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School of Business and Economics

Master Spatial, Transport and Environmental Economics

"Exploring the Impact of Population Changes on Oil Extraction: A Two-Region, Two-Period Model Analysis"

Master thesis

by

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Abstract

The paper investigates the effect of population changes on oil extraction using a two-period, two-region model. The model considers perfectly competitive and clearing markets with rational actors and the oil price determined by the Hotelling rule. Three scenarios are analysed: a partial equilibrium with fixed interest rate and capital stock, and a general equilibrium with and without capital. Results show that in the case of fixed oil reserves, current oil extraction decreases, and this effect is amplified in the general equilibrium without capital due to the dominant relative demand effect. Introducing capital weakens this effect due to the presence of the capital market amplifying the relative supply effect. The model is extended to include the possibility of exploring additional oil reserves, and in all scenarios, current oil extraction decreases but less than in the case with fixed reserves due to exploration costs amplifying the relative supply effect. Cumulative extraction increases as current oil prices increase, resulting in a proportional increase in cumulative carbon emissions.

1. Introduction

According to the International Energy Agency (IEA) the production and consumption of energy is responsible for more than two-thirds of all greenhouse gas emissions worldwide (IEA, 2021). These emissions come from the burning of fossil fuels for electricity and heat, as well as from the use of fossil fuels in transportation. More than one-third of these emissions are generated by the combustion of oil. Meanwhile, the United Nations estimates suggest that the world's population could grow to around 8.5 billion in 2030, 9.7 billion in 2050 and 10.4 billion in 2100 (United Nations, 2022). Population growth leads to increasing demand for energy and consumption, for which fossil fuels are mostly used. There is an ongoing debate on the importance of population size as a driving force of emissions.

A review of studies by O'Neill et al. (2012) found that population size can influence carbon emissions from energy, but the relationship between the two is not always clear. Some studies suggest a proportional relationship, while others suggest a less than proportional relationship. O'Neill et al. (2012) suggest that policies aimed at reducing population growth could be an effective tool in mitigating global warming. However, Bretschger (2020) found contrasting results while Kruse-Andersen (2019) considers the positive effect that population growth could have on climate change, due to increased labour for the resource and development sector. Satterthwaite (2009) argues that it is not population growth, but the growth in consumers and their level of consumption that drives emissions and contributes to climate change.

The notion that population growth has negative external effects has been around for at least a few hundred years. In the 18th century, Thomas Malthus (1798) developed the theory of the Malthusian trap, in which he suggests that population growth will eventually outstrip the ability of the Earth to support it, leading to widespread famine and other catastrophes. Similar predictions were made by Ehrlich (1968) when he published the book "The Population Bomb" more than fifty years ago. Ehrlich warned of the dangers of overpopulation and argued that immediate action was needed to address the problem. It sparked widespread debate and controversy at the time, with some critics arguing that Ehrlich's predictions were exaggerated and that his proposed solutions were unethical. Despite the controversy, the book remained an important work in the field of population studies and continues to be discussed in the context of the ongoing global debate about population growth and its effects on the environment. Since the publication of the book, there have been a great number of studies published focusing on the relationship between population growth and carbon emissions.

Several studies, reviewed by O’Neill et al. (2012), found a positive relationship between population size and emissions. Since the production of energy is responsible for most of the emissions worldwide, these studies focused on the emissions coming from the combustion of fossil fuels in their research. By using the STIRPAT (STochastic Impacts by Regression on Population, Affluence, and Technology) method, the reviewed papers demonstrated that population size influences carbon emissions from energy. Some variation is reported, with some studies indicating a proportional relationship while others find a less than proportional one. Based on these results, O’Neill et al. (2012) suggest that imposing policies that reduce population growth could be an effective tool in mitigating global warming. More recently, Khan et al. (2020) examined the impact of natural resources, energy consumption, and population growth on the ecological footprint and CO2 emissions applying the general linear method (GLM), general method of moment (GMM) and Robust Least Squares approaches. The results indicated the existence of unidirectional causality that runs from population growth to energy consumption and to carbon emissions. Despite the similarity with the results from O’Neill et al. (2012), Khan et al. (2020) derive a different policy implication, suggesting that the growing population should be stimulated to adopt a sustainable lifestyle which would reduce emissions.

Bretschger (2020) found results which contrast the findings of the papers discussed above. He showed that climate change is independent of population growth in a steady state by using a multi-sector growth model, and that there is no causal relationship between climate and population during the transition to steady state. He argues that population policy is not warranted and may be counterproductive because of the importance of labour for the research sector. This argument follows from his earlier research on the possibility of obtaining positive innovation and consumption under a growing population and with bounded resource stocks (Bretschger 2013), where he assumed that policymakers would be able to influence the rate of technical change. Acemoglu et al. (2012) emphasised that environmental policy cannot only influence the rate, but also the direction of technical change. In their paper, production involves the use of both polluting and non-polluting inputs. Scientists can choose to focus on improving either polluting or non-polluting technologies, based on which direction is more profitable. Environmental policy can impact the direction of research by altering the demand for different types of inputs. For example, if there is a tax on pollution emissions, the demand for polluting inputs will decrease, making research on polluting technologies less profitable. Kruse-Andersen (2019) developed a model that considers this idea of directed technical change and combines it with population growth for his research on how to achieve a specific climate goal.

However, he concluded that population growth is a strain on the environment, even when all research is focused on non-polluting technologies. Therefore, he argues that it is necessary to implement population control policies in addition to research subsidies for non-polluting technologies to achieve environmental sustainability. Results from the model used in my paper suggest that an increase in population size will lead to an increase in oil extraction and hence emissions in the long term. Therefore, my suggestion is in line with recommendations from O'Neill et al. (2012) and Kruse-Andersen (2019), that implementing population control policies can be an effective tool to mitigate climate change.

The notion that population growth negatively affects climate change is nuanced by Satterthwaite (2009). He argues that there is a significant difference in the consumption patterns among individuals around the world: 20 percent of the global population is responsible for more than 80 percent of all human-caused emissions. Moreover, most nations with the highest population growth have the lowest emission levels per person. Therefore, he suggests that climate mitigation policies should allow low-income, low-consumption households to increase their consumption while staying below a “fair share” level of emissions. My research does not allow for differences in consumption patterns between various groups within the world population. Further research on the effect of population growth on climate change could allow for a division of different groups of population, where each group has its own consumption pattern. This would make the results more applicable to the real world.

This research aims to examine the effects of an increase in population on current oil extraction using a two-period-two-regions general equilibrium model, based on the model used by Van der Meijden et al. (2015). The model takes the interest rate and the prices of oil in both the present and the future into account. The Hotelling rule, which determines the optimal oil extraction based on changes in the interest rate, is used to guide my analysis. The prices of oil and the interest rate are determined based on the conditions that enable the clearing of financial assets and oil markets. I assume that all markets operate under perfect competition and that firms only in the importing region produce final goods which can be used for consumption and investment. Oil is needed as an input to produce these final goods. To examine the impact of changes in future population size on current oil extraction, I first develop a basic model with a given stock of oil. Then I extend this model by adding the possibility of exploration of new oil reserves to examine cumulative oil extraction. The latter is important, because the amount of oil that remains unexploited in the earth's crust can have an impact on the ultimate level of global warming.

In a general equilibrium, the interest rate plays a role in both production and consumption in the economy. The demand for oil is influenced by oil prices, which are related over time through the Hotelling rule. These oil prices consider the opportunity cost of conserving oil, which is represented by the interest rate. The level of investment is also influenced by the interest rate, as it determines the marginal cost of renting a unit of capital. Furthermore, the interest rate determines the relative price of current and future consumption on the demand side.

This paper adds to the literature by providing insights in the interaction between the oil market and the goods market when the population size increases over time. The paper is structured as follows: section 3 sets up the two-period-two-region model without exploration costs and with a fixed oil reserve, introducing the firms, households, and equilibrium conditions. Section 4 discusses how the results under different equilibria are derived when there is a fixed oil reserve. Section 5 discusses how the results under different equilibria are derived when there is partial exhaustion and exploration costs. Section 6 concludes.

3. The model

I use a two-period-two-regions general equilibrium model, based on the model used by Van der Meijden et al. (2015). One region imports oil while the other region, denoted by an asterisk, exports oil. Both regions demand final goods, which are only produced by the oil-importing region, using capital, oil, labour, and land, where oil is modelled as a non-renewable resource with a finite stock, and labour and land are fixed factors. Population growth is captured by changes in labour supply, based on the assumption that if a population size increases, the workforce increases proportionally. In this paper, labour is treated as a non-fixed factor, which allows examining the effect that a change in population growth has on oil extraction. Assets owned by the oil-exporting region consist of capital, bonds and given oil resources. These oil resources will be completely exhausted once period two has ended and oil-extractors face no costs when extracting the oil. Assets owned by the oil-importing region solely consist of capital and bonds. The markets are perfectly competitive and clear in both periods. All actors in the markets have rational foresight. The oil price follows the price path determined by the Hotelling rule. This paper examines the effect of an increasing population on the intertemporal pattern of oil extraction within three scenarios: a general equilibrium with and without capital as a factor of production and a partial equilibrium model, in which the interest rate and capital stock are fixed. In each scenario, the effects of an increase in population in the importing region, exporting region or in both regions are examined separately.

3.1 Firms

The final goods demanded by both regions are produced by firms in the oil-importing region. The income identity of firms in the oil-importing region is, with constant returns to scale:

$$F(K_t, R_t, L_t) = w_t L_t + (r_t + \mu)K_t + q_t R_t, \quad (1)$$

where K_t gives us the employed capital, R_t the oil-extraction rate and L_t the population (which equals labour supply) in the periods $t = 1$ and $t = 2$. Wages of the employed are denoted by w_t, the interest rate by r_t and the constant rate of depreciation by μ.

The profit of final good producers in the exporting region, which equals the revenue of output minus labour costs, minus capital costs, minus the world price of oil times the quantity of oil extracted in that period is given by:

$$\Pi_t = F(K_t, R_t, L_t) - w_t L_t - (r_t + \mu)K_t - q_t R_t \quad (2)$$

Since the market is perfectly competitive and clears in both periods, profits will be zero. Maximising the profit function yields the following first-order conditions or factor demand equations:

$$F_L(K_t, R_t, L_t) = w_t \quad (3)$$
$$F_K(K_t, R_t, L_t) = r_t + \mu \quad (4)$$
$$F_R(K_t, R_t, L_t) = q_t \quad (5)$$

where w_t denotes labour demand, $r_t + \mu$ denotes capital demand and q_t denotes oil demand in period t. To maximise profit, marginal products must equal marginal costs of these three production factors. Oil exporters face the real interest rate r_t. Thus, profit maximisation by oil exporters yields the Hotelling rule:

$$q_2 = (1 + r_2)q_1 \quad (6)$$

The Hotelling rule states that the world price of oil in the future must equal the current world price of oil adjusted to the interest rate and thus can be used to predict the price of oil

(Hotelling, 1931). If, for example, interest rates exceed the appreciation of oil, the extractor will decide to extract oil and invest the revenues in an interest-bearing security to earn a higher yield. The increased supply of oil will push down the current oil price and will cause the depletion date to shift closer to the present, which will boost the appreciation rate of oil. Extraction of oil continues to the point where the appreciation rate equals the interest rate. Hence, if the interest rate increases, the price of oil must also increase at a similar pace. If I rewrite the Hotelling rule:

$$q_2 - q_1 = r_2 q_1, \tag{7}$$

where the price of oil in period 2 minus the price in period 1 is the return on the conservation of oil. This must equal the return on extraction of oil.

3.2. Households

Households in both regions demand consumption goods and face the following budget restrictions in each period:

$$C_1 + A_2 = (1 + r_1)A_1 + w_1 L_1,$$
$$C_2 = (1 + r_2)A_2 + w_2 L_2,$$
$$C_1^* + A_2^* = (1 + r_1)A_1^* + q_1 R_1,$$
$$C_2^* = (1 + r_2)A_2^* + q_2 R_2,$$

where C_t represents consumption in period t and the exporting region is denoted by an asterisk. The budget restriction for the importing region in period 1 says that $C_1 + A_2$, which denotes the current consumption and the savings of the region, should equal the return on assets, plus wage income in period 1. The savings and consumption of the exporting region in period 1 equals their returns on future assets, plus income generated from oil extraction.

Wealth of each region can be derived from the present value budget constraints, in which the initial assets A_1 and A_1^* are given:

$$C_1 + \frac{C_2}{1+r_2} = (1 + r_1)A_1 + w_1 L_1 + \frac{w_2 L_2}{1+r_1} = M \tag{8}$$

$$C_1^* + \frac{C_2^*}{1+r_2} = (1 + r_1)A_1^* + q_1 R_1 + \frac{q_2 R_2}{1+r_2} = M^* \tag{9}$$

Wealth in the oil-importing region is denoted by M and equals the sum of the net return on assets and the present discounted value of wage income. Wealth in the oil-exporting region is denoted by M^* and equals the sum of the net return on assets and the present discounted value of oil revenues.

3.1 Equilibrium conditions:

Market equilibrium requires the following conditions to hold. Equilibrium on the asset market requires that total asset holdings must equal the value of capital stock:

$$K_1 = A_1 + A_1^* \quad (10)$$

$$K_2 = A_2 + A_2^* \quad (11)$$

Equilibrium on the oil market (OME) requires that the initial oil stock S_1 equals total oil demand in period one and period two:

$$S_1 = R_1 + R_2 \quad (12)$$

The equilibrium on the goods market (GME) requires that production equals consumption plus investment in the same period. Investment in period 1 equals K_2 and investment in period 2 equals zero, as the world ends after period 2. Hence, the good market equilibrium conditions are for periods 1 and two are:

$$F(K_1, R_1, L_1) + (1-\mu)K_1 = C_1 + C_1^* + K_2 \quad (13)$$

$$F(K_2, R_2, L_2) + (1-\mu)K_2 = C_2 + C_2^* \quad (14)$$

In the general equilibrium model, households in the importing and exporting regions face the following CES utility functions respectively:

$$(C_1, C_2) = \mathrm{L}_1 \frac{(\frac{C_1}{L_1})^{1-\eta} - 1}{1-\eta} + \frac{1}{1+\rho} L_2 \frac{(\frac{C_2}{L_2})^{1-\eta} - 1}{1-\eta} \qquad if\ \eta \neq 1 \quad (15)$$

$$= \mathrm{L}_1 lnC_1 + \frac{1}{1+\rho} L_2 lnC_2 \qquad if\ \eta = 1$$

$$U^*(C_1^*, C_2^*) = \mathrm{L}_1 \frac{C_1^{1-\eta^*} - 1}{1-\eta^*} + \frac{1}{1+\rho^*} L_2 \frac{C_2^{1-\eta^*} - 1}{1-\eta^*} \quad if\ \eta^* \neq 1 \tag{16}$$

$$= \mathrm{L}_1 lnC_1^* + \frac{1}{1+\rho^*} L_2 lnC_1^* \qquad if\ \eta^* = 1$$

where $\eta > 0$ and $\eta^* > 0$ denote the elasticities of marginal utility and $\rho \geq 0$ and $\rho^* \geq 0$ are the rates of pure time preference.

In the general equilibrium model with capital as a factor of production, output is produced according to the following CES production function:

$$F(R, K, L) = (\beta R^{\frac{\sigma-1}{\sigma}} + \lambda K^{\frac{\sigma-1}{\sigma}} + (1 - \lambda - \beta) L^{\frac{\sigma-1}{\sigma}})^{\frac{\sigma}{\sigma-1}} \tag{17}$$

which gives the technical relationship between the input quantities of oil, capital and labour and the output quantity. Here, σ denotes the elasticity of factor substitution and λ measures the weight of capital. Hence, $\lambda = 0$ in the model without capital as a factor of production and $\lambda > 0$ in the model with capital as a factor of production.

4. Fixed oil reserve

I start with the case of fixed oil reserves. I consider the effects of an increase in future labour supply on the current oil supply in the three following scenarios; the partial equilibrium where interest rate and capital stock are fixed, the general equilibrium without capital and the general equilibrium with capital.

4.3 Partial Equilibrium

In the partial equilibrium, interest rate r_2 and capital K_2 are taken as exogenous and fixed, meaning that the oil market is examined in isolation. Substitute oil demands for both periods and the Hotelling rule in the basic OME to get the OME for partial equilibrium:

$$R_1(q_1) + R_2((1+r_2)q_1, L_2) = S_1 \tag{18}$$

The effect of an increase in the future labour supply is visualised in figure 1. The initial equilibrium is at point 0. The OME shifts upward due to postponement of oil extraction to the future and the new equilibrium will end up in point 1, as interest rates remain fixed.

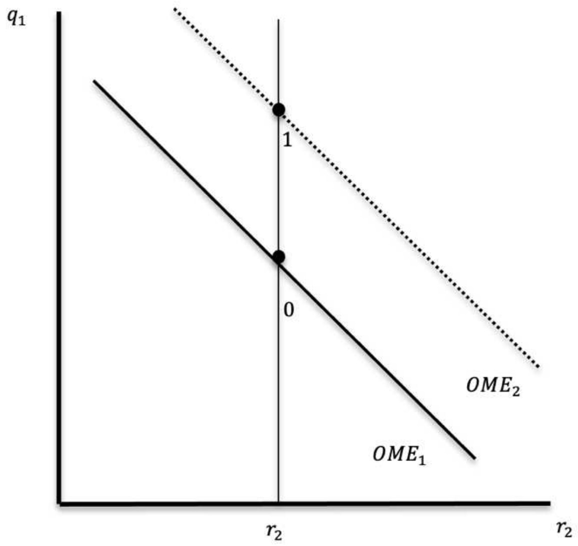

Figure 1

4.1 General Equilibrium: no capital

Equilibrium on the oil market (OME) requires that the initial oil stock S_1 equals current demand and future demand for oil. Current supply of oil depends on the current oil world price q_1, future supply of oil depends on the future oil world price $(1+r_2)q_1$ and future labour supply L_2. Current labour supply will be constant throughout and is not included as an argument to simplify notation. Substitute this in (12) to obtain the OME locus in the scenario without capital:

$$S_1 = R_1(q_1) + R_2((1+r_2)q_1, L_2) \tag{19}$$

Using the Hotelling rule, profit maximisation and the OME from (19), the present-value budget constraints (8) and (9) become:

$$C_1 + \frac{C_2}{1+r_2} = F\big(R_1(q_1)\big) - q_1 R_1(q_1) + \frac{F(R_2\big((1+r_2)q_1, L_2\big) - (1+r_2)q_1 R_2((1+r_2)q_1, L_2)}{1+r_2} \equiv M(q_1, r_2)$$

(20)

$$C_1^* + \frac{C_2^*}{1+r_2} = q_1 R_1 + \frac{q_2 R_2}{1+r_2} = q_1 S_1 \equiv M^*(q_1) \tag{21}$$

For combinations of $(q_1, q_2, r_{2,})$ that satisfy Hotelling rule, the oil-exporting region derives demand for the final goods as a function of these price combinations. Perceived discounted income of the exporting region equals $q_1 S_1$. Based on this set of prices the oil-importing region determines the profit-maximising demand for oil and thus the discounted total income M. Then it follows that demand for final goods by the oil-importing region equals $C_t(r_2, M(r_2, q_1))$ and by the oil-exporting region $C_t^*(r_2, M^*(q_1))$, in both periods $t = 1, 2$. Equilibrium on the goods market (GME) requires that aggregate consumption equals aggregate production in both periods. Using equation (13) and (14) the GME locus in the scenario without capital is defined by:

$$\frac{C_2(r_2, M(r_2, q_1)) + C_2^*(r_2, M^*(q_1))}{C_1(r_2, M(r_2, q_1)) + C_1^*(r_2, M^*(q_1))} = \frac{F_2(R_2((1+r_2)q_1, L_2))}{F_1(R_1(q_1))}, \tag{22}$$

where the left-hand side gives the demand for future goods relative to demand for current goods and the supply for future goods relative to supply for current goods is given by the right-hand side. I rewrite this equation by substituting $(1 + r_2)q_1$ for $S_1 - R_1(q_1)$;

$$\frac{C_2 + C_2^*}{C_1 + C_1^*} = \frac{F(S_1 - R_1(q_1), L_2)}{F(R_1(q_1))} \tag{23}$$

The effects of an increase in future labour supply on both the oil market and goods market become apparent when visualised in (r_2, q_1)-space in which the OME locus and the GME locus intersect in general equilibrium, point 0 in figure 2. From the Hotelling rule, it follows that the interest rate and current oil price are negatively related, giving the OME a downward-sloping locus within this diagram: an increase in q_1 lowers oil demand in period 1, this requires a fall in r_2 to increase oil demand in period 2. The GME, on the other hand, has an upward-sloping locus, which can be explained by the positive relationship between the interest rate and the relative demand for future consumption goods: a rising future interest rate will incentivize households to consume relatively more in the future. This would lead to an excess demand for future goods. An increase in the current oil price is needed to increase relative future supply and restore the equilibrium.

In the general equilibrium, both the OME and GME are affected by an increase in future labour supply. The OME locus will shift upward since future oil demand will increase of each given combination of q_1 and r_2. Equilibrium shifts from point 0 to point 1 in figure 2.

The labour shock will shift the GME locus either upward or downward, depending on the strength of both the relative demand effect and relative supply effect. Following the relative demand effect, households will decrease their current consumption and increase their future consumption after an increase in future population, creating an excess demand for future goods. An increase in the current oil price is needed to reduce the excess demand for future goods, and the locus shifts upward. Considering the relative demand effect in isolation, the economy will end up in point 2 in figure 1.

The relative supply effect, on the other hand, shifts the GME locus in the opposite direction. An increase in the future population will increase future supply of consumption goods. Hence, a decrease in the current oil price is needed to reduce relative future supply, by increasing the current oil demand and thus the current oil supply. If I only consider the relative supply effect, the economy will end up in point 3 in figure 1. Depending on how far the GME shifts downward or upward, current oil price will either increase or decrease. The interest rate will increase by the upward shift in the OME locus, but the ultimate effect on the interest rate depends on the shift of the GME locus.

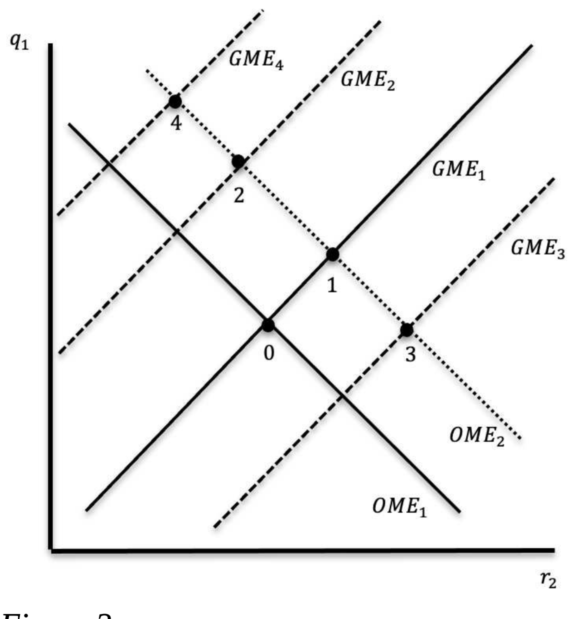

Figure 2.

4.2 General Equilibrium: With capital

Similar effects appear in the case with capital as in the case without capital. The difference lies in the presence of the capital market which strengthens the relative supply effect. Figure 2 visualises the effect of an increase in future labour supply on the demand side of the capital market, where total capital is fixed. The marginal product of capital will shift upward after the labour shock since more labour improves capital productivity. A higher productivity will increase capital demand which in turn pushes up the interest rate until it equals the marginal product of capital.

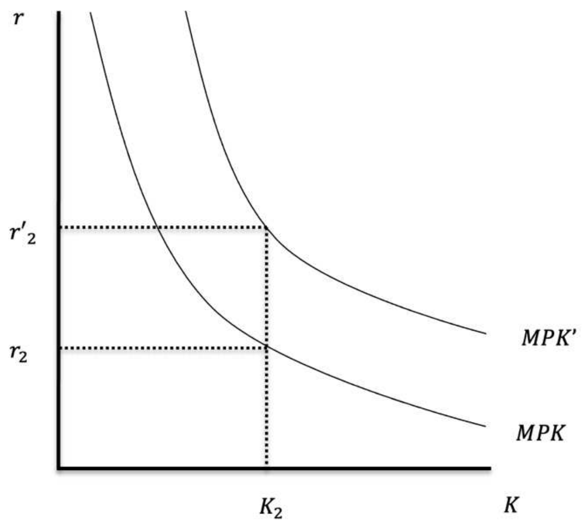

Figure 3.

The GME locus in the scenario with capital reads:

$$\frac{C_2+C_2^*}{C_1+C_1^*}=\frac{(1-\mu)K_2(r_2,S_1-R_1(q_1),L_2)+F(K_2(r_2,S_1-R_1(q_1),L_2),S_1-R_1(q_1),L_2)}{(1-\mu)K_1+F\big(R_1(q_1)\big)-K_2(r_{2,}S_1-R_1(q_1),L_2)} \tag{24}$$

On the right-hand side, the factor demand equations follow from (3) to (5). Now it becomes apparent that the relative future supply of consumption goods, denoted by the right-hand side of the equation, is not only dependent on the future labour supply and future oil supply, but also on future capital supply. An increase in the future capital supply will cause the relative future supply of consumption goods to increase. A stronger decrease in q_1 is needed to reduce relative future supply. Moreover, following the Hotelling rule, higher interest rates resulting from an increased demand for capital incentivizes oil-extractors to increase current oil extraction, which hampers the decrease in current oil extraction caused by the relative demand effect. This implies that the presence of the capital market in this scenario amplifies the relative supply effect. Again, if I only consider the relative supply effect, the economy will end up in point 3 in figure 1.

4.4 Results

For each scenario, the effect of an increase in future labour supply in either the exporting or in the importing region is examined. In the exporting region, households and oil exporters are present. Therefore, oil extraction rates will only be affected through the relative demand effect if labour increases in only this region. In the importing region, households and firms are present. Here, oil extraction rates will be affected through both the relative demand effect and the relative supply effect.

In the case of partial equilibrium where interest rate and capital stock are fixed, results suggest that an increase in future labour supply in the importing region alone leads to a decrease in current extraction. The OME locus shifts upwards and since the interest rate is fixed, only the current oil price increases. Equilibrium shifts from point 0 to point 1 in figure 1.

In general equilibrium without capital, the OME locus shifts upward as the increase in future labour supply increases the future oil demand of each given combination of q_1 and r_2. If the relative future demand increases, the interest rate goes up, leading to a decrease in current extraction. If relative future supply increases, interest rate goes down, leading to an increase in current extraction. The net effect depends on the strengths of the relative demand and supply effects and is visualised by the direction of the shift in the GME locus. Results suggest that an increase in future labour supply in either the exporting or the importing region decreases current oil extraction, hence the relative demand effect dominates the relative supply effect. The effect is weaker if labour increases in only the importing region due to the presence of the relative supply effect, which counteracts the relative demand effect and thus inhibits the decrease of current oil extraction. Hence, the GME locus shifts less upward if future labour supply increases in only this region.

In the general equilibrium with capital, current oil extraction decreases by less than in the case without capital. The interest rate decreases by more than in the case without capital. Again, the OME locus shifts upward following an increase in future oil demand. The presence of the capital market amplifies the relative supply effect through an increase in the interest rate that follows from an increasing demand for capital. Thus, the GME locus shifts less upward or more downward compared to the case without capital.

5.4 Intuitive comparison of results

In the partial equilibrium, current oil extraction decreases after an increase in future labour supply due to an increase in future oil demand, shifting the OME locus upward. The economy will end at point 1 in figure 1. The effect on current extraction is stronger in the general equilibrium without capital compared to the effect in the partial equilibrium. The OME locus also shifts upward, but because of the upward shift of the GME locus following a dominant relative demand effect, the economy ends up at point 4 in figure 2, implying a higher current oil price, and thus lower current oil extraction compared to the partial equilibrium.

Adding capital to the general equilibrium results in a weaker effect on the current extraction compared to the general equilibrium without capital. This can be explained by amplification of the relative supply effect due to the reaction of the interest rate in the capital market: A higher future labour supply will increase marginal productivity of capital, pushing up demand for capital which causes interest rate to rise. Both the higher interest rate and increased demand for capital will increase the relative supply for goods and thus strengthen the relative supply effect. Since the relative supply effect results in a decrease in current oil price, current oil extraction will not decrease as much as in the general equilibrium without capital and the GME locus will shift less upward, towards point 2 in figure 2.

5.5 Numerical results

Throughout this paper I have assumed that the parameters of the benchmark scenario are set to: $A_1 = 1,\ A_1^* = 1,\ \beta = 0.1,\ \lambda = 1/3,\ \eta = \eta^* = 1,\ \mu = 0.1,\ S_1 = 1$ and that L_2 increases from 1 to 1.05. In the partial equilibrium model, where capital and interest rate are fixed, an increase in the future labour supply will lead to an increase in the current oil price. The general equilibrium model without capital suggests that an increase in future labour supply will lead to a stronger increase in the current oil price and thus stronger decrease in current oil extraction compared to the partial equilibrium. In the general equilibrium with capital, an increase in future labour supply will also lead to a stronger increase in the current oil price and thus a stronger decrease in current oil extraction compared to the partial equilibrium. However, due to the amplification of the relative supply effect by the presence of the capital market, the increase will be smaller compared to the general equilibrium model without capital. Moreover, the interest rate decreases in both the case with and without capital, with the strongest decrease in the model with capital. These results suggest that the general equilibrium effect strengthens the reaction of current extraction on population growth.

I present a robustness analysis to examine how the model responds in the case that certain parameter values differ from the assumed parameter values. I provide an analysis on how current oil extraction responds to changing values of η, the elasticity of marginal utility, and σ, the elasticity of factor substitution.

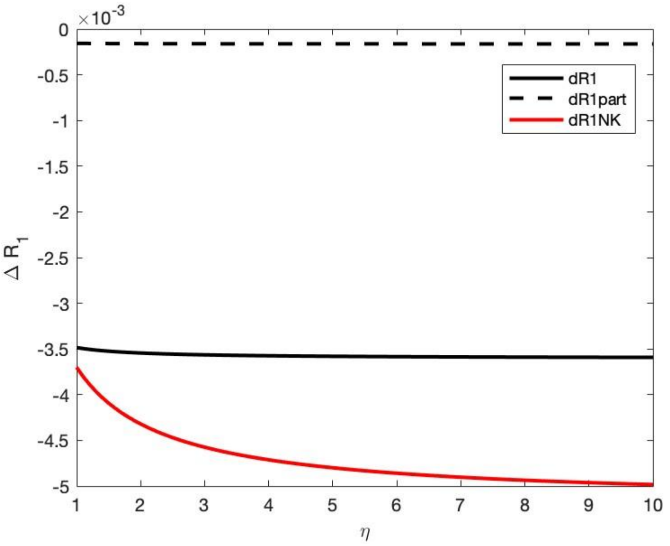

Figure 4. The changes in current oil extraction for different values of η after L_2 increases from 1 to 1.05. Partial equilibrium is depicted by the black dashed line, general equilibrium without capital by the red line and general equilibrium with capital by the black line.

To see how the effect of population growth on current oil extraction changes for different values of the elasticity of marginal utility, I plotted an (η, R_1) diagram, figure 4. The elasticity of marginal utility determines the sensibility of households to the level of consumption. A high elasticity of marginal utility implies that the marginal utility of goods is highly sensitive to changes in quantities consumed: if consumption of a good increases, the marginal utility of each additional good decreases rapidly. Hence, the elasticity of marginal utility affects the strength of the relative demand effect. When households have a high elasticity of marginal utility, they must increase their consumption relatively more to reach the desired level of utility compared to the case with a low elasticity of marginal utility.

The increase in future labour supply on current oil extraction remains strongest for the general equilibrium without capital, followed by general equilibrium with capital and the partial equilibrium for all other values of η as well. In the partial equilibrium, oil extraction does not change for different values of the elasticity of marginal utility, which can be explained by the absence of the relative demand effect in this equilibrium. In the general equilibrium without capital, the relative demand effect dominates the relative supply effect. A higher elasticity of marginal utility implies that households must increase their future consumption relatively more to reach the desired level of utility, leading to a stronger relative demand effect and thus a stronger decrease in current oil extraction. In the general equilibrium with capital, the change in oil extraction with respect to changing elasticities of marginal utility is smaller compared to the general equilibrium without capital. This can be explained by the presence of the capital market which amplifies the relative supply effect, counteracting the relative demand effect.

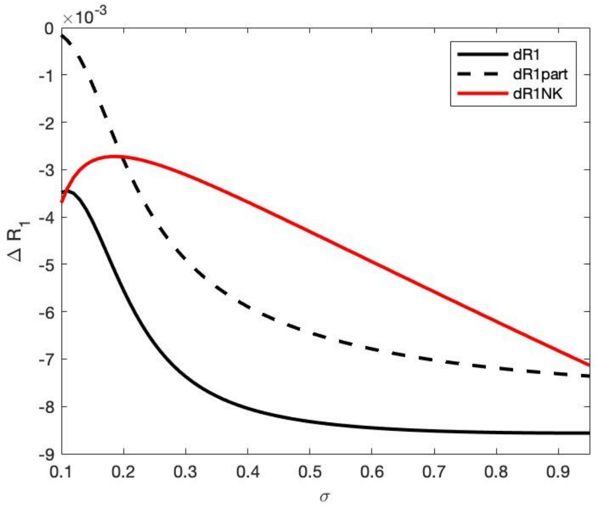

Figure 5. The changes in current oil extraction for different values of σ after L_2 increases from 1 to 1.05. Partial equilibrium is depicted by the black dashed line, general equilibrium without capital by the red line and general equilibrium with capital by the black line.

To see how the effect of population growth on current oil extraction changes for different values of the elasticity of substitution, I plotted a (σ, R_1) diagram. A higher elasticity of substitution is associated with a weaker relative supply effect, which explains the increasingly stronger negative effect of population growth on oil extraction rates as sigma increases in value. In the general equilibrium without capital, the effect on oil extraction becomes weaker compared to the partial equilibrium as sigma increases. This is because in the general equilibrium the relative supply effect includes the interest rate which increases as population grows, strengthening the relative supply effect. In the general equilibrium with capital, both capital and labour are affected by higher values of sigma and thus the relative supply effect is weakened. Therefore, compared to the partial equilibrium, the negative effect of population growth on current oil extraction is the strongest in general equilibrium with capital.

6. Exploration costs and partial exhaustion

In the first section I assumed that the oil reserve is fixed and independent of population size and growth. Introducing the possibility for oil extractors to explore additional oil reserves allows me to examine the effect of population growth on total oil extraction over time, or cumulative extraction. Hence, I now assume that the initial oil stock S_1 is not fixed but can be recovered, depending on exploration activities. Exploration requires investment costs, which are endogenous. The recoverable stock of oil:

$$S_1 = H(I), \tag{25}$$

where I denotes exploration investment and $H' > 0, H'' < 0$, implying that revenue on oil exploration decreases as less accessible oil fields must be explored. Profit maximising oil-extractors face the Hotelling rule, exploration investment and initial reserves as an increasing function of the initial oil price:

$$q_1 H'(I) = 1, \tag{26}$$

where the left-hand side denotes marginal revenue for each oil-extractor and the right-hand side marginal costs; for one additional dollar invested in exploration, the oil extractor yields $q_1 H'(I)$ oil. Equation above implies that $I = H^{-1}(\frac{1}{q_1}) \equiv I(q_1)$, with $I' > 0$, and $S_1 = S_1(q_1)$ with $S'_1(q_1) > 0$. This implies that the initial oil stock depends positively on the oil-price. Including exploration costs, I obtain a new OME condition:

$$R_1(q_1) + R_2(r_2, (1 + r_2)q_1, L_2) = S_1(q_1). \tag{27}$$

6.1 Results

In the partial equilibrium scenario, where interest rate and capital stock are fixed, an increase in future labour supply of either the importing region or in both regions curbs current oil extraction, while the current oil price increases. This is similar to the case without exploration costs. Additionally, cumulative extraction goes up due to increased investment in exploration caused by the increased current oil price.

In the general equilibrium with and without capital, an increase in future labour supply also curbs current oil extraction while the current oil price increases. In general equilibrium with capital and partial exhaustion the GME condition (28) takes the Hotelling rule, the OME condition (27), investment in exploration and dependence of initial oil reserves on the oil price into account. Again, the left-hand side gives the demand for future goods relative to demand for current goods and the supply for future goods relative to supply for current goods is given by the right-hand side. Note that on the right-hand side, the exploration costs $I(q_1)$ are subtracted from current supply.

$$\frac{C_2(r_2, M(r_2, q_1)) + C_2^*(r_2, M^*(q_1))}{C_1(r_2, M(r_2, q_1)) + C_1^*(r_2, M^*(q_1))} = \frac{(1-\mu)K_2(r_2, S_1(q_1) - R_1(q_1), L_2) + F_2(K_2(r_2, S_1 - R_1(q_1), L_2), S_1(q_1) - R_1(q_1), L_2)}{(1-\mu)K_1 + F_1\big(R_1(q_1)\big) - K_2(r_2, S_1(q_1) - R_1(q_1), L_2) - R_1(q_1) - I(q_1)} \tag{28}$$

The effects of an increase in future labour supply on the current oil supply work through the relative shifts of the GME and OME loci, like in the case without exploration costs.

An increase in future population curbs current oil extraction in general equilibrium with and without capital. Also, the decrease in current extraction implies an increase in cumulative supply, due to exploration.

6.2 Numerical comparison of the results of fixed reserves and full exhaustion

The partial equilibrium model suggests that the current oil price increases more than in the partial equilibrium with fixed reserves. In the general equilibrium model with and without capital, current oil price increases by less than in partial equilibrium. Compared to the general equilibrium model without capital with fixed reserves, current oil price also increases less. The explanation is that the increased exploration costs strengthen the relative supply effect, therefore pushing the current oil price to a lower point than in the case without exploration.

Taking partial exhaustion and exploration costs into account allows for examining the effect of an increasing population on cumulative extraction. The level of cumulative extraction directly affects the amount of carbon being emitted into the atmosphere, and by that affecting climate change. Based on the results of this model, more carbon will be emitted in the future compared to the present if future population increases, and cumulative carbon emissions will increase as oil extractors invest in exploration due to higher current oil prices.

6. Conclusion

This paper uses a two-period model with two regions to study the effect of changes in population on oil extraction. The model is based on a previous study that explored the effect of a future tax on oil extraction, and it has been adjusted to examine the effects of changes in population. In the model, one region imports oil while the other region exports it. The markets are assumed to be perfectly competitive and clear, and all actors in the market have rational foresight. The oil price is determined by the Hotelling rule. The effects of changes in population on oil extraction were examined for three different scenarios: a partial equilibrium in which the interest rate and capital stock are fixed and a general equilibrium with and without capital. First, I analysed the effect in the case of fixed oil reserves, then I extended the model with the possibility of exploration. In the case of fixed oil reserves, current oil extraction goes down. In general equilibrium without capital, this effect is amplified because of the presence of the dominant relative demand effect, which causes the current oil price to increase more and hence current oil extraction to decrease less compared to the partial equilibrium. Introducing capital, I find that the effect is weakened compared to the scenario without capital. This can be explained by the presence of the capital market, which amplifies the relative supply effect. A stronger relative supply effect will push down the current oil price to a lower point compared to the scenario without capital, and hence result in a lower decrease in current oil extraction.

These results seem counterintuitive: in all cases, a higher population growth slows down current oil extraction, as extractors decide to postpone extraction. This decision follows from the Hotelling rule: due to future population growth, the interest rate decreases. This curbs current extraction, as oil extractors are waiting for higher interest rates in the future, so they can invest their sales proceeds from oil extraction and expect the returns on their investments to be higher due to the increased interest rate.

In the last section I extended the model by introducing the possibility for oil extractors to explore additional oil reserves, which allows for the examination of the effect of population growth on total oil extraction over time, or cumulative extraction. I found that in all scenarios, current oil extraction decreases, but less than in the case with fixed reserves. The explanation is that the exploration costs amplify the relative supply effect, which causes the current oil price to increase less and hence the current extraction rate to decrease less compared to the case with fixed reserves. Cumulative extraction increases as current oil prices increase, which means that cumulative carbon emissions will increase proportionally. This is because the Hotelling rent goes up, which leads to higher investments in exploration.

Based on the results from this research, I would suggest that implementing population control policies, in addition to policies that promote a more sustainable lifestyle and assign research subsidies to non-polluting technologies, can be an effective tool to mitigate climate change. As consumption patterns vary across the world, it would be interesting to divide the world population into different groups where each group has its own level of consumption. Investigation of the effect of population growth on climate change would then be more applicable to the real world.

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