to zero.

The loci of points where $\hat{x}$ or $\hat{y}$ are zero are given by

$$(\hat{x} = 0): \qquad y = \frac{x - \rho}{1 - \alpha(1 - v)}$$
$$(\hat{y} = 0): \qquad y = x$$

A phase diagram is presented in Figure **??**. Were the economy to ever reach the line $y = x - x_{\infty,q=0}$, it would remain thereafter under Regime 2 and would eventually diverge to infinity:

Proposition 5. Suppose, at time t', the economy is on or below the line $y = x - x_{\infty,q=0}$, with $q(t) = r(t), \quad \forall t \geq t'$. Then, $\lim_{t\to\infty} x(t) = \infty$.

Proof. Suppose the economy is on the line, which has unit slope. Then, if $\dot{x} > \dot{y}$, the economy will move to the right and away from the line. The above condition reduces to

$$x^2 + \big(1 - \frac{\alpha}{1-\beta}\big)y^2 + \alpha\big(1 - (1-v)(1-\beta)\big) - \rho x > 0$$

It is straightforward to show to show that, on the line, the LHS reaches its minimum value at $x = x_{\infty,q=0}$, i.e. at the bottom of the line, where the condition holds. It is similarly straightforward to show that the LHS increases with both x and y, so that the condition will hold in perpetuity. □

The following proposition regarding the steady state behaviour under Regime 2 can now be given (not illustrated in Figure 5:

Proposition 6. The only steady state with $q = r$ that the economy may tend to is the one in which x and y both increase asymptotically to

$$x_{\infty,q=r} = y_{\infty,q=r} = \frac{\rho}{\alpha}$$

with Country E's asset stock asymptotically consumed: $\lim_{t\to\infty} A = 0$.

Proof. By inspection of the phase diagram, possible steady states (in terms of x and y) are $(0, 0)$ and the steady state given in the proposition.

By the argument used in proving Proposition 1, paths on which x and y both grow without bound are not feasible. Furthermore, paths ending on or above the 45-degree line, including all paths converging to $(0, 0)$, the saddle path approaching $(x_{\infty,q=r}, y_{\infty,q=r})$ from above (or beginning directly from it), are not feasible: all would eventually have $y > x$ in perpetuity, and so feature non-decreasing extraction rates as

$$\hat{R} = \frac{\alpha}{1-\beta}(y - x)$$

The only possibility is the saddle path leading to the steady state from below. For this to be an optimal path, the transversality conditions have to be satisfied. Thus, in the limit, $\mu_A A$ has to grow at a rate lower than ρ:

$$\frac{\frac{\mathrm{d}}{\mathrm{d}t}\mu_A A}{\mu_A A} = \hat{\mu_A} + \hat{A} = \rho + \frac{\beta y_{\infty,q=r} - v_{\infty,q=r} x_{\infty,q=r}}{z_{\infty,q=r}} < \rho$$

Suppose $z_{\infty,q=r} > 0$. Then, as $v_{\infty,q=r} = 0$, it is required that $y_{\infty,q=r} < 0$—which does not hold. On the other hand, if $z_{\infty,q=r} < 0$, the economy will never reach this, switching into the regime with $q = 0$. However, there may exist an optimal path along which $A \to 0$. Then, transversality conditions are trivially satisfied, as $K \to 0$ and the clearing of financial markets also implies $B \to 0$. □

I have now established that, along an equilibrium with $A(0) > 0$, the system will necessarily have $q(0) = r$. Further, unless the equilibrium solution is just the approach to steady state along the lower arm of the saddle path in regime $q = r$, Country E will have negative assets in the long run and the steady state will require $q = 0$. The behaviour of the system can now be characterised further:

Proposition 7. In an open-loop equilibrium with $A(0) > 0$, asset taxation is initially given by $q = r$. The tax rate is changed at most once (lowered to $q = 0$).

Proof. The case in which the tax rate remains at $q = r$ was covered by Proposition 6. Note that at any switches between regimes, the trajectories of the costate variables must be continuous, and hence, by the first-order conditions, the time paths of both aggregate consumption and depletion rate must also be continuous. Suppose now that at time t', $x(t') \geq x_{\infty,q=0}$ and the tax rate is being switched to $x = 0$. This implies $A(t') = 0$, $\dot{A}(t') = \beta F(t') - v(t') C_W(t') < 0$. Consider some short period $t \in (t', t'+\epsilon)$, in which $A(t) < 0$. In this period, $\dot{v} = 0$. Thus, if $\hat{F}(t) < \hat{C}_W(t)$, then $\beta F(t) - v C_W(t)$ will certainly still be negative; furthermore, rA will also be negative as $r > 0$ for all t. But I have supposed $x(t') > x_{\infty,q=0}$, i.e.

$$\hat{C} - \hat{F} = \frac{\alpha}{1-\beta} x - \rho > \frac{\alpha}{1-\beta} x_{\infty,q=0} - \rho = 0$$

Thus, once the tax rate switches to zero, A will be forever negative and the tax will never switch back. Note that were the economy to loop back to $x < x_{\infty,q=0}$, it would then always drift towards the origin; this would not an optimum. For the path considered to be an equilibrium, the switch must occur precisely on the saddle-path for the regime $q = 0$.

Suppose now, instead, that the economy is to the left and below the steady state $(x_{\infty,q=0}, y_{\infty,q=0})$. Suppose further that at time t', the system switches to the regime $q = r$, i.e. that $A(t') = 0$, $\dot{A}(t') > 0$. By the converse of the above argument, it must hold that $\dot{A} > 0$ as long as the economy remains to the left of the steady state: βF, initially higher than vC_W, grows at a rate faster than C_W; moreover, v will continue decreasing again. Thus, the economy would never switch back to $q = 0$. Furthermore, now $\mu_A A$ would change at a rate $\rho + rA + \beta F - vC_W > \rho$, and so the transversality condition would not be satisfied. Thus the suggested path cannot be part of an equilibrium path. Hence, if the economy has switched to $q = 0$ already, it must henceforth remain in this regime and so be on the saddlepath to the steady state.

Finally, a path could loop around, starting from the bottom left, switching to $q = 0$, then transiting the line $x = x_{\infty,q=0}$. It could feasibly switch back to $q = r$ to the right of this line; then, at t', $A(t') = 0$, $\dot{A}(t') > 0$. But note that

$$\frac{\frac{\mathrm{d}}{\mathrm{d}t} vC_W}{vC_W} = -\rho, \qquad \frac{\frac{\mathrm{d}}{\mathrm{d}t}\beta F}{\beta F} = \frac{\alpha}{1-\beta}(y-x)$$

and so, in the period following the switch, $\dot{A} > 0$ certainly when

$$\frac{\alpha}{1-\beta}(y-x) > -\rho$$

or $y > (x - x_{\infty,q=0})$ (see Figure 6). If this condition is satisfied, the economy will remain in $q = r$ forever and cannot be on an optimal path leading to a steady state. On the other hand, paths which have, for any t', $y(t') < x(t') - x_{\infty,q=0}$ will satisfy this condition $\forall t > t'$, as shown in Proposition 5, and thus will have $x \to \infty$. Any switch to the regime $q = 0$ would have to be the final switch, placing the economy on the saddlepath to the steady state. Clearly, the saddlepath will never lie in this region. □

Three possible equilibrium outcomes hence exist:

- The economy starts from $x < x_{\infty,q=r}$, $y < y_{\infty,q=r}$ and heads directly to the steady state $(x_{\infty,q=r}, y_{\infty,q=r})$;
- The economy starts from $y < x$, transits to $q = 0$ when it hits the lower arm of the saddlepath for $q = 0$ and then approaches the steady state $(x_{\infty,q=0}, y_{\infty,q=0})$; and
- The economy starts from a position which satisfies either $y < x$ and/or $x \geq x_{\infty,q=0}$. It transits to $q = 0$ when it hits the upper arm of the saddlepath for $q = 0$ and then approaches the steady state $(x_{\infty,q=0}, y_{\infty,q=0})$.

The latter two outcomes may exhibit rather complicated behaviour, as the loci of points $\hat{x} = 0$ under Regime 2 is tilting upwards as v falls. Which of these outcomes prevails depends on the parameters and the initial state. It cannot be ruled out that we may have several possible equilibrium outcomes.

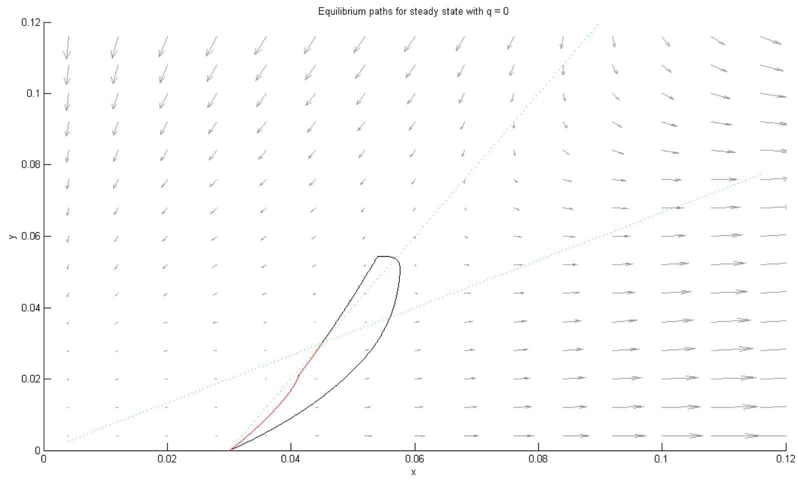

Figure 6: Phase diagram for Regime 1 ($q = 0$), with paths to steady this particular steady state illustrated by solid lines. The dashed lines indicate the loci of points for which $\hat{y} = 0$ or $\hat{x} = 0$. Equilibrium paths begin under the Regime 2, with $q = r$, but eventually switch to Regime 1, and move down the saddle path towards the steady state.

Clearly, under 'selfish' climate policy, the economy will never achieve the global optimum[5]. How will such a policy achieve environmental objectives?

Proposition 8. Under selfish climate policy, when initial resource stocks are high, selfish climate policy delays depletion compared to no policy: initial resource depletion rate is lower and ultimate depletion rates higher. Terminal capital stock is higher under the selfish policy, as is aggregate consumption.

Proof. With a high initial resource stock, the economy will eventually approach equilibrium along the upper arm of the saddle-path. Suppose that in the final phase with $q_A = 0$ depletion rates are identical irrespective of whether selfish or no policy prevails. Rolling back time, at some point t'—at which the selfish policy undergoes its regime switch—the paths will diverge. For $t < t'$, under no policy, depletion rates will have decreased at rate

$$\hat{R} = -\frac{\alpha}{1-\beta}x < -\frac{\alpha}{1-\beta}x_\infty = -\rho$$

Under $q_A = r$, depletion rates have fallen at rate

$$\hat{R} = \frac{\alpha}{1-\beta}(y-x) > -\frac{\alpha}{1-\beta}x_\infty = \rho$$

[5]Comparisons between welfare outcomes are difficult to make and require numerical simulation. These may be conducted for a future version of the paper.

where the inequality follows from Proposition 5. Thus, before the final phase, under no policy depletion rates will have fallen at a faster rate than under selfish policy. This implies that, should it hold that $R_{\text{no policy}}(t') = R_{\text{selfish}}(t')$, under selfish policy some of the resource would never be extracted. For the resource constraint to hold, the entire time path of R must rise. In particular, $R_{\text{no policy}}(t') < R_{\text{selfish}}(t')$. Thus, the integral of extraction from t' onwards must be higher under selfish policy: in other words, $S(t')$ is higher under selfish policy—extraction of the stock has been delayed. Also, as at $y_{nopolicy}(t') = y_{selfish}(t')$, we must have $K_{nopolicy}(t') < K_{selfish}(t')$; hence, also, $C_{W,nopolicy}(t') < C_{W,selfish}(t')$. Eventually, under selfish climate policy, resource stocks, capital stocks and consumption are higher than under no policy. □

Hence, if initial resource stocks are plentiful, a politically weak climate regulator armed with a remit to tax capital income will succeed in curbing climate change, despite this not being its goal. As the trajectory of the economy diverges significantly from the trajectory under either optimal or no policy, further general statements are hard to make. Numerical solutions remain work in progress.

5 Conclusions

The use of capital income taxation has been proposed as a potential solution to the Green Paradox (Sinn [2008]). Such instruments have not, to our knowledge, been carefully analysed in the literature to date. I have provided an initial analysis of the problem. In principle, taxes on financial returns earned by sovereign wealth funds of resource-rich countries can be used as an instrument of climate policy. In particular, this instrument acts as a supply-side measure to tackle pollutants resulting from the use of an exhaustible resource, the cumulative supply of which is inelastic. I have shown that a climate policy based on these instruments can achieve the efficient aggregate consumption and resource depletion schedules. The policy will have substantial distributional effects between the importers and exporters of a resource. In other words, the policy attains efficiency, but at the cost of potentially detrimental distributional outcomes. Note, however, that the decentralised outcome will not achieve distributional optimality either (apart from the fluke case in which initial assets just happen to imply equal consumption shares between importers and exporters).

Using taxes on capital income may have significant domestic political advantages over more conventional instruments, such as carbon pricing. Legislators in resource-importing countries may be politically shielded from voters averse to taxes levied on themselves. Any painful economic readjustments will follow not from carbon taxes, not tariffs on imported fossil fuels, but from resource-owning countries' rational responses to the tax on their financial returns. Further, the instruments will have a positive net fiscal effect. Crucially, the instrument relies on resource-rich countries planning their depletion schedule according to the Hotelling Rule. Hence, the validity of this rule—often questioned—in the long term is essential to determining whether the proposed policy instrument would be effective.

The foreign and geopolitical implications, on the other hand, and anything but advantageous. Taxation of assets, instead of products, is likely to be seen as an aggressive policy and may harm international relations. Furthermore, the distributional outcomes may be perceived as inequitable. Lump-sum transfers could alleviate such issues.

By reducing the rate of return available on foreign investments, the policy could actually encourage domestic investment in resource-rich countries. This might have the positive effect of ultimately reducing reliance on resource revenues and encouraging diversification of the economy. However, it could also blunt the effectiveness of policy. Shifting the source of dependence from resource revenues to aid flows is unlikely to have such positive effects.

If the climate regulator is politically weak, and susceptible to pressure from the governments of its patron countries—the resource-importing countries—it may use its powers to just tax away the return to sovereign wealth, instead of seeking to mitigate climate change. In an open-loop equilibrium, the resulting policy will, nevertheless, end up slowing down depletion of the resource and thus the build-up of CO_2 emissions. However, this outcome is sub-optimal in global terms.

Like any other climate policy mechanism, the success of the proposed tax instruments relies on the cooperation among the countries seeking to mitigate climate change. The tax instruments clearly give individual countries incentives to defect, by taxing investments at less than the agreed rate, attracting a disproportionate share of investment and the resulting tax revenues and income for the fixed factor. Such deviations might be difficult to observe and thus reduce the usefulness of the proposed instrument.

The research presented in this paper remains very much work in progress. Numerical solutions to the present models are to be obtained imminently. More interestingly, there are obvious extensions to the study which would make the model substantially more realistic. Most important is modeling an eventual substitute ('backstop') technology. This would bring the Green Paradox into sharper focus. It would also likely make it feasible to obtain closed-loop solutions (by numerical methods), as the difficulties associated with the eventual decay of the economy in the current version of the model would be avoided. Such extensions remain work in progress.

A Proof of proposition 1

By inspection of the phase diagram, it is apparent that any trajectory will either have $x \to x_{\infty,q=0}$, $x \to 0$ or $x \to \infty$. Then, respectively, $y \to y_{\infty,q=0}$, $y \to 0$ or $y \to \infty$[6].

Any trajectories with $x \to \infty$ are clearly not feasible, as along any such path there exists t' such that, for all $t > t'$,

$$\frac{C_W}{F} = \frac{C_W/K}{F/K} = \frac{x}{y} > \frac{1-\alpha-\beta+\alpha\beta}{1-\alpha-\beta} > 1$$

Clearly, it is not feasible that consumption exceeds production by a non-infinitesimal amount for an unbounded time interval, as production decays to zero and the entire capital stock would eventually be used up.

Any paths converging to $(0,0)$ will break the resource constraint. For the resource constraint to hold, it is required that $R \to 0$; I will show that this does not hold when the system converges to the origin in (x,y)-space. As $\hat{R} = -\frac{\alpha}{1-\beta}x$,

$$R(t) = R(0)\exp\big(-\frac{\alpha}{1-\beta}\int_0^t x(s)\,\mathrm{d}s\big)$$

Taking the limit as $t \to \infty$, for any positive $R(0)$, $R(t)$ will tend to zero only if the integral does not converge, instead tending to (positive) infinity. However, if the system tends to $x = y = 0$, then $\hat{x}$ tends to $-\sigma\rho < 0$. Thus there will exist a time t' after which x decays exponentially, at some rate $\rho - \epsilon$ or faster (for arbitrarily small ϵ). Break up the integral,

$$\lim_{t\to\infty}\int_0^t x(s)\,\mathrm{d}s = \int_0^{t'} x(s)\,\mathrm{d}s + \lim_{t\to\infty}\int_{t'}^t x(s)\,\mathrm{d}s$$

we note that the second integrand decays exponentially, and so the integral converges. Furthermore, as $x(t)$ is well behaved, the first term also takes a finite value. Hence, the whole integral converges to a finite value. But this implies $R(t)$ tends to a strictly positive value, breaking the resource constraint.

Hence, the only feasible path is the one converging to (x_∞, y_∞). The transversality conditions imply a value for z_∞ (see Appendix A.1). As $p(t) = p(0)\exp(rt)$, the intertemporal budget constraint becomes

$$A(0) + p(0)S_0 = \int_0^\infty \exp(-rt)(1 - s_{C,\infty})C_W(t)\,\mathrm{d}t$$

which we can solve for $(1 - s_C) \equiv \frac{C_E}{C_W}$, the share of Country E consumption out of total consumption.

[6]Note that x will never turn negative, as suggested by Pezzey and Withagen [1998]. Note also that it will never be the case that $x \to 0$, $y \to \overline{y} > 0$; once x is very close to zero, y will certainly fall at some negative rate bounded away from zero.

A.1 Transversality conditions

It is already noted in the text that (**??**) implies $S \to 0$. It holds that

$$\mu_G \in \left[-\frac{D'(S_0)}{\rho}, 0\right], \qquad G \in [0, S_0]$$

and so (**??**) is also necessarily satisfied. Finally, along an optimal path, the system will eventually come arbitrarily close to (x_∞, y_∞). Note that

$$\begin{aligned}
&\lim_{t\to\infty} \exp\big(-\rho t\big)\mu_K(t)K(t) \\
=&\mu_K(0)K(0)\lim_{t\to\infty}\exp\big(-\rho t\big)\exp\left(\rho t + \int_0^t (1-\alpha)y(s) - x(s)\,\mathrm{d}s\right) \\
=&\mu_K(0)K(0)\lim_{t\to\infty}\exp\left(\int_0^t (1-\alpha)y(s) - x(s)\,\mathrm{d}s\right)
\end{aligned}$$

As $(1-\alpha)y - x \to \frac{-\rho}{\left(1-\alpha-\beta\frac{1-\sigma}{\sigma}\right)} < 0$, the integral will not converge and the limit will take the value of zero. Thus, the third transversality condition (**??**) will also be satisfied.

For the case of no climate policy, the transversality conditions for S and G follow the same logic and have the same implications. The transversality condition for A is

$$\begin{aligned}
&\lim_{t\to\infty} \exp\big(-\rho t\big)\mu_A(t)A(t) \\
=&\lim_{t\to\infty} \exp\big(-\rho t\big)\mu_A(t)z(t)K(t) \\
=&\lim_{t\to\infty} \mu_A(t')z(t')K(t')\exp\left(\int_{t'}^t \frac{\beta y(s) - v(s)x(s)}{z(s)}\,\mathrm{d}s\right) = 0
\end{aligned} \tag{36}$$

which is satisfied if the integral does not converge, but rather goes to $-\infty$. I will establish that, unless z tends to a steady state, the integral in fact converges and hence the transversality condition cannot hold. Convergence certainly occurs if the integrand decays exponentially at a rate bounded away from zero.

Suppose the $|z(t)|$ grows without bound. To avoid a knife-edge case, suppose $v \neq \frac{\beta(1-\alpha-\beta)}{(1-\alpha)(1-\beta)}$, so that $\lim_{t\to\infty}\beta y(t) - v(t)x(t) \neq 0$. Then the rate of change of the integrand tends to

$$\lim_{t\to\infty}\frac{\beta\hat{y}y - v\hat{x}x}{\beta y - vx} - \big(x - (1-\alpha)y\big) - \frac{\beta y - vx}{z} = -\sigma\rho$$

as $\hat{y}$ and $\hat{x}$ tend to zero, and as eventually the system will be arbitrarily close to (x_∞, y_∞), with $|z(t)|$ arbitrarily large. But then the integrand in (36) will converge to a finite value and the transversality condition will not hold. If z does not change signs, so that the integrand is devoid of singularities, one can simply set $t' = 0$. If sign changes exist, the same argument holds using a value for t' strictly greater than the last of the sign changes.

Thus, transversality conditions require that $z(t)$ converge to a steady state, as stated by Chiarella [1980]. This steady state is

$$z_\infty = \frac{vx_\infty - \beta y_\infty}{\rho}$$

It is straightforward to show that the satisfaction of (36) necessarily implies the transversality condition for B is also satisfied.

B Proof of proposition 4

As $t \to \infty$, our assumptions on the utility, production and climate change impact functions imply $d_W \to 0$. Hence, the capital income taxes approach zero, and $s_F \to s_K$. It follows that the equations of motion for x and y tend to the corresponding ones for the case with no Country E production technology. Thus, by arguments employed in Appendix A, the subsystem $(x, y$ tends to the steady state given in 1.

We only need to consider the transversality conditions. As $A+B = K_W$, and $K_W \to \infty$, $|A| \to \infty \Leftrightarrow |B| \to \infty$. The transversality conditions are certainly satisfied if either A or B converges to a finite number. We consider B first. We have

$$\hat{B} = -(r_I - q_E)\frac{A_I/K_I}{B_I/K_I} + (1-\beta)\frac{y_I}{B_I/K_I} - \frac{x_I}{B_I/K_I}$$

Now, following a similar line of proof as in Appendix A.1, the transversality condition becomes

$$\begin{aligned}
&\lim_{t\to\infty} \exp -\rho t \mu_B(t) B(t) \\
&\quad = C \lim_{t\to\infty} \exp \int_{t_0}^{t} \Big(\frac{-(r_I - q_E)}{B_I/K_I} - q_E + \frac{(1-\beta)y_I - x_I}{B_I/K_I}\Big)\, \mathrm{d}s \\
&\quad = C \lim_{t\to\infty} \exp \int_{t_0}^{t} \frac{(1-\alpha-\beta)y_I - x_I + q_E}{B_I/K_I} - q_E \,\mathrm{d}s \\
&\quad = 0
\end{aligned}$$

where C is a constant. As before, this holds only if the integral does not exist, but rather converges to $-\infty$. This certainly does not happen if the integrand decays exponentially at some strictly positive rate. With all variables referring to limiting values as $t \to \infty$, but omitting notation to this effect for clarity, the growth rate of the integrand (denoted by Γ) tends to

$$\lim_{t\to\infty} \hat{\Gamma} = -\frac{B}{K_I} q_E \left(\frac{-\hat{q}_E - \hat{B} + \hat{K}_I}{(1-\alpha-\beta)y_I - x_I + q_E\big(1 - \frac{B}{K_I}\big)} \right) - (\hat{B} - \hat{K}_I)$$

Suppose that $q_E \frac{B}{K_I} \to \pm\infty$. Then

$$\lim_{t\to\infty} \hat{\Gamma} = \lim_{t\to\infty} \hat{d}_W = -\rho$$

and the integrand decays, in the limit, at a strictly positive rate. Suppose instead that $q_E \frac{B}{K_I}$ tends to some non-zero constant. Then $\lim_{t\to\infty} \hat{\Gamma} = -(\hat{B} - \hat{K}_I) = \hat{d}_W = -\rho$. Again, the integral converges. The only possibility is $q_E \frac{B}{K_I} \to 0$, with the integral not necessarily converging is $\hat{B} - \hat{K}_I \to C \leq 0$. But as $\hat{K}_I \to \hat{K}_W = \frac{A}{K_W}\hat{A} + \frac{B}{K_W}\hat{B}$, this implies $\hat{B} - \hat{A} \to C \leq 0$.

By a similar argument, from Country E's transversality condition, we obtain $\hat{A} - \hat{B} \to C \leq 0$. Thus, in the limit, the rates of change of A and B must be equal to each other, and also to K_W. Hence the countries' shares of financial assets must converge to a steady state. This steady state can be solved for as in the previous case.

C Outline of numerical solution

Use reverse shooting methods. Consider first the case of Country E having no productive opportunities. Start at some large time T, from the vicinity of $(x_\infty, y_\infty, z_\infty)$.

1. Guess $\mu_{S,W}(T)$. Calculate $d_W(T)$ assuming $G(T) = \bar{(}G)$.
2. Guess $K(T)$
3. Integrate the system (27) and (25c) backwards.
4. If do not pass sufficiently close to (K_0, S_0), go to step 2.
5. Otherwise, use the time of closest pass to the initial state as t_0.
6. Calculate the derivative of aggregate welfare with respect to S, equalising consumption rates. If this does not equal $\mu_{S,W}(t_0)$, go to step 1.
7. Calculate the (constant) shares of consumption from the intertemporal budget constraint.

In the case with a productive technology, use the same procedure, except guessing also for $s_C(T)$. Notice that the guess of $\mu_{S,W}(T)$ pins down the tax, and hence Country I shares of capital and output s_K, s_F.

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