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Resource Dependence, Recycling, and Trade

Abstract

Recycling waste from used goods can substitute for scarce raw materials and reduce resource dependence. This paper presents a model of waste collection, recycling and final goods production using raw and recycled materials. Non-recycled waste must be safely stored by landfill to avoid environmental damage. The costs of waste disposal create externalities. An optimal allocation requires a trash tax to make producers pay for the costs of waste disposal, and an input subsidy to recycling firms to compensate for the savings in disposal costs. We study trade between resource poor economies exporting final goods, and resource rich countries exporting raw materials. We find rich welfare effects of trade policy with non-trivial interactions between terms of trade effects and distortions in recycling and resource extraction.

JEL-Codes: D620, Q320, Q530, F180.

Keywords: waste, recycling, externalities, resource dependence, trade.

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1 Introduction

Decaying climatic and environmental conditions on the planet dictate a change in consumption and production behavior. The United Nations identify natural resource dependence and the creation and management of waste as two cornerstones in the pursuit of sustainable production and consumption patterns.[1] Much the same goals are shared in the EU's 'Fit-for-55' agenda, including a 'circular economy action plan',[2] or by the influential McArthur Foundation report (2013) on developing a circular economy. The United Nations report that the reliance on natural resources has increased by more than 65% in the decade from 2010 onwards, a rate that drastically exceeds population growth. Reducing resource dependence requires to economize on the extraction and supply of raw materials from excavated natural resources. If a substantive restriction of consumption is to be avoided, big steps towards resource substitution in a technically feasible, environmentally friendly, and economically affordable way are mandatory. Natural resource substitution in production must involve recycling on a big scale to curb extraction. The endowment with and the extraction of natural resources and the use of raw materials in manufacturing are vastly unevenly distributed across countries. The emergence of recycling on a larger scale should thus have substantial international economic ramifications.

We think of *traditional production* of final goods in the following simplified way. Natural resources which can be extracted to obtain raw materials are available in one part of the world, say, *abroad*. At *home*, the production of manufactures combines imported raw materials with domestic primary production factors. Upon usage, manufactures become *used goods* – trash or waste. Used goods are disposed of by, e.g., landfill. However, trash and waste disposal is costly, as valuable land is consumed and resources are spent on landfill and safe storage to prevent environmental damage, littering or leakage of toxic substances.[3] With a *modern production* of final goods, it is technologically feasible to recycle

[1]See https://sdgs.un.org/goals/goal12.

[2]See https://environment.ec.europa.eu/topics/waste-and-recycling_en.

[3]The World Bank's (2018) "What A Waste 2.0" Report estimates the global cost of waste at about bn. 205 US dollars in 2019 and to rise to bn. 375 US dollars by 2025.

used goods by extracting valuable components and converting them into new materials that can be used by final goods production as substitutes of raw materials. Substitution combines the benefit of reducing the dependence on ever scarcer raw materials and resources with reducing waste and environmental damages.

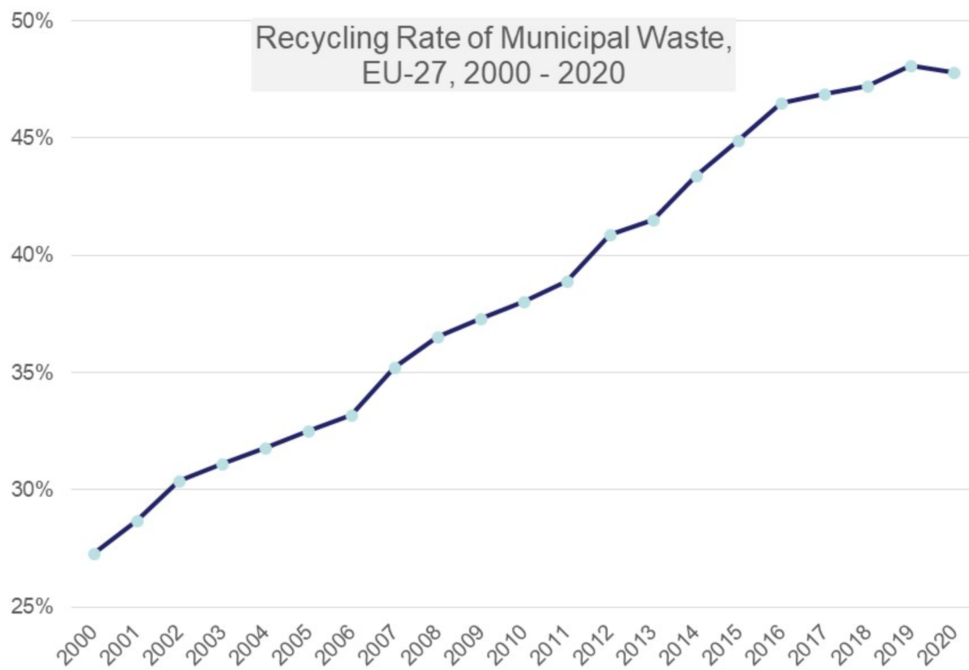

Figure 1: Recycling Rate

Figures 1 and 2 document the growing importance of recycling and report two indicators that play a key role in our framework. The data are extracted from a set of indicators in the area of *Waste Management* under the heading *Circular Economy*, published by Eurostat. The recycling rate in Figure 1 measures the percentage of recycled waste in total municipal waste generation.[4] Throughout the EU, municipalities aim to separate the waste into components that can be recycled (metals, glass, paper and pulp, polyethylene, textiles, etc.). The remainder is burnt and used in energy production (wood and wood products, plastics, etc.), or is hazardous and must be further processed to avoid environmental damage, or is stored in landfill sites. The recycling rate in the EU has grown from

[4]See https://ec.europa.eu/eurostat/cache/metadata/en/cei_wm011_esmsip2.htm.

27 to 48 percent in the last two decades.

The circular material use rate reported in Figure 2 measures the share of recycled materials in total inputs.[5] Aggregate domestic material consumption is obtained from economy-wide material flow accounts and is corrected for imports and exports of waste. A higher circularity rate means that more secondary materials substitute for primary raw materials, thereby saving natural resources and reducing the adverse environmental impact from extraction of natural resources. Recycled materials are becoming increasingly important in final goods production. Between 2004 and 2020, their share in total material use has grown by more than 50 percent, from 8.4 to over 12.8 percent in 2020.

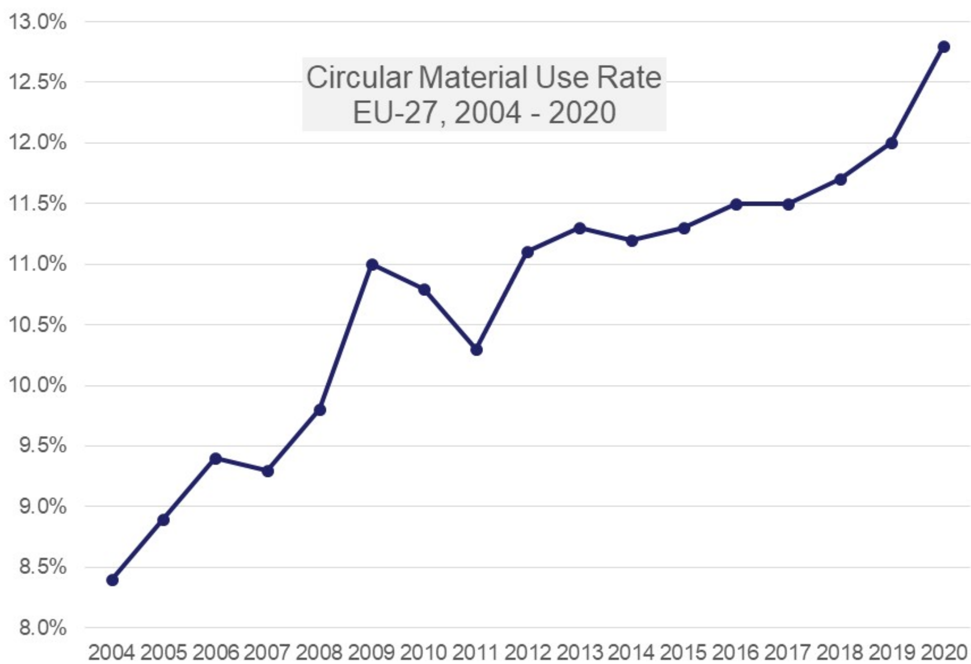

Figure 2: Circular Material Use Rate

Can recycling protect the competitiveness and growth of resource poor countries? What is the potential to postpone or slow down the depletion of exhaustible resources? What prevents a country to make a more productive use of waste in the first place? Can

[5]See https://ec.europa.eu/eurostat/cache/metadata/en/cei_srm030_esmsip2.htm.

recycling help to reduce a country's resource dependence and what are the implications for trade in goods and raw materials? Existing economic theory does not appear to devote the deserved volume of attention to recycling in general (see e.g., Fullerton et al., 2022). And where it does, it largely focuses on closed economies. As a consequence, an internationally integrated view of resource depletion and trade on the one hand and using recycling technologies as well as policies on the other hand is largely missing (see the critical review in McCarthy et al., 2018).

We hope to contribute to the debate by offering such an integrated view of recycling and resource depletion in a trade model that features production of final goods using labor and intermediate inputs in the form of materials. Once used, final goods turn into waste that is either recycled or destined for final disposal by protected landfill or burning. Raw and recycled materials are perfect substitutes that are traded at the same price. To produce new materials, the recycling industry uses trash and the extraction industry uses raw materials extracted from natural resource endowments. In resource poor countries, the domestic supply of materials may be augmented by imports from resource rich countries. Countries thus trade materials in exchange for final goods.

Our theory links to important strands of existing research. Our model of recycling builds on and extends early contributions by Fullerton and Kinnaman (1995), Fullerton and Wu (1998), Kinnaman and Fullerton (2000) and Fullerton and Wolverton (2000) which triggered a body of related research including Choe and Fraser (1999), Calcott and Walls (2000 and 2005), Eichner and Pethig (2001), Runkel (2003) and Eichner and Runkel (2005). This literature emphasizes recycling distortions due to costly waste disposal and recommends corrective policies in various forms such as a deposit refund system. Kinnaman (2006) argues for a landfill tax as a simple way to internalize the external costs of garbage disposal, and Viscusi et al. (2011) point to the important role of social norms in complementing economic incentives for recycling. Carattini et al. (2018) empirically show that taxing waste via pricing garbage by the bag is a very effective policy that has reduced unsorted garbage by about 40% in Swiss municipalities. In our framework, however, corrective policies are implemented on the production side with the same purpose of internalizing external costs of waste. Kinokuni et al. (2019) show that waste disposal fees should be higher when firms choose product durability. Nicolli et al. (2012) informally discuss the role of innovation in improving the recycling technology, and Kostakis and Tsagarakis (2022) provide econometric evidence on determinants of recycling, including a significant role of R&D.

Existing research largely considers closed economies and does not investigate in any detail the role of recycling for endogenous resource extraction. Our theory links to existing microeconomic research on business models for a circular economy which offers more detail on firm and consumer behavior, see, e.g., Buehler et al. (2022) and the work cited therein. This literature is mostly partial equilibrium in nature and predominantly considers closed loops of recycling within the firm. Large firms take back their own products after they have been used. In contrast, we analyze recycling in general equilibrium. Specifically, a recycling sector collects trash in waste collection centers, sorts it into different components (old paper, wood, metals, glass, clothing, etc.) and processes it to produce new materials used in final goods production.

Our paper also connects to the theory of exhaustible resources which explains how the depletion of scarce resources gives rise to exponentially increasing prices in raw materials and necessitates continuous substitution by other inputs. Influential contributions are, e.g., Dasgupta and Stiglitz (1981), Gaudet and Howitt (1989), Van der Ploeg (2011) and Martimort et al. (2018). How recycling could break the trend and slow down resource depletion is not the subject of this literature. Our model formalizes in a simple static framework the scarcety of natural resources and explains how the discovery of new resources facilitates extraction and reduces prices of raw materials. It also shows that an improvement in the recycling technology can relax resource constraints in the same way. Zhong and Su (2023) find empirical evidence on some of our results on trade in raw materials, such as the role of resource taxes or the material intensity in production.

Finally, existing research on how recycling can affect trade in goods and raw materials appears to be extremely sparse, and the few exceptions that do exist are not informative about the effects of recycling on resource dependence. The exhaustive review by Copeland et al. (2022) is concerned with trade and climate change and discusses renewables, resource management and trade. Recycling is apparently omitted in existing research. As an exception, Copeland (1991) analyzes trade in final goods and 'waste disposal services'. Waste is a by-product of goods production and requires 'waste or garbage disposal services' to dispose of waste at home or abroad. Dubois and Eyckmans (2015) emphasize extended producer responsibility where manufacturing requires 'waste management services' offered by a recycling industry which manages the local or foreign disposal of waste. The role of material inputs in production and the importance of recycling to substitute raw materials with recycled materials is not considered.

In broad lines, our framework links to existing research in trade theory showing how the use of intermediate inputs determines the production of final goods (Costinot and Rodríguez-Clare, 2014, for example). In emphasizing the role of innovation on recycling and trade, we borrow to some extent on our earlier work (Egger and Keuschnigg, 2015). We also wish to point out a parallel to the recent climate literature which is concerned with clean and dirty energy inputs in production, with dirty energy being the source of a negative externality leading to global warming (Golosov et al., 2014). Acemoglu et al. (2012) specifically explore the role of directed technical change with clean and dirty inputs and show that the optimal climate policy involves both a carbon tax and research subsidies. Hassler et al. (2022) study the role of technical change to relax natural resource scarcety. Our new contribution is that intermediate inputs stem from recycled and raw materials, with recycling relaxing the resource constraint. The supply of recycled and raw materials is subject to differential frictions just as the use of clean and dirty energy differs by their climate externalities. The market frictions in the circular economy with recycling arise from the need for environmentally safe disposal of waste.

We believe that the proposed framework of recycling, circular production, and scarce resources offers policy relevant and novel insights at a fundamental level. First, the production and use of new goods entails additional social costs of environmentally safe waste disposal. Recycling directly reduces the need for costly waste disposal which is an additional benefit external to individual firms in the recycling industry. Second, these negative and positive externalities rationalize a policy that makes firms pay for external trash costs, and compensates recycling firms for external savings in waste disposal costs. Steering the market economy to an optimal allocation thus requires a trash tax combined with a recycling subsidy. Third, we find rich welfare effects of trade and industrial policy with non-trivial interactions between terms of trade changes and distortions in recycling. For example, a country importing material inputs could enjoy a triple welfare gain from launching a domestic innovation program to improve the recycling technology. The welfare gains from improving the terms of trade are magnified by the reduction in two distortions related to recycling and the production of new goods. Finally, a large foreign resource discovery reduces the world price for materials. Being an importer of materials, the home economy benefits from a terms of trade improvement. However, to reap the full potential for welfare gains, it would need to prevent a contraction in recycling due to lower prices of materials. For example, it could launch an innovation program or offer a cost subsidy to strengthen the competitiveness of its recycling industry.

The paper proceeds by introducing the theoretical framework in Section 2, which also characterizes the distortions in the circular production process and the optimal policy for an efficient allocation. Section 3 analyzes comparative static effects and welfare changes of various policy interventions in a second best world. We first consider a small open economy and then turn to trade in the world economy with endogenous terms of trade. Section 4 summarizes key insights and concludes.

2 The Model

Countries have fixed endowments of labor L and natural resources K. Production of final goods uses labor together with materials. Material inputs M consist of recycled and raw materials. Raw materials are extracted from natural resources. Countries trade final goods and raw materials.

Recycled materials are produced from used goods (trash, waste). After consumption and investment, households and firms are left with a depreciated quantity s of new goods while a share $1-s$ is used up. Government regulations require agents to return used goods to collection centers and recycling stations. We assume that regulations are enforced with sufficiently high fines to prevent littering. Recycling extracts the material components (a car consists of many materials) and converts them into new materials in quantity X. Recycled materials can replace raw materials Q extracted from nature. In a circular economy, materials are turned into output, and used output is turned into materials, thereby saving on natural resources. Figure 3 illustrates the key mechanisms.

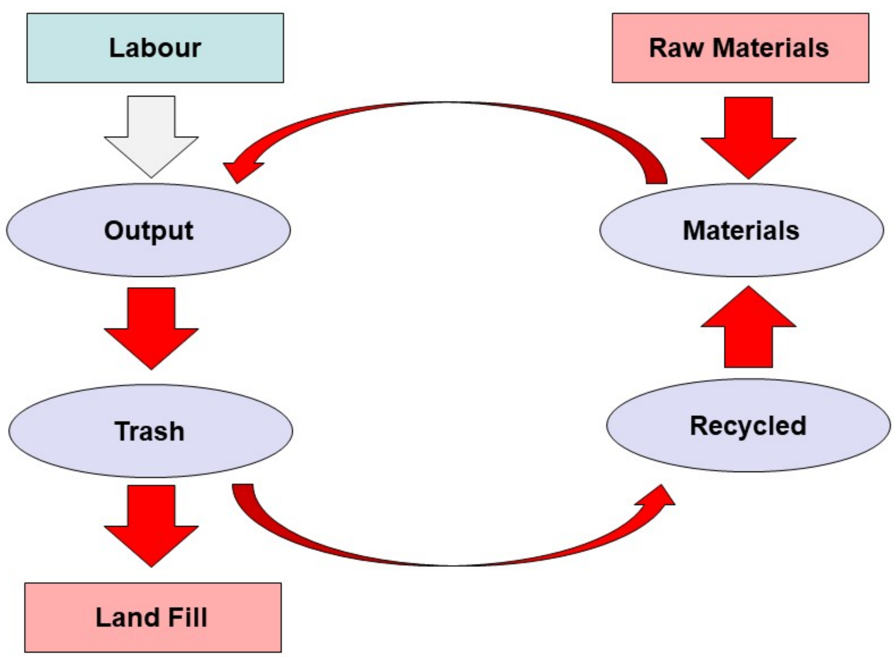

Figure 3: A Snapshot of the Model

2.1 Final Goods

There are three types of firms, final goods producers, recyclers and prospectors. Recyclers collect waste and transform it into new materials X. Prospectors extract natural resources and supply raw materials Q. The two types of materials are assumed to be perfect substitutes, with a common price p. Along with imports J, materials are

$$M = Q + X + J. \tag{1}$$

Final goods producers combine labor and materials to produce output Y, using a linear homogeneous technology. The final good is the *numeraire.* Profits are

$$\pi_y = \max_{L,M} \; Y - wL - pM, \quad Y = AM^{\alpha}L^{1-\alpha}. \tag{2}$$

Using subscripts to denote derivatives, optimality conditions are

$$Y_L = w, \quad Y_M = p, \tag{3}$$

where $Y_L = (1-\alpha) A (M/L)^{\alpha}$ and $Y_M = \alpha A / (M/L)^{1-\alpha}$. Factor prices are equal to marginal products. Eliminating M/L yields the factor price frontier $w(p)$ with negative slope $w'(p) < 0$,

$$w(p) = (1-\alpha) \left[A (\alpha/p)^{\alpha} \right]^{1/(1-\alpha)}, \quad \frac{M}{L} = \frac{\alpha}{1-\alpha} \frac{w}{p}. \tag{4}$$

A higher price for materials reduces the wage.

The total waste volume results from the domestic use of final goods for consumption, investment and government spending, $C + I + G$. In an open economy, total waste is no longer equal to output since part of output may be exported (E) and used abroad,

$$W = s \cdot (C + I + G) = s \cdot (Y - E). \tag{5}$$

If exports are positive $(E > 0)$, the national 'waste footprint' is smaller than domestic output. If a country is a net importer of final goods $(E < 0)$, the waste footprint is larger since the domestic use of goods $C + I + G$ exceeds domestic output.

Lemma 1 ***(Waste Footprint)*** *Waste W is a fraction s of demand for new goods (domestic absorption) and is an input to recycling. A country's waste footprint W is larger than domestic output, if it is a net importer of materials.*

2.2 Resource Extraction

Firms in the extraction industry (prospectors) invest output to extract part of the natural resource endowment K and convert it into raw materials in quantity Q. The cost function $N(Q,K)$ is convex increasing in Q, satisfies the Inada condition $\lim_{Q\to K} N_Q \to \infty$, and is decreasing in the endowment K. In particular, the marginal extraction cost decreases when new resources are discovered. We specify

$$N(Q,K) = \frac{\psi}{1/\mu - 1}(K-Q)^{1-1/\mu}, \quad \mu < 1. \tag{6}$$

Convexity implies $N_Q = \psi(K-Q)^{-1/\mu} > 0$ and $N_{QQ} = \frac{\psi}{\mu}(K-Q)^{-1/\mu-1} > 0$. Note $\frac{N_Q}{(K-Q)N_{QQ}} = \mu$. Since $N_{Q,K} = -\frac{\psi}{\mu}(K-Q)^{-1/\mu-1} < 0$, resource discoveries reduce marginal extraction cost. A higher use of raw materials depletes the resource endowment. 'Remaining reserves' $K-Q$ get very scarce when the endowment is close to being used up, and marginal extraction costs rise progressively.

Prospectors must pay a royalty r for the license to exploit resources. For the most part, we set the resource tax to zero initially. To produce raw materials Q, firms must invest a quantity N of the final good in resource extraction. A larger supply of materials expands the output of new goods which eventually turn into trash. To correct for potential distortions in circular production, we allow for a 'trash tax' at rate τ. Profits are

$$\pi_q = \max_Q \ (1-\tau)pQ - N(Q,K) - rQ \quad \Rightarrow \quad (1-\tau)p - r = N_Q(Q,K). \tag{7}$$

An increasing price for materials and lower royalties boost resource extraction and the supply of raw materials. Discovery of new resources K reduces marginal extraction cost, $N_{Q,K} < 0$, and thus leads to a larger supply of raw materials.

2.3 Recycling

Recycling firms invest final output to operate waste collection centers and convert a part $R < W$ of waste into new materials. The remainder $W - R$ must be disposed of by communities in safe waste deposits (landfill) at a cost γ per unit. Public spending is

$$G = \gamma \cdot (W - R) + \omega(\theta), \quad R < W. \tag{8}$$

Spillovers from public research increase private knowledge about recycling processes and boost the productivity θ in the recycling industry. More spillovers require a larger investment in tax financed public research. Cost $\omega(\theta)$ is convex increasing in research output $\theta \geq \bar{\theta}$. Productivity is low when there is no public R&D investment, $\omega\left(\bar{\theta}\right) = 0$.

The recycling technology for converting collected waste R into new materials X is

$$X = \theta f(R), \quad f(R) = R^{1-\delta}, \quad 0 < \delta < 1. \tag{9}$$

Firms invest a quantity R of final goods to process a waste volume of R. Marginal cost is one. Costs result from collecting and sorting used goods by different types (plastic, wood, electronics, clothes, paper, etc.) and preparing them for the recycling process.

Recycled material is a perfect substitute for raw materials and earns the same price p. Like producers of raw materials, recyclers are subject to a trash tax at rate τ. However, they receive an input subsidy σ for processing waste which reduces private cost by σR. The subsidy could even dominate the trash tax, making firms net beneficiaries. Profit is

$$\pi_x = \max_R \ (1-\tau) pX - (1-\sigma) R \quad \Rightarrow \quad (1-\tau) p\theta f'(R) = 1 - \sigma. \tag{10}$$

A higher price for materials, a higher productivity θ thanks to knowledge spillovers from public research, and a more generous input subsidy all boost investment and output in the recycling industry.

2.4 Equilibrium

A tariff t applies on material imports J, where p^w is the world price. The government levies a trash tax on production of materials at rate τ, a resource tax r on extraction, and a lump-sum tax T. It spends σR on input subsidies to recycling, and G on waste disposal and public research on recycling processes. The fiscal constraint then is

$$T = G + \sigma R - \tau p\left(Q + X\right) - rQ - tp^{w}J. \tag{11}$$

Labor supply is fixed at $\bar{L}$. Households consume all income, consisting of wages and profits net of a lump-sum tax T. The budget constraint restricts consumer spending to

$$C = w\bar{L} + \pi - T, \quad I \equiv R + N. \tag{12}$$

The second equation records total investment in recycling and resource extraction.

Households receive total profit income $\pi = \pi_y + \pi_q + \pi_x$. Use (2), (7) and (10) together with $X = \theta f\left(R\right)$ and investment I to get total profit income

$$\pi = \pi_y + \pi_q + \pi_x = Y - wL - I + \sigma R - rQ - \tau p\left(X + Q\right) - p\left(M - Q - X\right). \tag{13}$$

A country with a small resource endowment imports natural resources and pays with exports of the final good. Denote imports and exports by J and E, respectively. Market clearing conditions for final output, labor and materials are

$$Y = C + I + G + E, \quad \bar{L} = L, \quad M = X + Q + J. \tag{14}$$

Imports of raw materials are potentially subject to a tariff at rate t.[6] Free arbitrage links domestic and world prices for materials, p and p^{w}, by

$$p = \left(1 + t\right)p^{w}. \tag{15}$$

World prices are taken as given by a small country. Trade is balanced,

$$p^{w}J = E. \tag{16}$$

The trade balance must hold as a consequence of Walras' Law (see Appendix A).

[6]Actually, recycled and raw materials are perfect substitutes so that imports are for materials, irrespective of whether they are raw or recycled.

Lemma 2 ***(Externalities)*** *The domestic use of final goods causes waste and requires clean disposal of non-recycled waste (landfill) equal to* $\gamma \cdot (W - R)$. *Disposal costs of hazardous waste are external to individual producers. Production of new goods increases disposal costs (negative externality), and recycling reduces them (positive externality).*

2.5 Efficiency

For a welfare analysis, we characterize a Pareto optimum in a small open economy that takes the world market price p^w as given. Appendix B characterizes a first best allocation and derives optimal policies that can decentralize the optimal allocation in a competitive equilibrium. The result is

Proposition 1 ***(Efficiency)*** *Supporting an efficient allocation in market equilibrium requires an input subsidy* σ *to recycling, a 'trash' tax* τ *on the domestic production of materials. Efficiency requires neither a tariff nor a resource tax:*

$$\sigma^* = \gamma, \quad \tau^* = s\gamma = s\sigma^*, \quad r^* = t^* = 0. \tag{17}$$

The trash tax τ^* *internalizes the external waste disposal costs originating with the production of recycled and raw materials. The input subsidy to recycling* σ^* *compensates for the external savings of disposal costs.*

In addition, with an optimal trash tax in place, public R&D is optimal if

$$(1 - \tau^*) \, pf \, (R) = \omega' \, (\theta) \, . \tag{18}$$

The government should thus invest in basic research on recycling processes and generate knowledge spillovers until the marginal value of productivity gains in recycling match marginal fiscal costs $\omega' \, (\theta)$. In raising private sector productivity, the government expands the supply of materials, output and trash.

The trash tax internalizes the external costs of induced changes in trash $W = s \, (Y - E)$. Using $Y_M = p$, private resource extraction in (7) is determined by $(1 - \tau) \, Y_M = N_Q + r$

and is optimal when the government imposes an appropriate trash tax τ^* as in (17). More extraction increases the supply of raw materials, expands output and thereby leads to more trash, $\frac{dW}{dQ} = sY_M$, which raises the fiscal costs of waste disposal by $\gamma \frac{dW}{dQ}$ at the margin. In imposing an optimal trash tax, the government makes firms pay for the negative fiscal externality by the term $s\gamma$. A resource tax would further reduce extraction and is not required, $r^* = 0$. If the government wished to extract resource rents, it should use a lump-sum tax that does not interfere with investment.

The trash tax on recycling internalizes the externalities created by induced trash in the same way as with extraction. The difference is that recycling directly reduces the public costs $\gamma (W - R)$ of waste disposal (landfill) by γ at the margin. The optimal recycling subsidy $\sigma^* = \gamma$ compensates recycling firms for the savings in landfill costs. The supply of raw materials yields no such savings in trash disposal costs. The optimal policy thus favors the supply of materials via recycling relative to natural resource extraction. With the optimal tax subsidy scheme in place, the private investment calculus in (10) is $p\theta f'(R) = \frac{1-\sigma^*}{1-\tau^*}$. The optimal policy satisfies $\tau^* < \sigma^*$ and implies $\frac{1-\sigma^*}{1-\tau^*} < 1$. On net, the recycling industry gets subsidized by the scheme while the extraction industry is left to pay a trash tax. The policy thus shifts the production from raw materials to recycling, thereby reducing resource dependency.

The supply of raw materials stimulates production in new goods which eventually turn into trash. The induced costs of waste disposal are a negative externality which is not accounted for by individual firms. In the absence of a trash, or if it is too small, resource extraction in free market equilibrium is larger than optimal. The same applies to recycling, except for one important difference. Since recycling uses waste as an input, it directly reduces the residual waste volume that needs to be stored in costly waste deposits (landfill). These savings dominate over the negative externality. If firms are not compensated for the net external benefits, the scale of recycling is too small in free market equilibrium. In consequence, and whenever the corrective tax subsidy scheme is too small or missing at all, an expansion of recycling and a restriction of resource extraction yields positive welfare gains. In (B.6) of Appendix B,[7] we derive the marginal welfare effects from variations in extraction and recycling,

$$\hat{u} = (\sigma^* - \sigma)\left[\frac{1-\tau}{1-\sigma} - s\right](1-\delta)\,\alpha s_m s_x \cdot \hat{R} - (\sigma^* - \sigma)\,s\alpha s_m\,(1-s_x)\cdot\hat{Q}. \tag{19}$$

We assume that welfare is equal to consumption, $u = C$,[8] and express welfare changes in percent of GDP, $\hat{u} \equiv du/Y$. In restricting attention to a proportional tax subsidy scheme $\tau = s\sigma$ as suggested in (18), we use $\tau^* - \tau = (\sigma^* - \sigma)\,s$. Whenever the trash tax is smaller than optimal, $\tau^* > \tau$, the waste footprint of expanding resource extraction by $\hat{Q} \equiv dQ/Q$ reduces welfare. Since $\frac{1-\tau}{1-\sigma} \approx 1 > s$,[9] stimulating recycling by $\hat{R}$ would increase welfare in proportion to $\sigma^* - \sigma$. Scaling up the tax subsidy scheme taxes resource extraction and, on net, subsidizes recycling. It thus shifts input supply from raw to recycled materials, $\hat{R} > 0 > \hat{Q}$, and yields welfare gains on both margins by steering the economy towards a Pareto optimum. Obviously, such gains vanish when the tax subsidy scheme is scaled up to the welfare maximizing level $\sigma = \sigma^*$ and $\tau = \tau^*$. This logic is key in understanding the second best welfare effects of the policy scenarios in the following section.

3 Resource Dependence, Recycling and Trade

Recycling can reduce resource dependence and thereby affect trade in final goods and (raw) materials. Given distortions, policy reform can steer the economy towards a better outcome with higher welfare. This section investigates the comparative static effects and the potential welfare gains of policy changes. We start with a small open economy, taking the world price p^* as given, and then investigate world equilibrium with trade among large countries. Most importantly, we compute the consequences of a trash tax τ on all output and an input subsidy σ to recycling. We analyze the effects of targeted public research that

[7] Note the cost share of materials in final output, $\alpha = MY_M/Y$, the share $s_m \equiv M_s/M$ of domestic supply $M_s = X + Q$ in total materials, and the share $s_x \equiv X/M_s$ of recycling in total domestic supply.

[8] Environmental degradation due to waste disposal could introduce an additional negative externality. To simplify, we abstract from utility costs since we already include direct costs of waste disposal.

[9] Using the optimal combination $\tau = s\sigma < \sigma$ of the tax subsidy scheme implies $\frac{1-\tau}{1-\sigma} > 1 > s$.

yields knowledge spillovers and boosts productivity θ in recycling. We further consider a resource discovery which augments the endowment K, and changes in the resource tax r and a tariff t on imports of (raw) materials.

3.1 Small Open Economy

We solve for the changes in imports which represent the domestic excess demand function for materials, $J(p;\tau,\ldots) = M - X - Q$. Hats denote percent changes relative to initial values, $\hat{M} \equiv dM/M$. The exceptions are $\hat{\sigma} \equiv d\sigma/(1-\sigma)$, $\hat{\tau} \equiv d\tau/(1-\tau)$, $\hat{t} \equiv dt/p$, and $\hat{r} \equiv dr/p$ to allow rates to be zero initially. The tax subsidy scheme $\tau = s\sigma$ thus changes by $\hat{\tau} = s \cdot \hat{\sigma}$. We investigate piecemeal reforms relative to a laissez-faire equilibrium.

RAW MATERIALS: The supply of raw materials requires investment in extraction. By (6) and (7), noting $r = \tau = 0$ initially, extraction changes by $\hat{p} - \hat{\tau} - \hat{r} = \hat{N}_Q$. Extraction makes 'remaining reserves' $K - Q$ more scarce which motivates an index of resource abundance, $\chi \equiv \frac{K-Q}{Q}$, implying $\frac{Q}{K-Q} = \frac{1}{\chi}$ and $\frac{K}{K-Q} = \frac{1+\chi}{\chi}$. Marginal cost thus changes by $\hat{N}_Q = -\frac{1}{\mu}\left[\frac{1+\chi}{\chi}\hat{K} - \frac{1}{\chi}\hat{Q}\right]$, and the supply of raw materials responds by

$$\hat{Q} = \mu\chi \cdot (\hat{p} - \hat{\tau} - \hat{r}) + (1+\chi) \cdot \hat{K}. \tag{20}$$

A higher materials price boosts extraction. Taxes discourage it. A resource discovery $\hat{K}$ reduces marginal extraction cost and boosts the supply of raw materials.

The degree of resource abundance affects the price elasticity of extraction and of the supply of raw materials. A higher use of raw materials depletes the resource endowment and makes natural resources less abundant, $\frac{d\chi}{dQ} = -\frac{K}{Q^2} < 0$. Natural resources get very scarce and the abundance index goes to zero when the endowment is close to being used up, i.e., $\chi \to 0$ when $Q \to K$. New discoveries increase resource abundance, $\frac{d\chi}{dK} = \frac{1}{Q}$. Quite intuitively, when resources are very abundant (χ is large), any price increase induces a strong increase in extraction, $\hat{Q} = \mu\chi \cdot \hat{p}$. The price elasticity of supply μ is scaled up by the abundance index. When the resource is scarce (χ is small), extraction is increased only by a small amount, i.e., supply is price inelastic.

RECYCLING: Starting from a laissez-faire position of $\tau = \sigma = 0$, log-differentiating the condition $(1-\tau)\, p\theta f'(R) = 1-\sigma$ in (10) gives $\hat{p} - \hat{\tau} + \hat{\theta} - \delta \cdot \hat{R} = -\hat{\sigma}$. In consequence, investment and output $X = \theta R^{1-\delta}$ in the recycling industry change by

$$\hat{R} = \frac{1}{\delta} \cdot \left(\hat{\sigma} - \hat{\tau} + \hat{p} + \hat{\theta}\right), \quad \hat{X} = \frac{1}{\delta} \cdot \hat{\theta} + \frac{1-\delta}{\delta} \cdot (\hat{\sigma} - \hat{\tau} + \hat{p}). \tag{21}$$

A rising price of materials and a higher input subsidy, net of the trash tax, stimulate investment and output of recycled materials. More public R&D, via knowledge spillovers, raises productivity in the recycling industry and similarly boosts investment and supply.

EXCESS DEMAND: Given fixed labor supply, condition (3) determines demand for materials in final goods production,

$$\hat{M} = -\frac{1}{1-\alpha} \cdot \hat{p}, \quad \hat{Y} = \alpha \cdot \hat{M}, \quad \hat{w} = -\frac{\alpha}{1-\alpha} \cdot \hat{p}. \tag{22}$$

Both a higher input price and a larger trash tax shrink demand and, in turn, the production of final goods. With fixed labor supply, higher costs depress wages, see (4).

The home economy is assumed to export final goods and import materials. Domestic excess demand for materials is $J = M - X - Q$ as in (14). We express the change of imports in percent of material demand, $\hat{J} \equiv dJ/M$. Domestic supply delivers a share $s_m \equiv M_s/M$ of total material demand. Imports $J = M - M_s$ thus adjust by $\hat{J} = \hat{M} - s_m \cdot \hat{M}_s$. Domestic supply $M_s \equiv X + Q$ reflects adjustments in recycling and resource extraction. Recycled materials make up a share $s_x \equiv X/M_s$ of total domestic supply which thus changes by $\hat{M}_s = s_x \cdot \hat{X} + (1-s_x) \cdot \hat{Q}$. Combining the relationships and substituting (20-22) gives

$$\hat{J} = -\varepsilon_p \cdot \hat{p} + \varepsilon_\tau \cdot \hat{\tau} - \varepsilon_\sigma \cdot \hat{\sigma} - \varepsilon_\theta \cdot \hat{\theta} + \varepsilon_r \cdot \hat{r} - \varepsilon_K \cdot \hat{K}, \tag{23}$$

where elasticities are all positive and are given by

$$\begin{aligned}
\varepsilon_p &\equiv \frac{1}{1-\alpha} + s_m s_x \frac{1-\delta}{\delta} + s_m (1-s_x)\, \mu\chi, \\
\varepsilon_\tau &\equiv \left[s_x \frac{1-\delta}{\delta} + (1-s_x)\, \mu\chi \right] s_m, \quad \varepsilon_\sigma \equiv s_m s_x \frac{1-\delta}{\delta}, \\
\varepsilon_\theta &\equiv s_m s_x \frac{1}{\delta}, \quad \varepsilon_r \equiv s_m (1-s_x)\, \mu\chi, \quad \varepsilon_K \equiv s_m (1-s_x)(1+\chi).
\end{aligned}$$

Interpretations are intuitive. The slope of the excess demand function is negative. A higher domestic price shrinks demand for materials and expands domestic supply. Both effects reduce import demand. A higher trash tax depresses domestic supply of materials and, in turn, boosts imports. Both a higher input subsidy and a productivity gain in recycling boost supply, thereby squeezing important demand. A domestic resource tax would restrict extraction and domestic supply of raw materials. More imports would fill the gap. Finally, a domestic resource discovery entails the opposite effects.

Noting $E = p^w J$, the country's waste footprint is $W = s\,(Y - p^w J)$ and changes by $dW = s \cdot (dY - p^w \cdot dJ - J \cdot dp^w)$. Using $\hat{J} \equiv dJ/M$, expressing the change in the waste volume relative to GDP, starting from $p = p^w$ and using the cost share $\alpha = pM/Y$ and the trade share $s_e \equiv E/Y = p^w J/Y$ gives

$$\hat{W} \equiv dW/Y = s \cdot \left(\hat{Y} - \alpha \cdot \hat{J} - s_e \cdot \hat{p}^w\right). \qquad (24)$$

TERMS OF TRADE SHOCK: A small open economy takes world market prices as given and is exposed to exogenous price shocks. The home economy is assumed to be a net importer of materials. With balanced trade, exports of final goods must thus pay for the value of imports at world market prices, $E = p^w J$. The terms of trade $1/p^w$ are the price of imports in terms of exports. Given a world price, the domestic price of materials depends on the import tariff by $p = (1+t)\,p^w$. Starting from $t = 0$ and using $\hat{t} \equiv dt/p$, a small import tariff raises the domestic price by

$$\hat{p} = \hat{p}^w + p \cdot \hat{t}. \qquad (25)$$

A higher price of materials due to events on world markets, $\hat{p} = \hat{p}^w$, restricts demand for materials and output at home, and stimulates recycling and resource extraction. For these reasons, imports shrink by $\hat{J} = -\varepsilon_p \cdot \hat{p}$. What is the impact on welfare? If the optimal policy were in place, all variations in recycling, and resource extraction would have zero welfare effects, see (19). An increasing world market price of materials deteriorates the terms of trade of an import country. The higher cost of imports reduces welfare by

$du = -(1 - s\gamma) p^w J \cdot \hat{p}$. To see this, apply the envelope theorem to (B.1) in Appendix B. As mentioned above, we conveniently express the welfare change in percent of GDP, $\hat{u} \equiv du/Y$, note $p = p^w$ in the initial situation, and use $\tau^* = s\gamma$. Denoting the trade share by $s_e \equiv pJ/Y$ thus gives $\hat{u} = -(1 - \tau^*) s_e \cdot \hat{p}$. The welfare loss from deteriorating terms of trade is a classical result, except that it is modified by the presence of externalities relating to waste disposal as measured by $\tau^* = s\gamma$. In the absence of policy intervention, the impact on welfare additionally depends on the induced changes in recycling and resource extraction as in (19).[10] Starting from an untaxed equilibrium, noting $\tau^* = s\sigma^*$, and adding the terms of trade effects results in an overall ambiguous welfare change,

$$\hat{u} = \sigma^* (1 - s)(1 - \delta) \alpha s_m s_x \cdot \hat{R} - \tau^* \alpha s_m (1 - s_x) \cdot \hat{Q} - (1 - \tau^*) s_e \cdot \hat{p}. \tag{26}$$

Starting from an untaxed situation, a terms of trade shock changes welfare in offsetting ways. In an import country, the standard terms of trade effect is negative. However, a higher price of materials stimulates both recycling and resource extraction. Both activities are subject to externalities and entail additional welfare effects. The expansion of resource extraction is welfare deteriorating and thereby magnifies the welfare loss from the terms of trade shock. The expansion of recycling, in contrast, is welfare improving and partly offsets the welfare losses. The total welfare effect of a higher world price of materials is, in principle, ambiguous but likely to be negative. If recycling contributes little to the supply of materials (s_x is small), the total effect is negative. However, the country could attenuate the terms of trade shock by imposing a resource tax that eliminates the expansion of domestic resource extraction and eliminates the welfare loss on this margin.

Proposition 2 ***(Terms of Trade Shock)*** *(i) A higher price of materials boosts domestic resource extraction and recycling, restricts demand for materials and output, and reduces imports of materials; (ii) The expansion of resource extraction magnifies the welfare loss from deteriorating terms of trade, the increase in recycling dampens it.*

[10] A variation of imports has a zero marginal welfare effect since $Y_M = p = p^w$ initially, see (B.2.iv).

3.2 Policy Reform

Starting from laissez-faire, we explore options for welfare improving policy reform.

IMPORT TARIFF: The first option is in the spirit of 'infant industry protection' for recycling. The strategy is to levy an import tariff combined with a resource tax. The tariff raises the domestic price of materials which benefits recycling as well as resource extraction. We complement the tariff with a resource tax to prevent an increase in extraction. By (20), the required resource tax is

$$\hat{r} = \hat{p} = p \cdot \hat{t} \quad \Rightarrow \quad \hat{Q} = 0. \tag{27}$$

The policy restricts domestic demand for materials and boosts the supply of recycled materials while raw materials extraction is unchanged. By (23), imports thus decline by $\hat{J} = -(\varepsilon_p - \varepsilon_r)\, p \cdot \hat{t} < 0$ where $\varepsilon_p - \varepsilon_r = \frac{1}{1-\alpha} + s_m s_x \frac{1-\delta}{\delta}$. By levying a resource tax, the country can shut off the welfare reducing increase in domestic resource extraction. Given an absence of terms of trade changes, welfare in (26) increases by

$$\hat{u} = \sigma^* (1-s)(1-\delta)\, \alpha s_x \cdot \hat{R} > 0. \tag{28}$$

More recycling directly reduces the amount of trash that must be safely stored with protected landfill, and thereby leads to savings in the costs of waste disposal. On the negative side, recycling also leads to more trash which augments the costs of waste disposal. The derivation of (B.6) in Appendix B as discussed in (19) showed that the positive externality from recycling unambiguously dominates and thereby leads to a net welfare gain. By shifting material supply from imports to recycling and keeping extraction constant, the policy is welfare improving. It increases the volume of trash $W = s\,(Y - p^w J)$. However, by stimulating recycling, it reduces the costs of waste disposal from landfill, $G = \gamma\,(W - R)$. Substituting $\hat{Y} = -\frac{\alpha}{1-\alpha} \cdot \hat{p}$ and $\hat{J} = -\left(\frac{1}{1-\alpha} + s_m s_x \frac{1-\delta}{\delta}\right) \cdot \hat{p}$ from above into (24) gives

$$\hat{W} = s\alpha s_m s_x \frac{1-\delta}{\delta} \cdot \hat{p}, \quad \hat{G} \equiv \frac{dG}{Y} = -\gamma \alpha s_x s_m (1-s) \frac{1-\delta}{\delta} \cdot \hat{p} < 0. \tag{29}$$

In parallel to $\hat{W}$, we express the change in landfill costs in percent of GDP so that $\hat{G} = \gamma \left[\hat{W} - (R/Y) \cdot \hat{R}\right]$. The analysis following equation (B.6) in Appendix B establishes

$R/Y = (1-\delta)\,\alpha s_x s_m$. Using this and substituting $\hat{W}$ together with $\hat{R} = \frac{1}{\delta} \cdot \hat{p}$ gives the second equation above. The policy thus reduces the net cost of waste disposal. The negative externality is reduced and welfare increases.

Proposition 3 ***(Import Tariff Cum Resource Tax)*** *(i) An import tariff raises the price, expands the domestic supply of materials, restricts output and demand for materials, and reduces trade; (ii) A complementary resource tax can prevent an increase in domestic resource extraction; (iii) With a constant world price and unchanged resource extraction, domestic welfare improves on account of a larger recycling of used goods. Trash increases, but more recycling reduces disposal costs of hazarduous waste.*

TAX SUBSIDY SCHEME: Starting from a free market equilibrium, the government could introduce a tax subsidy scheme $\tau = s\sigma$ to make a step towards a Pareto optimum. The market price of materials is set on world markets, and the changes in tax and subsidy rates are expressed in percent of the initial material price. By simultaneously raising the tax and subsidy rates by $\hat{\tau} = s \cdot \hat{\sigma}$, the policy shifts domestic supply from raw to recycled materials and thus promises an unambiguous welfare gain.

By (20), the trash tax reduces extraction by $\hat{Q} = -\mu\chi \cdot \hat{\tau}$. However, the combined effect of the tax and subsidy scheme stimulates recycling as in (21), thereby expanding investment and output by $\hat{R} = (1-s)\,\frac{1}{\delta} \cdot \hat{\sigma}$ and $\hat{X} = (1-s)\,\frac{1-\delta}{\delta} \cdot \hat{\sigma}$, respectively. Using $\hat{\tau} = s \cdot \hat{\sigma}$, the change in imports is ambiguous, $\hat{J} = (s\varepsilon_\tau - \varepsilon_\sigma) \cdot \hat{\sigma} \gtrless 0$. Turning to welfare, we first note that a variation of imports has a zero welfare effect since material use is efficient at the outset (see (B.2.iv) in Appendix B). In the absence of terms of trade changes, and using $\hat{\tau} = s \cdot \hat{\sigma}$ as well as $\tau^* = s\sigma^*$, the policy initiative unambiguously boosts welfare in (26),

$$\hat{u} = \sigma^* \left[(1-s)^2 \, s_x \frac{1-\delta}{\delta} + s^2 \,(1-s_x)\, \mu\chi \right] p\alpha s_m \cdot \hat{\sigma} > 0. \tag{30}$$

The first term in the square bracket captures the welfare gain from *increasing* recycling, and the second one the gain from *reducing* resource extraction. The policy reduces resource dependence and promises unambiguous welfare gains by shifting the domestic production of materials from resource extraction to recycling.

Proposition 4 ***(Tax Subsidy Policy)*** *(i) Combining a trash tax with a selective input subsidy to recycling reduces domestic resource extraction and stimulates recycling. The effect on trade is ambiguous; (ii) The policy yields unambiguous welfare gains by shifting domestic supply of materials from resource extraction to recycling.*

3.3 The World Economy with Large Countries

In this section, we investigate policy spillovers among large countries. We aim to shed light on two policy problems. First, how can a resource poor economy reduce its dependency on scarce natural resources? Specifically, the country could invest in directed public R&D to increase general knowledge about recycling processes. The knowledge spillovers should then boost productivity in the recycling sector. How are foreign economies affected? Second, if there is a large discovery of new resources in some foreign country, how should the home country react if at all?

WORLD PRICE: The terms of trade are endogenously determined in the world economy. Foreign countries are identical in structure but may differ in resource endowments K or levels of technology. Advanced economies typically are short of natural resources. Being technologically advanced, they feature high productivity in final goods production and require large quantities of materials. For these reasons, rich countries are typically importers of raw materials and exporters of final goods. Less advanced and resource rich economies have a comparative advantage in materials and import final goods. Denoting foreign countries by an upper index i, world market clearing for materials requires $M + \sum_i M^i = X + \sum_i X^i + Q + \sum_i Q^i$. Using $J^i = M^i - X^i - Q^i$ gives

$$J + \sum_i J^i = 0. \tag{31}$$

The home country is a net importer of raw materials ($s_m \equiv M_s/M < 1$). Foreign countries may be exporters or importers ($s_m^i \gtrless 1$).

We have expressed the change in imports in percent of total material demand, $\hat{J} \equiv dJ/M$. Home's share in world demand for materials is s_w where $s_w \to 1$ and $s_w \to 0$ are the cases of a closed and of a small open economy. Trade in materials, and correspondingly in final goods, changes by

$$s_w \cdot \hat{J} + \sum\nolimits_i s_w^i \cdot \hat{J}^i = 0, \quad s_w^i \equiv M^i/M^w, \quad M^w \equiv M + \sum\nolimits_i M^i. \tag{32}$$

We consider public research spending $\omega(\theta)$ at home to boost the productivity θ of the recycling technology. We also study the consequences of an endowment shock K^i in some foreign country. Noting (23), these shocks affect trade by

$$\hat{J} = -\varepsilon_p \cdot \hat{p}^w - \varepsilon_\theta \cdot \hat{\theta}, \quad \hat{J}^i = -\varepsilon_p^i \cdot \hat{p}^w - \varepsilon_K^i \cdot \hat{K}^i. \tag{33}$$

Substitute into (32) and write separately the foreign country that is subject to a resource shock and others that are not. The impact on the world price for materials is

$$\hat{p}^w = -s_w \frac{\varepsilon_\theta}{\bar{\varepsilon}_p} \cdot \hat{\theta} - s_w^i \frac{\varepsilon_K^i}{\bar{\varepsilon}_p} \cdot \hat{K}^i, \quad \bar{\varepsilon}_p \equiv s_w \varepsilon_p + \sum\nolimits_i s_w^i \varepsilon_p^i. \tag{34}$$

The price elasticity of excess demand in the world market is a weighted average of country specific elasticities with weights equal to each country's share s_w^i in the world market.

DOMESTIC INNOVATION: A larger investment in directed public R&D improves the domestic recycling technology. On impact, at constant world prices, recycling expands while resource extraction is unaffected, see (20-21). Imports decline by $\hat{J} = -\varepsilon_\theta \cdot \hat{\theta}$. Depending on the home country's weight in the world economy in (34), the world market price for materials falls. The price erosion dampens the expansion in recycling, discourages resource extraction and stimulates material demand at home which squeezes imports. Substitute $\hat{p}^w = -\frac{s_w \varepsilon_\theta}{\bar{\varepsilon}_p} \cdot \hat{\theta}$ into $\hat{J} = -\varepsilon_p \cdot \hat{p}^w - \varepsilon_\theta \cdot \hat{\theta}$ and calculate a net effect of

$$\hat{J} = -\frac{\bar{\varepsilon}_p - \varepsilon_p s_w}{\bar{\varepsilon}_p} \varepsilon_\theta \cdot \hat{\theta} = -\sum\nolimits_i \frac{s_w^i \varepsilon_p^i}{\bar{\varepsilon}_p} \varepsilon_\theta \cdot \hat{\theta} < 0. \tag{35}$$

While the price erosion dampens the direct effects, it cannot reverse them.

The innovation policy to improve the recycling technology yields a triple welfare gain for the home economy, see (26). First, since recycling investment is inefficiently small in the absence of corrective policy intervention, the expansion of recycling yields a first order welfare gain. Second, since resource extraction is too large in the free market equilibrium, the price erosion yields an additional welfare gain by discouraging extraction. Third, the reduction in the world price is an improvement in the terms of trade and yields first order welfare gains to an import country.

Can foreign countries benefit as well? The policy spillovers depend on their trade position. Foreign import countries benefit from a terms of trade improvement. They also experience a welcome contraction of resource extraction. However, the price erosion inflicts a welfare loss by impairing their recycling industry. Import countries could possibly neutralize this effect by offering an input subsidy to recycling firms, or by launching their own innovation program. Such a strategy would, of course, reinforce the decline in prices and magnify the terms of trade effects for all countries. The policy spillovers are more unfavorable to resource rich export nations. These countries would suffer from deteriorating terms of trade, in addition to discouraging any attempts at developing more recycling. They could resort to levying a resource tax to restrict the supply of raw materials and offset the negative terms of trade effects. This would also offer some relief to their recycling industry.

Proposition 5 ***(Domestic Innovation)*** *(i) Improving the recycling technology with a public R&D program expands recycling and reduces imports of materials. The declining world price stimulates demand for materials and output, discourages resource extraction, and dampens the growth in recycling and the decline in trade; (ii) The home country experiences a triple welfare gain from improved terms of trade, more recycling and less resource extraction; (iii) Foreign import countries benefit from better terms of trade and reduced extraction. The contraction in recycling dampens welfare gains; (iv) Foreign export countries suffer from deteriorating terms of trade and a declining recycling industry.*

FOREIGN RESOURCE DISCOVERY: How should the resource dependent home country react to a resource discovery in a foreign country? The discovery of new resources abroad stimulates resource extraction and expands world supply of materials which depresses the world price by $\hat{p}^w = -\frac{s_w^i \varepsilon_K^i}{\bar{\varepsilon}_p} \cdot \hat{K}^i$, see (34). This terms of trade gain definitely benefits the resource dependent home country. The reduction in domestic resource extraction is also beneficial. However, a lower price for materials further discourages investment in the recycling sector which is already inefficiently low and is, thus, a source of welfare losses. This unfavorable development calls for policy initiatives in favor of recycling. An input subsidy or a larger effort at directed innovation would be two alternatives to prevent increased resource dependence due to a decline in recycling. For example, the government could launch a public innovation program to boost productivity in the recycling sector to offset the effects of a declining price. Such a policy initiative is particularly advisable if starting from a free market equilibrium with $\theta = \bar{\theta}$ and $\omega\left(\bar{\theta}\right) = 0$, and would be part of an optimal policy package to achieve a Pareto optimum, see (18). By (21), preventing a contraction in recycling, $\hat{R} = \frac{1}{\delta} \cdot \left(\hat{p}^w + \hat{\theta}\right) = 0$, requires to step up public R&D spending when the world price declines, until the induced productivity gain is equal to $\hat{\theta} = -\hat{p}^w$. Substituting this into (34), and rearranging gives a net change in the world price equal to

$$\hat{p}^w = -\frac{s_w^i \varepsilon_K^i}{(\varepsilon_p - \varepsilon_\theta)\, s_w + \sum_i s_w^i \varepsilon_p^i} \cdot \hat{K}^i, \quad \varepsilon_p - \varepsilon_\sigma = \frac{1}{1-\alpha} + s_m\,(1 - s_x)\,\mu\chi > 0. \tag{36}$$

Since the denominator is smaller than in (34), the world price declines by even more since the domestic innovation response further increases world supply of materials. The innovation program prevents a reduction in the domestic recycling activity and avoids any welfare loss from this source. The domestic policy response, in fact, reinforces the erosion of the world market price and thereby magnifies the terms of trade gains of the home economy. It also cuts back domestic resource extraction more strongly and offsets the initial distortion of too much extraction even more powerfully. The home economy can benefit significantly more from a foreign resource descovery by strengthening efforts to develop and protect its recycling industry.

Proposition 6 ***(Foreign Resource Discovery)*** *(i) A foreign resource discovery creates excess supply and reduces the world price of materials. The lower price stimulates* *demand and output, reduces recycling and resource extraction, and boosts imports of materials in the home country; (ii) The home country can prevent a welfare reducing decline in recycling with a compensating policy of public R&D or an input subsidy. It thereby enjoys unambiguous welfare gains from improving terms of trade and a reduction in domestic resource extraction.*

4 Conclusions

Recycling makes valuable use of trash to supply fresh materials for the manufacturing of new goods, instead of using up scarce natural resources. In absorbing trash, it also reduces the need for environmentally safe and costly waste disposal. The key challenge in a circular economy is to make buyers of new goods pay for the public costs of waste disposal, and to compensate recycling firms for the savings in these costs. Achieving an efficient allocation would thus require a trash tax combined with an input subsidy to recycling firms. Developing the recycling industry also holds the potential to relax the bottlenecks in production that are created by rising prices of increasingly scarce exhaustible resources. When there is trade, countries exchange final goods for raw materials to make the best use of unevenly distributed natural resources. If optimal policy is not implemented, trade and national fiscal policy can yield rich welfare effects which arise from non-trivial interactions between terms of trade effects and distortions in the circular production process.

Recycling is particularly valuable in resource poor advanced economies. By improving the recycling technology, resource poor countries can reduce their resource dependence. By relaxing the scarcety of materials, recycling also benefits the competitiveness of the final goods industry. In fact, by launching a public innovation program to improve the recycling technology, a resource poor country could potentially reap a triple welfare gain by improving its terms of trade and at the same time offset the distortions in the production process. A resource poor country importing raw materials must also specifically react to assure the full welfare gains from a foreign resource boom. While a lower world price promises terms of trade gains, the home country would need to prevent a welfare reducing contraction in domestic recycling. It could do so by launching a public innovation program to increase the productivity in the recycling industry.

Appendix

A. Walras' Law: By Walras' Law, the sum of valued excess demands is $p^w J - E = 0$, which implies balanced trade in (16). To prove this, substitute profits (13) into the household sector budget $C = w\bar{L} + \pi - T$, and use the fiscal constraint (11) to get $(C + I + G - Y) + w\left(L - \bar{L}\right) + p\left(M - Q - X\right) = tp^w J$. Use market clearing conditions (14) together with $p = (1+t)\,p^w$ to get the required result $p^w J = E$, where domestic excess demands for materials and final goods are $J = M - Q - X$ and $-E = C + I + G - Y$, respectively. In a closed economy, $J = E = 0$, and the waste footprint is $W = sY$. In an open economy without capital flows, exports must pay for imports, $E = p^w J$. In a small economy, world prices for materials p^w are fixed which gives a domestic price $p = (1+t)\,p^w$ and equilibrium with imports and exports.

B. Efficiency: Welfare of households is equal to consumption, $u = C$. The planner maximizes welfare subject to resource constraints for materials $M = Q + X + J$, labor $\bar{L} = L$, and final output $Y = C + G + I + E$. Public and private investments are $G = \gamma\left(W - R\right) + \omega\left(\theta\right)$ and $I = R + N\left(Q, K\right)$, respectively. In an open economy, the total volume of waste is $W = s\left(Y - E\right)$ where exports are paid with imports, $E = p^w J$. Using technology $X = \theta f\left(R\right)$ and $Y\left(L, M\right)$, the problem is

$$\begin{aligned} u &= \max_{Q,R,\theta,J}\; Y - \gamma\left(W - R\right) - \omega\left(\theta\right) - R - N\left(Q, K\right) - p^w J, \\ &: \; s.t. \quad Y = Y\left[\bar{L}, Q + \theta f\left(R\right) + J\right], \quad W = s\left(Y - p^w J\right). \end{aligned} \tag{B.1}$$

The planner takes account of the fact that the waste volume changes along with domestic absorption, giving $\frac{dW}{dR} = sY_M\theta f'(R)$, for example. Noting this, optimality conditions are

$$\begin{aligned} (i) &: \frac{du}{dQ} = (1-s\gamma) Y_M - N_Q = 0, \\ (ii) &: \frac{du}{dR} = (1-s\gamma) Y_M \theta f'(R) + \gamma - 1 = 0, \\ (iii) &: \frac{du}{d\theta} = (1-s\gamma) Y_M f(R) - \omega'(\theta) = 0, \\ (iv) &: \frac{du}{dJ} = (1-s\gamma)(Y_M - p^w) = 0. \end{aligned} \tag{B.2}$$

All four conditions together determine the Pareto optimal allocation.

How can the Pareto optimum be decentralized? By (3), the market price of materials satisfies $Y_M = p$. Use this and compare the recycling condition (10) with (B.2.ii),

$$\begin{aligned} \text{markets}: \quad (1-\tau)\cdot Y_M\theta f'(R) &= 1-\sigma, \\ \text{optimal}: \quad (1-s\gamma)\cdot Y_M\theta f'(R) &= 1-\gamma. \end{aligned} \tag{B.3}$$

To steer the market allocation to a Pareto optimum, the government must offer a recycling subsidy and impose a trash tax,

$$\sigma^* = \gamma, \quad \tau^* = s\gamma, \quad r^* = t^* = 0. \tag{B.4}$$

The trash tax internalizes a negative externality in production of raw and recycled materials. The externality is that producers do not account for the costs of waste disposal of used goods. The trash tax also assures an efficient investment in resource extraction. Using τ^* and noting that $Y_M = p$ in market equilibrium shows that private investment in resource extraction in (7) is identical to the optimal investment condition in (B.2.i). A resource tax is not required. Finally, a small open economy faces a fixed price p^w of materials on world markets. By (B.2.iv), it is optimal to expand production and imports of materials until the marginal value is equal to the world price, $p^w = Y_M = p$. The second equality reflects demand for materials as given by $Y_M = p$. To support $p = p^w$ in (15), the import tariff is optimally set to zero.

The derivatives (B.2) also pin down marginal welfare changes. Using (B.4) gives $\frac{du}{dQ} = (1-\tau^*) Y_M - N_Q$. Since the resource tax is assumed to be zero initially, $r = 0$, and using $p = Y_M$, private investment follows from $(1-\tau) Y_M = N_Q$ in (7). Expanding resource extraction reduces welfare if the actual trash tax τ is absent or too small,

$$\frac{du}{dQ} = -(\tau^* - \tau) Y_M, \quad \frac{du}{dR} = (\sigma^* - \sigma) - (\tau^* - \tau) Y_M \theta f'(R). \tag{B.5}$$

More recycling changes welfare by $\frac{du}{dR} = (1-\tau^*) Y_M \theta f'(R) + \sigma^* - 1$. Private firms decide as in (10), $(1-\tau) Y_M \theta f'(R) + \sigma = 1$. Using this gives the second equation.

Optimal policy requires the simultaneous use of a trash tax combined with an input subsidy to recycling. We will confine our analysis to a proportional scaling of the tax subsidy scheme $\tau = s\sigma$, rather than changing each instrument separately. We also want to express the marginal welfare effects in relative terms. To this end, we write $M = M_s + J$ with $M_s = X + Q$ and use the shares $s_x \equiv X/M_s$ and $s_m \equiv M_s/M$ as defined in the main text. We also express the welfare change in percent of GDP, $\hat{u} \equiv du/Y$. Using $\tau = s\sigma$, the marginal welfare change in (B.5) is $du = -(\sigma^* - \sigma) sY_M \cdot dQ$. Dividing by Y and expanding gives $\frac{du}{Y} = -(\sigma^* - \sigma) s \frac{MY_M}{Y} \frac{M_s}{M} \frac{Q}{M_s} \cdot \frac{dQ}{Q}$. Using the shares above and noting the cost share of materials in final output, $\alpha = \frac{MY_M}{Y}$, gives marginal welfare changes

$$\hat{u} = -(\sigma^* - \sigma) s\alpha s_m (1 - s_x) \cdot \hat{Q}, \quad \hat{u} = (\sigma^* - \sigma) \left[\frac{1-\tau}{1-\sigma} - s\right] (1-\delta) \alpha s_m s_x \cdot \hat{R}. \tag{B.6}$$

Using the tax subsidy scheme $\tau = s\sigma$ in (B.5.ii) and results in a marginal welfare change $\hat{u} = (\sigma^* - \sigma) \left[\frac{R}{Y} - s\frac{Y_M}{Y} \cdot R\theta f'(R)\right] \cdot \hat{R}$. To sign the square bracket, note first that $R\theta f'(R) = (1-\delta) X$ by the specification in (9). Multiplying the f.o.c. in (10) by R and using this together with $p = Y_M$ gives $\frac{R}{Y} = \frac{1-\tau}{1-\sigma} (1-\delta) Y_M \frac{X}{Y}$. Substituting into the square bracket results in $[\cdot] = \left[\frac{1-\tau}{1-\sigma} - s\right] (1-\delta) \frac{Y_M}{Y} X$. Using $\frac{Y_M}{Y} X = \frac{MY_M}{Y} \frac{M_s}{M} \frac{X}{M_s} = \alpha s_m s_x$ gives the second equation in (B.6). The square bracket is necessarily positive in a neighborhood of the laissez-faire equilibrium with $\tau = \sigma = 0$. Relating tax and subsidy rates by $\tau = s\sigma$, as the optimal policy requires, we have $\frac{1-\tau}{1-\sigma} > 1 > s$, which makes the square bracket unambiguously positive.

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