The Australian Journal of
Agricultural and Resource Economics
Journal of the Australian Agricultural and Resource Economics Society

*Australian Journal of Agricultural and Resource Economics*, 58, pp. 244–262

# Does China's demand boom curb Australian iron ore mining depletion?*

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Australia's resources boom is underpinned by increased demand from industrialising China and a rise in export prices. Current depletion rates will soon exhaust currently known reserves of iron ore and coal. This paper presents a dynamic optimisation model of a growing open economy where a social planner chooses the time path for depletion of a non-renewable resource during a demand-led resources boom. We find that for particular functional forms and in the absence of extraction and social costs, the optimal depletion rate equals the difference between the price elasticity of export demand times the world interest rate and growth in export demand. In contrast to the existing literature, we show that the optimal depletion rate is unaffected by a temporary increase in price, but reduced by growth in demand which is in turn sustained by offshore steel production and urbanisation. The main theoretical implication is that growth in export demand from China reduces the depletion rate. Australian iron ore exports, simulated using this theory, move together with actual volumes over the period 1995–2011, and the error between simulated and actual iron ore exports is lower for the model in this paper than it is for the model without growth in export demand.

**Key words:** export demand, mining boom, non-renewable resources, open economy, optimal depletion.

## 1. Introduction

Steel intensive growth in industrialising Asia, notably China, has driven a strong increase in global demand and particularly large increases in the price of key resources, which are plentiful in Australia, but non-renewable. Based on current extraction rates, Australia's identified iron ore and black coal reserves could last 75 and 110 years, respectively (Geoscience Australia 2013). To put this in perspective, if human habitation of Australia was scaled to fit in a 24 hour day, these resources will run out in less than 5 minutes.

The current mining boom and associated depletion of non-renewable resources raises two questions. First, what is the optimal depletion over time of non-renewable resources for export? Second, how does resource intensive growth in China affect this optimal depletion path? These questions have

* This paper benefited from the helpful suggestions of two anonymous referees and the editor, Allan Rae. The usual disclaimer applies.

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doi: 10.1111/1467-8489.12035

relevance for the debate on social management of non-renewable resources in an open economy and associated role for policy.

An extensive literature on the optimal depletion of non-renewable resources dates back to the seminal work of Stiglitz (1975) and Dasgupta *et al.* (1978), following the oil crisis of the 1970's. Taking the lead of Stiglitz (1975), recent literature analyses optimal depletion for closed economies (Groth and Schou 2007; Perez-Barahona 2011). Useful insights for the management of non-renewable resources are readily obtained by interpreting these models as applying to the world as a whole. An important insight is that the value of resources in the ground must increase over time at the rate of interest (Hotelling 1931). However, the closed economy assumption is a shortcoming when analysing optimal management at the individual country level. Resource rich countries, such as Australia, typically export resources.

Dasgupta *et al.* (1978) show that insights from the Hotelling rule can be incorporated to derive the optimal depletion of non-renewable resources for a small open economy. Despite this, the question of optimal depletion of non-renewable resources for export is little examined in the literature. van der Ploeg (2011) analyses the effect of an increase in the stock of resources. This analysis provides useful insights for a major resource discovery like North Sea oil or resource bonanzas in developing small open economies. More pertinent to Australia's recent resources boom is the effect of increases in global demand.

The analysis in this paper extends the existing theoretical literature in two ways. First, the model in this paper incorporates the effects of resource intensive growth in China by allowing for a shift parameter in export demand. Second, with this extension we analyse the impact of a demand-led resources boom that may be temporary or sustained over time. We present a dynamic optimisation model of a growing economy endowed with a non-renewable resource which can be exported. Within the framework which abstracts from the extraction and social costs of resource depletion, a social planner chooses the rate at which resources are depleted over time so as to maximise social welfare. Dynamic optimisation techniques are widely applied to the socially optimal management of renewable resources, such as fisheries (Grafton *et al.* 2007, 2010). This paper applies analogous techniques to the intertemporal management of non-renewable resources.

This paper provides a novel contribution to theoretical work on the Hotelling rule for an open economy by establishing that growth in export demand reduces the optimal depletion rate. Intuitively, optimal extraction is a dynamic problem, and sustained growth in export demand raises the payoff to leaving the marginal unit in the ground a little longer. According to the existing literature, for Cobb–Douglas production, constant intertemporal elasticity of substitution (CIES) utility and constant elasticity demand, the optimal depletion rate equals the product of the price elasticity of export demand and the world interest rate (Dasgupta *et al.* 1978; van der Ploeg

2011). This is the first paper to show that growth in export demand also affects the optimal depletion rate. van der Ploeg (2010) analyses the open economy Hartwick rule and shows that an oil rich economy selling resources at a price on the world market that differs from the world price charged by its competitors will delay depletion if it anticipates increases in the world price, but overlooks the source of increases in price. Moreover, the differential pricing model of oil exporters is not relevant to Australia. In contrast, the analysis in this paper focuses on the growth in demand from China that has sustained large increases in the price of Australia's resource exports during the contemporary mining boom.

The second contribution of this paper is an empirical application of the model to Australia's contemporary mining boom. The main testable implication of the theoretical analysis is that growth in demand from China leads to a lower extraction rate. The empirical approach applied here is to simulate Australia's iron ore for the period 1995–2011 using both the model in this paper and the model of Dasgupta *et al.* (1978), which is a special case of our model where growth in export demand is zero. Econometric tests compare each simulated series with actual export volumes. Simulated iron ore exports for the model in this paper move together well with actual volumes over the period 1995–2011, and the error between simulated and actual iron ore exports is lower for the model in this paper than it is for the model without growth in export demand.

Two particularly interesting results of the analysis in this paper are, firstly, that the optimal depletion rate of resources for export equals the difference between the price elasticity of export demand for the resource times the world interest rate and growth in export demand. This finding contrasts with optimal depletion in a closed economy and has a wide range of implications for future empirical research and government policy. Secondly, the model simulation indicates that the actual path for Australian iron ore exports for 1995–2011 fits the theoretical prediction that growth in export demand from China reduces the rate of extraction. This result suggests that whether recent growth in demand for Australia's resource exports is likely to be sustained is an important consideration when assessing the optimality of depletion rates.

## 2. Australia's resources boom

Australia's current mining boom is much larger as a share of the economy than previous mining booms in terms of export revenue. The value and, to a lesser extent, volume of resource exports increased sharply between 2005 and 2011 (Christie *et al.* 2011; Gregory 2012). Resource exports now stand at around 60 per cent of Australia's total exports, with iron ore and coal the largest and second largest exports, respectively (ABS 2012).

Garnaut (2012) aptly describes this as a China boom so far. Figure 1 depicts the recent exponential growth in exports to China as a share of

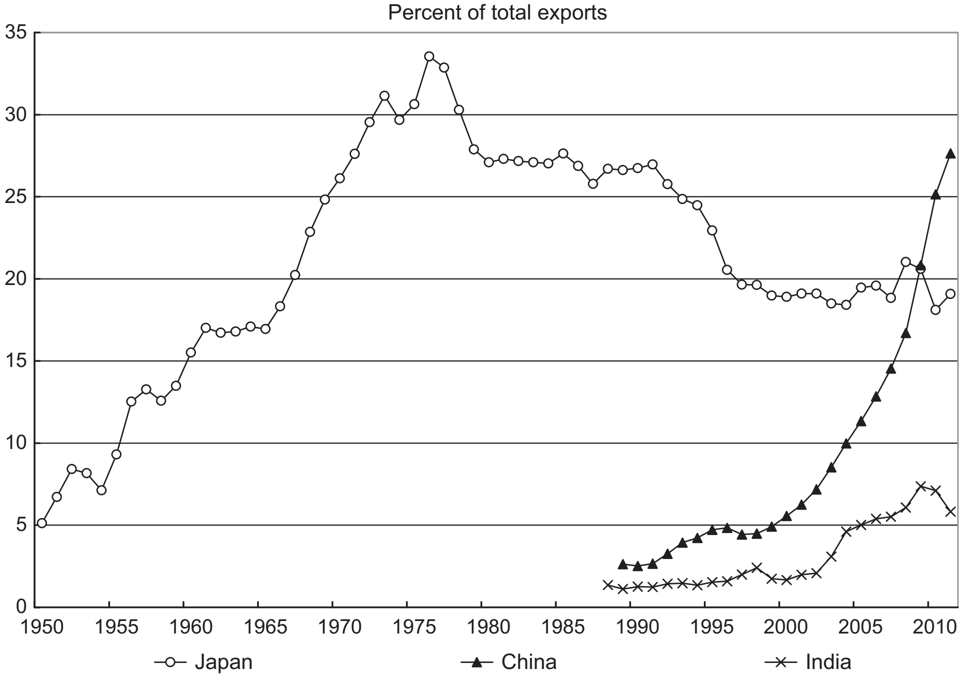


**Figure 1** Australia's exports by destination (as per cent of total exports), 1950–2012. RBA Historical Statistics, Occasional Paper No. 8.

Australia's total exports. The share of total exports to Japan grew over the 1960s and 1970s to reach 34 per cent in 1977, however exports to China have grown at a faster rate over a shorter period. The common factor underpinning the contemporaneous China boom and the previous Japan boom is steel intensive growth.

Sustained rapid steel intensive growth in China has led to a strong increase in global demand for steel making commodities. Australia has been well placed to benefit from the associated sharp rise in key commodity prices, with endowments of iron ore and coking coal that rank in the top five worldwide (Geoscience Australia 2013). Australia overtook Brazil during the decade to become the world's largest producer of iron ore and is second only to China in the production of coking coal (Connolly and Orsmond 2011).

Global steel production has long been the source of demand for Australian iron ore and coking coal. Figure 2 reveals two extended periods of growth in world steel production. The steel intensity of China has risen over the past 30 years, as did the steel intensity of the Japanese economy during the 1960s and 1970s. The two phases differ in one important respect. Referring to Figure 2, China has grown to dominate world steel production in a way that Japan never did. China's steel production now accounts for around half of global steel production. By implication, a slowing in the process of steel

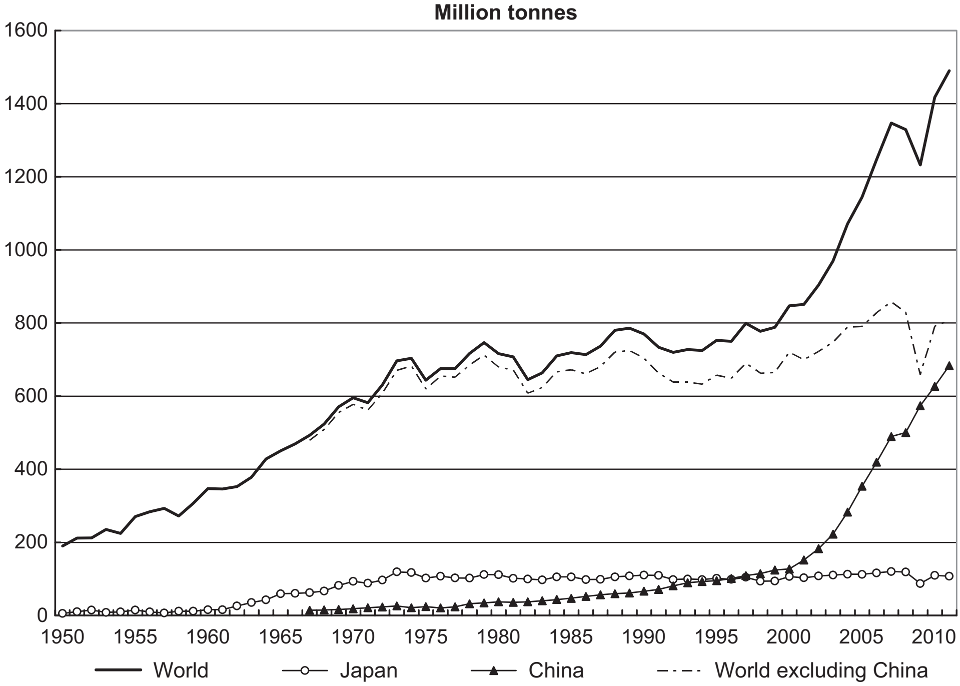


**Figure 2** World Steel Production, 1950–2012. World Steel Association.

intensification in China would likely have a significant impact on demand for Australian exports. To shed light on prospects of a slowdown, we now consider the factors underpinning rising steel intensity.

A sustained period of rapid urbanisation and industrialisation has driven growth in steel production. Figure 3 shows the rapid rate of urbanisation in China over the past 30 years, requiring high levels of investment in infrastructure, buildings and machinery. Japan's urban population grew at a slightly lower rate during their 30 year industrialisation phase. China's urban population is expected to grow well into the middle of this century, but at a slower rate (United Nations 2011).

This raises the question of whether growth in global demand for iron ore and coal will likely be sustained. On the one hand, global development does not end with China, just as it did not end with Japan. Almost 70 per cent of Australia's iron ore exports are currently exported to China. The main export markets for Australia's coking coal, in order of market share, are Japan, India and China (Christie *et al.* 2011). Referring to Figure 1, recent albeit modest growth in exports to India has buoyed Australia's coal exports, sparking interest in growth prospects in India. On the other hand, the United Nations (2011) projections shown in Figure 3 suggest that it is unlikely that rising steel intensity in India will resemble that of China. This accords with recent analysis suggesting that expectations of continued rapid growth in demand for resources are likely to be disappointed (Garnaut 2012). The

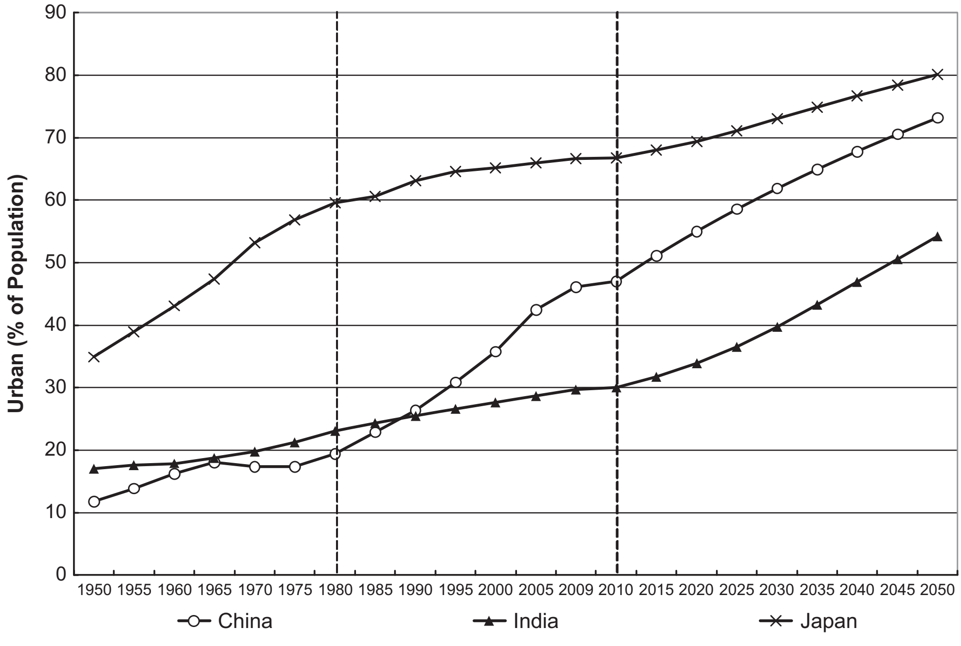


**Figure 3** Past and Projected Urbanisation in Asia, 1950–2050. United Nations (2011).

modelling in this paper therefore allows for growth in demand for resource exports that may either be sustained or slow over time.

## 3. Model

Consider a small resource rich economy, where natural resources may be used in domestic production or sold on the world market. The production of domestic output is given by

$$Y(t) = F(A(t), K(t), R(t)) = A(t)K(t)^{\alpha}R(t)^{\beta}; \quad \alpha + \beta < 1\,, \tag{1}$$

where $K(t)$ and $R(t)$ denote domestic capital stock and resources used in domestic production, respectively, at time $t$, and $A(t) = A_0e^{gt}$, where the initial level of technology and rate of technological progress are $A_0 > 0$ and $g > 0$. Domestic production features decreasing returns to scale to rival factors $K$ and $R$. Taking the lead of Dasgupta *et al.* (1978) and van der Ploeg (2011), the stock of labour is normalised to 1, for the purpose of focusing on the optimal intertemporal use of resources and capital, and we abstract from the extraction and social costs associated with resource depletion. Intuitively, the socially optimal depletion rate would be lower in the presence of these costs, but the relative comparison of optimal depletion rates for the model in this paper and Dasgupta *et al.* (1978) would remain unaffected.

Natural resources may be exported at the price $p$, according to a constant elasticity of demand schedule

$$E(p) = \gamma p^{-\eta}, \tag{2}$$

where $\gamma$ is a shift parameter and $\eta$ denotes the price elasticity of export demand. Consistent with evidence that exchange rate appreciation somewhat insulates commodity exporters from increases in world commodity prices (Clements *et al.* 2008), $p$ may be denominated in domestic currency.[1]

The aggregate stock of natural resources, $S$, depletes over time according to

$$\dot{S}(t) = -E(p(t)) - R(t); \quad S(0) = S_0\,. \tag{3}$$

In this open economy, the three sources of domestic income are output from domestic production, revenue from resource exports and interest earned on net foreign assets. Domestic income is given by

$$Y(t) + E(p(t))p(t) + r(W(t) - K(t)), \tag{4}$$

where $W$ denotes the economy's stock of total wealth or assets, comprising $K$ domestic capital and $(W{-}K)$ foreign capital earning a rate of return, $r$. The stock of domestic wealth accumulates from domestic income that is not consumed. Thus, the aggregate stock of domestic wealth accumulates according to

$$\dot{W} = r(W(t) - K(t)) + Y(t) + E(p(t))p(t) - C(t); \quad W(0) = W_0\,, \tag{5}$$

where $E(p(t))p(t)$ and $C(t)$ denote the value of resource exports and consumption, respectively, at time $t$.

The model structure up to this point with respect to state equations and specification of the dynamic optimisation problem corresponds to Dasgupta *et al.* (1978) and van der Ploeg (2011). Importantly, there is no state equation governing capital accumulation. It is implicit in state Equation (5) that capital is perfectly mobile and malleable in the sense that domestic capital can be instantly and costlessly transformed into foreign capital and vice versa. The small open economy takes the world interest rate as given and employs capital up to the point where the marginal product of capital equals $r$. In the absence of adjustment costs, this optimality condition holds continuously.

The social planner's dynamic optimisation problem in continuous time is defined as

[1] Expressing the demand for exports as dependent on $p$ implicitly assumes the country to be a price taker, however, because demand is isoelastic, we may equivalently express $p$ as a function of $E$. Thus, the analysis herein applies to either a price maker or price taker on world markets. This flexibility is useful, as Australia is, on the one hand, currently responding to a boom in world commodity prices and, on the other hand, a dominant exporter of iron ore and possibly coal, in the sense that large export volumes place downward pressure on world prices (Clements and Fry 2008).

$$\max_{\{C(t),R(t),p(t),K(t)\}} \int_0^\infty \frac{C(t)^{1-\theta}}{1-\theta} e^{-\rho t} \mathrm{d}t \text{ subject to (3) and (5)}, \tag{6}$$

where $\rho$ is a strictly positive discount rate and $\sigma = 1/\theta$ is the intertemporal elasticity of substitution. Referring to the Appendix, expressions for efficient intertemporal consumption and resource depletion can be derived using the maximum principle.

Optimal intertemporal consumption is given by the familiar Keynes–Ramsey rule

$$\frac{\dot{C}}{C} = \sigma(r - \rho), \tag{7}$$

whereby consumption rises over time if $r > \rho$.

The expression for static efficiency is as follows:

$$F_R = \left(E_p p + E\right)/E_p = (1 - 1/\eta)/p, \tag{8}$$

where $\eta = -(pE_p)/E$. The intuition for this condition is straightforward. The return to holding the unextracted resource is the incremental earnings from using an extra unit, which is the marginal product if the resource is used domestically and the marginal revenue if the resource is exported. Efficient management of the resource equates the returns across the two activities.

The expression for dynamic efficiency is as follows:

$$r = F_K = \frac{\dot{F}_R}{F_R} = \frac{\mathrm{d}}{\mathrm{d}t} \frac{\left(p + E/E_p\right)}{\left(p + E/E_p\right)}, \tag{9}$$

whereby the rates of return on holding the three assets, foreign capital, domestic capital and resources, are equated. The rate of return to resources is the rate at which the effective price of the unextracted resource grows. Intuitively, a given unextracted stock of the resource yields a return to its owner by appreciating in value.

From (8) and (9), we obtain the Hotelling Rule, $\dot{p}/p = r$. What rate of depletion over time corresponds to this familiar arbitrage condition? In an open economy, the rate at which non-renewable resources appreciate in value is influenced by demand for resource exports. From (2), the price of resource exports could appreciate because the export demand schedule shifts outward. Observations from Australia's recent resources boom suggest that this is an important consideration. To allow for shifts in export demand over time, let us assume

$$\dot{\gamma} = \phi\gamma. \tag{10}$$

For Cobb–Douglas production, CIES utility and constant elasticity demand, we may obtain an explicit solution for the optimal rate at which resources are depleted over time. Equations (2), (9) and (10) imply that the optimal intertemporal extraction of resources for export is as follows:

$$\frac{\dot{E}}{E} = -[\eta r - \phi], \tag{11}$$

which remains feasible for sufficiently small growth in export demand at any given price, $\phi < r\eta$. The extraction policy is necessarily feasible if export demand is either constant or shifting inward over time, $\phi \leq 0$. Intuitively, the social planner is indifferent between keeping the resource in the ground, in which case the return is the capital gain on the reserves, and selling it at the market rate of return. The capital gain is the rate at which the resource appreciates in value, which is affected by the price elasticity and growth in export demand. In the absence of extraction and social costs associated with resource depletion, optimal depletion of non-renewable resources for export is given by Equation (11), as described in the following remark.

*Remark 1*. The optimal rate of depletion of resources extracted for export equals the difference between the price elasticity of export demand for the resource times the world interest rate and growth in export demand for the resource.

From Equations (1) and (9), optimal intertemporal extraction of resources for domestic production is as follows:

$$\frac{\dot{R}}{R} = \frac{-[(1-\alpha)r - g]}{(1-\alpha-\beta)}, \tag{12}$$

which remains feasible for a sufficiently small rate of technological progress, $g < (1-\alpha)r$. Feasibility means that the optimal depletion paths are downward sloping over time, so that the stocks of $E$ and $R$ remain non-negative, necessarily satisfying the constraint on resource depletion, (3).[2]

From (1) and (12), the optimal use of domestic capital over time is as follows:

$$\frac{\dot{K}}{K} = \frac{g - \beta r}{(1-\alpha-\beta)}, \tag{13}$$

where the rate of technological progress must be sufficiently high, $g > \beta r$, for physical capital to accumulate over time. Otherwise, the optimal extraction of resources over time involves the gradual phasing out of domestic industry. Intuitively, the marginal product of capital, $F_K$, is decreasing in $K/R$ and increasing in the stock of technology, $A$. The stock of $R$ declines over time and dynamic efficiency requires that $F_K$ remain constant for a given $r$. In the absence of technological progress, $K$ must decumulate to maintain a constant

[2] Having said this, constraint (3) in itself constrains neither $E$ nor $R$ to be non-negative. For instance, the case where the depletion rate for $R$ rises over time and the economy becomes a resource importer cannot be strictly ruled out in terms of constraint (3). For the purposes of this paper, $E \geq 0$ and $R \geq 0$ are assumed.

$F_K$. However, sufficient technological progress may maintain a constant $F_K$ even when $K$ accumulates.

Equations (11), (12) and (13) differ from Equation (7) in one important respect. In contrast to the optimal intertemporal rate of consumption, the optimal depletion of resources for export and domestic production, and the optimal rate of capital accumulation are independent of the social discount rate and the parameters of the social welfare function. The intuition for this result is similar to that from static trade theory where production in an open economy is determined by world prices and is independent of consumer preferences. The result holds for Cobb–Douglas production technology, CIES utility and constant elasticity demand. As in closed economy models, these functional assumptions allow explicit solutions to be reached.

This finding has practical importance. Whereas the social discount rate and parameters of the social welfare function are difficult to agree on, interest rates, price elasticity and growth in export demand, productivity growth and domestic production shares are observable or comparatively straightforward to estimate. By implication, the optimal intertemporal rate of depletion is quantifiable in an open economy setting. Also of importance are the effects of a resources boom on the socially optimal rate of depletion, which we now explore.

## 4. Resources boom

Integrating the differential Equation (3), after substituting for $E(t)$ and $R(t)$ from (11) and (12), the optimal $E_0$ and $R_0$ are related to the optimal $S_0$ as follows:

$$S_0 = \frac{E_0}{[\eta r - \phi]} + \frac{R_0(1-\alpha-\beta)}{[(1-\alpha)r - g]}, \tag{14}$$

where $S_0$, $\eta$, $\phi$, $r$, $\alpha$, $\beta$ and $g$ are exogenous parameters. Conditions relating the optimal $K_0$ and $R_0$, and optimal $K_0$, $R_0$ and $p_0$ are derived from Equations (8) and (9), respectively. Together these conditions imply that the optimal $R_0$ is related to $p_0$ as follows:

$$(R_0)^{-(1-\alpha-\beta)} = A_0^{-1}\left(\frac{r}{\alpha}\right)^{\alpha}\left(\frac{p_0(1-1/\eta)}{\beta}\right)^{1-\alpha}, \tag{15}$$

where $A_0$, $\eta$, $r$, $\alpha$, $\beta$ are exogenous parameters.

### 4.1 Qualitative analysis

*Case: Resource discovery (increase $S_0$).* It follows from (14) that a higher $S_0$ lifts both $E_0$ and $R_0$. We would observe a parallel upward shift in the declining paths of $E(t)$ and $R(t)$. From (11) and (12), resource discovery does not affect the respective rates of extraction. It follows from (15) that an upward shift in the declining path of $R(t)$ depresses the price trajectory. The intuition for this result lies in condition (8). An increase in $R_0$ reduces the marginal product of the resource in domestic use, $F_R(0)$. A fall in the resource export price, $p_0$, achieves static efficiency. Thus, a resources boom emanating from discovery raises the optimal levels of $E(t)$ and $R(t)$ and lowers the price of exported resources. These characteristics of a supply-led resources boom are at odds with observations from Australia's recent resources boom. Let us now consider a demand-led resources boom that may be temporary or sustained over time.

*Case: Increase in export demand (increase $\gamma_0$; $\phi = 0$).* By (2), an increase in $\gamma_0$ is consistent with an instantaneous increase in both $p_0$ and $E_0$. From (15), a contemporaneous rise in $p_0$ will reduce $R_0$. The intuition lies in the static efficiency condition (8). A rise in $p_0$ raises the marginal export revenue, inducing a fall in $R_0$, which raises the marginal product of resources in domestic use until it equals the marginal revenue from resource exports. For a given $r$, $K_0$ will fall. Intuitively, resources complement physical capital in domestic production. For a given $S_0$, a rise in $p_0$ reduces $R_0$ and raises $E_0$. Referring to Figure 4, the declining paths of $E(t)$ and $R(t)$ shift upward and downward, respectively. From (11) and (12), the respective rates of extraction are unaffected. This discussion may be summarised with the following remark.

*Remark 2.* An increase in export demand raises the price and shifts the optimal declining paths of resources depleted for export and domestic use, upward and downward, respectively. The intertemporal rate of resource depletion is unaffected.

*Case: Growth in export demand ($\phi > 0$).* How might a gradual expansion in demand for resource exports affect the extraction of resources? From (14), compared with the case where $\phi = 0$, allowing for $\phi > 0$ reduces the optimal $E_0$, for a given $S_0$. By (11), the optimal extraction rate of resources decreases. Referring to Figure 5, the declining path of $E(t)$ flattens, as it shifts outward. The intuition for this result lies in dynamic efficiency. An outward shifting demand for resource exports over time raises the growth rate in the effective price of unextracted resources. This confers the incentive to defer extraction. Extracting less today and more over time maximises the intertemporal wealth from export revenue. Similarly, a social planner facing a gradual contraction in demand has an incentive to bring forward extraction. The following remark summarises this discussion.

*Remark 3.* Growing (contracting) demand for resource exports flattens (steepens) the optimal declining path of resources depleted for export, whereby the instantaneous level falls (rises) and the depletion rate decreases (increases).

If the current boom has elements of increases in reserves, transitory increases in prices and increases in global demand for steel that can be

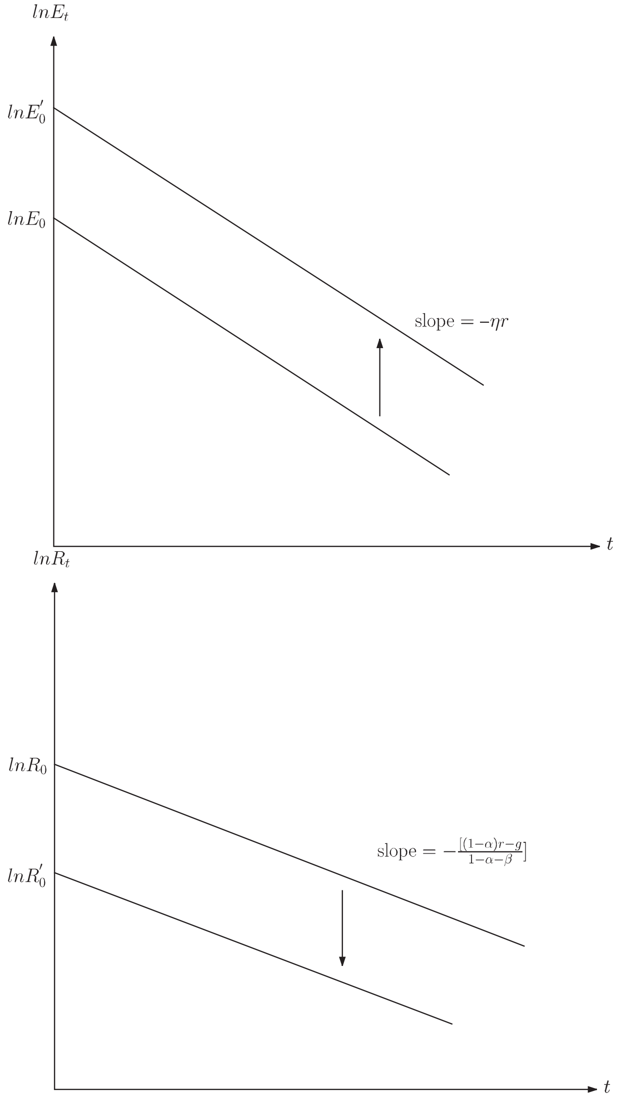


**Figure 4** Effect of price increase on optimal depletion paths of $E_t$ and $R_t$.

sustained over time, then the optimal time path of $E(t)$ will both shift up and flatten. For a given world interest rate, a social planner would deplete resources for export at a slower rate, because keeping the resource in the ground yields a higher capital gain. Alternatively, if growth in demand for exports is set to fall, then the optimal depletion rate of resources for export rises.

### *4.2. Empirical illustration*

An illustrative example first calibrates the model to data from Australia's iron ore sector and then compares iron ore exports predicted by both the model in this paper and the model of Dasgupta *et al.* (1978) with actual iron ore export

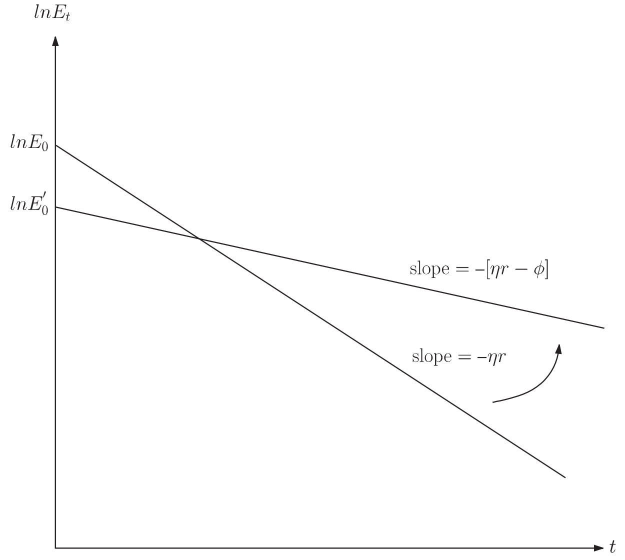


**Figure 5** Effect of growth in export demand on optimal depletion paths of $E_t$.

volumes for the period 1995–2011. This period covers the mining slowdown of the 1990s and the onset of an export demand-led mining boom around 2005.

Annual data on iron ore reserves ($S$), iron ore used in domestic production ($R$) and iron ore export prices, fob, ($p$) is used (Bureau of Resources and Energy Economics 2012; Geoscience 2013). Consistent with Dasgupta *et al.* (1978), $A_0$ is normalised to 1. The world interest rate ($r$) is proxied by the 10-year United States Treasury-bond rate deflated by the Consumer Price Index (OECD 2012). The parameter $\phi$ measures shifts in export demand that can be sustained over time. Cai (2010) and Garnaut (2012) find changes in the number of workers per total population play a pivotal role in whether China's increasing urbanisation and industrialisation will continue to sustain growth in demand for Australia's resources. Whilst growth in the working age population ratio has sustained growth in export demand over the last decade, the resource intensity of production in China is set to fall with an impending decline in the working age population ratio. This illustrative example measures $\phi$ by annual growth in the ratio of China's working age population to total population (United Nations 2011).

The values chosen for other key parameters are discussed next and are given in Table 1. Whilst the majority of Australian iron ore is exported, domestic iron and steel manufacturing contributes around 0.01 per cent to Australian Gross Domestic Product, GDP (IBIS World 2012). There is no estimate of the price elasticity of demand for iron ore exports in the literature. However, it is well known that demand for steel is price inelastic. Several studies estimate the price elasticity of demand for steel to be −0.3 (Mathieson and Maestad 2004). This value is consistent with estimates of price elasticity of demand for coking coal exports (Ball and Loncar 1991). The results

**Table 1** Parameter assumptions

| Parameter | Description | Parameter value |
|---|---|---|
| $\alpha$ | Domestic capital income share of GDP | 0.3 |
| $\beta$ | Domestic iron and steel income share of GDP | 0.01 |
| $g$ | Rate of technological progress | 0.01 |
| $\eta$ | Price elasticity of export demand for iron ore | −0.3 |

reported herein are robust, since higher or lower values for parameters other than $\phi$ affect simulated exports for the model in this paper and Dasgupta *et al*. (1978) equally.

Using parameterized Equations (14) and (15), the approach taken is to simulate the effect of a change in actual $p_0$ on optimal iron ore extracted for domestic use, $R_o$, and then, given actual initial reserves, $S_o$, simulate the optimal iron ore extracted for export, $E_o$. Figure 5 depicts actual export volumes of iron ore and simulated export volumes of iron ore for the model in this paper and that of Dasgupta *et al*. (1978), which is a special case of the model where $\phi = 0$. Actual iron ore exports have risen over the last decade due to increases in reserves and export prices. This is consistent with the qualitative analysis predicting that the optimal time path of $E(t)$ shifts up.

Referring to Figure 5, we make the following observations. First, simulated iron ore exports for the model in this paper more closely resemble actual export volumes than do simulated exports for Dasgupta *et al*. (1978). Second, the export profile for Dasgupta *et al*. (1978) is relatively flat. Their model, where $\phi = 0$, predicts that more iron ore will be extracted and exported in the 1990s due to higher returns on capital. Over the last decade, the effect of lower returns on capital has been offset by higher export prices and reserves of iron ore. Third, simulated exports for the model in this paper are below actual exports in the early 2000s and above actual exports from the onset of the mining boom in 2005. Growth in China's working-age population ratio peaked around 2000. The theoretical extraction rate of iron ore for export would slow in the early 2000s, because unextracted iron ore yields a higher capital gain. From 2005, the model predicts that more iron ore be extracted for export because the growth in China's working-age ratio that underpins steel demand is slowing, thereby diminishing the capital gain from iron ore left in the ground.

The main implication of the model in this paper is that growth in export demand from China reduces the rate of extraction. The actual path for Australian iron ore exports seems to fit the theory quite well for the period 1995–2011, although the metrics used to determine the co-movement and distance between simulated and actual export volumes have not yet been specified. We herein provide econometric tests of whether our model both tracks actual iron ore exports more closely than does the special case $\phi = 0$ over the period 1995–2011 and reduces the error between simulated and actual iron ore exports.

**Table 2** Co-integration of actual and simulated iron ore extraction for export

| Simulated series | Hypothesised co-integrating equations | Eigenvalue | Trace statistic | $P$-value |
|---|---|---|---|---|
| Model | None† | 0.93 | 44.77 | 0.0001 |
| Model with $\phi$ =0 | None | 0.78 | 26.01 | 0.0581 |

Note: †Denotes rejection of null hypothesis at 1% level (trace statistic critical value of 31.15).

To test how well the actual and simulated series move together over time, we may look for evidence of co-integration or a significant correlation coefficient for first differences. Augmented Dickey–Fuller tests do not reject the null hypothesis that each series in Figure 6 is integrated of order one.[3] Referring to Table 2, for the model with (without) growth in demand for exports from China, we can (cannot) reject the null hypothesis of no co-integration between simulated and actual iron ore extraction. The correlation coefficient for first differenced actual and simulated iron ore extraction for the model with (without) growth in demand from China is 0.47 (0.22) and significant (insignificant) at the 5 per cent level with a $P$-value of 0.0372 (0.2172).

The question arises as to what extent modelling the impact of growth in demand from China on extraction reduces the difference between simulated and actual iron ore export volumes. We therefore report metrics to compare model simulation errors based on the difference between actual and simulated exports. The Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE), for the model with (without) growth in demand from China is 0.45 (0.67) and 0.17 (0.29), respectively. The larger the error, the less accurate is the simulation. The RMSE and MAPE indicate that the error between simulated and actual iron ore exports is larger for the model with $\phi = 0$ than it is for the model in this paper by 48 and 70 per cent.

## 5. Concluding remarks

Rapid urbanisation and industrialisation in China has driven recent increases in global demand for steel-making commodities. In response to the associated rise in export prices, Australia is depleting reserves of iron ore and coking coal.

This paper analyses the depletion over time of non-renewable resources for export in a growing open economy and how increases in export demand that may be either temporary or sustained over time affect the optimal depletion path. The model presented in this paper shows that the rate of depletion equals the difference between the price elasticity of export demand times the world interest rate and growth in export demand. This conclusion is tempered by the qualification that the assumptions of Cobb–Douglas production, CIES utility and constant elasticity demand provide analytical tractability. The analysis finds that

[3] For actual, model and model special case ($\phi = 0$) simulated iron ore exports, the $t$-statistics ($P$-values) are 0.901 (0.992), −1.612 (0.7305) and −3.376 (0.098).

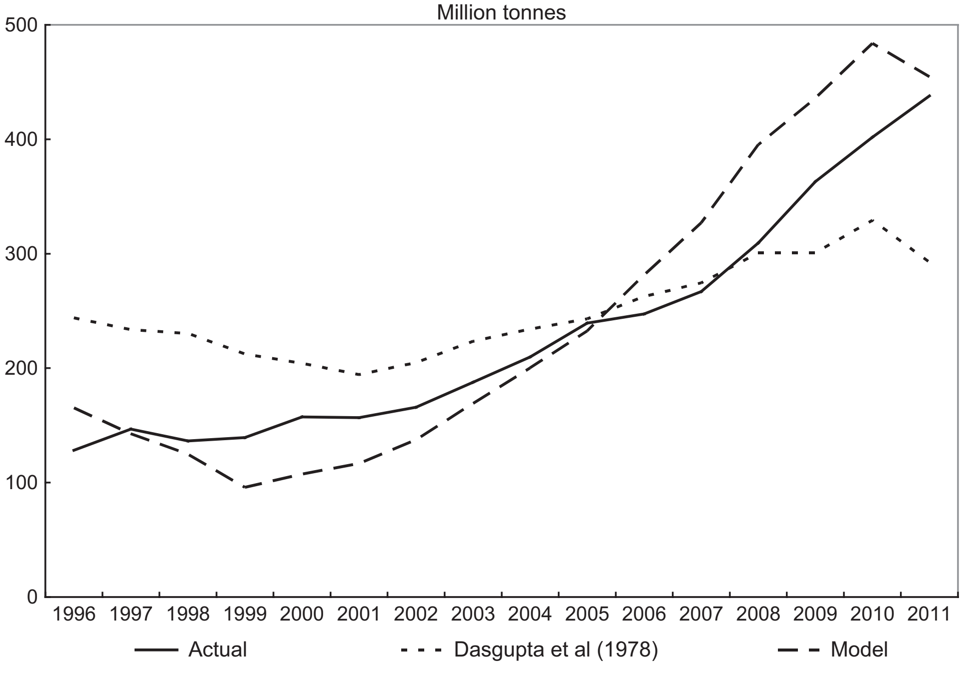


**Figure 6** Simulated and actual iron ore export volumes, Australia, 1996–2011.

1. A contemporaneous shift in export demand and price increase does not affect the rate at which resources are depleted over time.
2. Growth in export demand over time reduces the rate at which resources are depleted over time.
3. For the period 1995–2011, Australian iron ore exports simulated using the model in this paper move together well with actual volumes, compared with iron ore exports simulated using Dasgupta *et al*. (1978), which is a special case of the model where export demand does not grow over time.

The contribution of this paper is twofold. First, the theoretical analysis yields the main testable implication that growth in export demand reduces the rate at which resources are depleted for export. This previously unidentified result (cf. Dasgupta *et al*. 1978; van der Ploeg 2011) opens the way for future empirical and policy analysis of resource depletion during the contemporary mining boom. Second, simulated iron ore exports based on the theory in this paper that growth in export demand from China reduces the extraction rate move together well with Australia's actual iron ore export volumes over the period 1995–2011. Moreover, modelling the effect of growth in export demand on the extraction rate reduces the measurement error between simulated and actual iron ore exports.

Some interesting implications for policy makers arise. Firstly, the optimal rate of resource depletion is quantifiable for an open economy, as illustrated using data from Australia's iron ore sector. This contrasts optimal depletion under the closed economy assumption commonly featured in existing modelling. Secondly, observations from world steel production, China's working age population ratio and urbanisation rates suggest recent increases in export demand may not be sustained over time.

In analysing the effect of increases in export demand on the depletion of non-renewable resources, we do not deny the role of other factors, namely extraction and social costs, in determining the socially optimal depletion rate. Rather, the finding that growing demand for exports reduces the resource depletion rate is a previously unidentified effect that is worth considering in light of Australia's recent mining boom. Nesting pollution externalities and resource extraction costs in the model presented in this paper is an interesting direction for further research.

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## Appendix

### Optimal control problem

The current valued Hamiltonian is

$$\hat{H} = \frac{C^{1-\theta}}{1-\theta} + \lambda[r(W-K) + Y + E(p)p - C] - \mu[E(p) + R], \tag{16}$$

where $Y = F(A,K,R)$ as given by (1).

According to the maximum principle, the optimal solution for this dynamic optimisation problem must satisfy the following necessary conditions

1. The control variables are chosen to maximise $\hat{H}$ at each point in time. That is,

$$\begin{aligned} \hat{H}_C = 0 \Rightarrow &\quad C^{-\theta} = \lambda \\ \hat{H}_R = 0 \Rightarrow &\quad \lambda F_R = \mu \\ \hat{H}_p = 0 \Rightarrow &\quad \lambda\left[E_p p + E\right] = \mu E_p \\ \hat{H}_K = 0 \Rightarrow &\quad F_K = r\,. \end{aligned} \tag{17}$$

2. The state and co-state variables satisfy the differential equations

$$\begin{aligned} &\hat{H}_\lambda = \dot{W} \Rightarrow \dot{W} = r(W-K) + Y + E(p)p - C \\ &\hat{H}_\mu = \dot{S} \Rightarrow \dot{S} = -E - R \\ &\dot{\lambda} - \rho\lambda = -\hat{H}_W \Rightarrow \dot{\lambda} = (\rho - r)\lambda \\ &\dot{\mu} - \rho\mu = -\hat{H}_S \Rightarrow \dot{\mu} = \rho\mu\,. \end{aligned} \tag{18}$$

Referring to Leonard and Long (1996) (Theorem 9.3.1), the necessary conditions provided by the maximum principle are also sufficient for an optimal solution under the catching up criterion, whereby $\hat{H}$ is concave and the following transversality conditions are satisfied (Corollary 9.3.2)

$$\begin{aligned} &\lim_{t\to\infty} e^{-\rho t}\lambda(t)W(t) = 0; \lim_{t\to\infty} e^{-\rho t}\lambda(t) \geq 0; 0 \leq W(t) < M \text{ for some } M \\ &\lim_{t\to\infty} e^{-\rho t}\mu(t)S(t) = 0; \lim_{t\to\infty} e^{-\rho t}\mu(t) \geq 0; 0 \leq \mathrm{S}(t) < M \text{ for some } M. \end{aligned} \tag{19}$$

We show that the Hamiltonian is concave in the state variables $(S, W)$ after the controls $C$, $R$, $p$ and $K$ have been substituted by their maximising values. From (17), we get

$$\begin{aligned} C &= \lambda^{-1/\theta} \\ R &= \left(\frac{\lambda}{\mu}\beta\right)^{\frac{1-\alpha}{1-\alpha-\beta}} \left(\frac{\alpha}{r}\right)^{\frac{\alpha}{1-\alpha-\beta}} (A_0 e^{gt})^{\frac{1}{1-\alpha-\beta}} \\ p &= \frac{\lambda}{\mu}\left(1 - \frac{1}{\eta}\right) \\ K &= \left(\frac{\lambda}{\mu}\beta\right)^{\frac{\beta}{1-\alpha-\beta}} \left(\frac{\alpha}{r}\right)^{\frac{1-\beta}{1-\alpha-\beta}} (A_0 e^{gt})^{\frac{1}{1-\alpha-\beta}}. \end{aligned}$$

Inserting these values into (16) gives the maximised Hamiltonian

$$\begin{aligned} \hat{H}^* = \lambda r W + \frac{\theta}{1-\theta}\lambda^{1-\theta} + \lambda\gamma\left(\frac{\lambda}{\mu}\left(1 - \frac{1}{\eta}\right)\right)^{-\eta}\left(\frac{\lambda}{\mu}\left(1 - \frac{1}{\eta}\right) - \frac{\mu}{\lambda}\right) \\ + \left(\frac{\lambda}{\mu}\beta\right)^{\frac{\beta}{1-\alpha-\beta}} \left(\frac{\alpha}{r}\right)^{\frac{\alpha}{1-\alpha-\beta}} (A_0 e^{gt})^{\frac{1}{1-\alpha-\beta}} (1 - \alpha - \beta). \end{aligned}$$

It follows that $\hat{H}^*$ is concave in $W$, since $\hat{H}^*_W = \lambda r > 0, \hat{H}^*_{WW} = 0$. Referring to (16), the current valued Hamiltonian is not a function of the other state variable $S$. Allowing for the effects of global warming, whereby $S$ contributes to total factor productivity, $A$, and hence $Y$, cf. Groth and Schou (2007), is an interesting and feasible direction for future research.