ESSAYS IN ENERGY AND NATURAL RESOURCE ECONOMICS

by

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Abstract: This thesis is concerned with macroeconomic and fiscal implications of fossil fuel combustion. Despite an emerging focus among economic policy makers on the problem of curbing greenhouse gas emissions, much remains to be learned about this complex issue.

Fossil fuel related pollution, for example, is likely to impose a range of societal costs – including, potentially, on productivity, human health and household consumption patterns – which are typically not reflected in economic simulations aimed at informing the climate debate.

Analysis of a broader set of potential energy-environmental spillovers here highlights new insights on the importance of theoretical assumptions, including in relation to savings behaviour, welfare aggregation and potential consumption externalities for the macroeconomy and fiscal policy.

Distributional issues associated with potential energy tax reforms designed to control externalities and raise revenues are also studied in an effort to inform decision makers in the UK on the consequential risks - and mitigating strategies - to the well-being of societal groups, including lower income households.

A fuller summary is found at Chapter 2

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Abbreviations

3SLS Three stage least squares

ABI Association of British Insurers

AIDS Almost Ideal Demand System

C Celsius

CDD Cooling Degree Days

CO2 Carbon dioxide

CT Carbon tax

CV Compensating Variation

DECC Department of Energy and Climate Change

E-Z Epstein and Zin

EFS Expenditure and Food Survey

EIS Inter temporal substitution

EU European Union

FES Family Expenditure Survey

GCM General Circulation Models

GDP Gross Domestic Product

GEA Global Energy Assessment

GHG Greenhouse gases

GMM Generalized Method of Moments

HDD Heating Degree Days

IAM Integrated assessment model

ILLE Iterated Linear Least Squares Estimator

IMF International Monetary Fund

IPCC International Panel on Climate Change

IV Instrumental Variables

IWG Interdepartmental working group

LCF Living Costs and Food Survey

OECD Organisation for Economic Cooperation and Development

OLG Overlapping generation

OLS Ordinary Least Squares

OPEC Organization of Petroleum Exporting Countries

PM Particulate matter

RCM Regional Circulation Models

SCC Social cost of carbon

SRES Special Report on Emissions Scenarios

SWF Social welfare function

t Tonne

UK United Kingdom

US United States

VAT Value added tax

Mathematical Symbols

$1 - a_1 - a_2$ Income share to oil

α Parameter determining strength of external habit

α_0 Intercept term

α_i Coefficient on own price term

$\bar{t}$ Time threshold

$\bar{\bar{a_2}}$ Threshold on labour income share, endogenous mortality hazard

$\bar{a_2}$ Threshold on labour income share, exogenous mortality hazard

$\bar{S}$ Exogenous oil stock

$\bar{x}$ Exogenous depletion rate

$\blacksquare$ End of proof

$\breve{Z_W}$ $Z_W - Z_h$

χ Proportion of oil allocated to production

Δ Cobb Douglas price aggregator

$\dot{}$ Time derivative

γ Parameter determining the influence of average human capital on production

γ_{ij} Coefficient on cross price j on expenditure share on good i

$\hat{}$ Growth rate

$\int$ Integral

ι Externality from oil usage affecting human capital accumulation

Λ Ratio of oil used in consumption to production

λ Co state variable

λ_1 Co state variable

λ_2 Co state variable

$\mathbf{p}$ Vector of commodity prices

$\mathbf{z}$ Vector of controls

$||$ Determinant

$|$ Evaluated at given value

μ Co state variable in population

Ω Parameter determining the productivity of education

ω Demand coefficient on total expenditure squared

$\prod$ Product

ψ Externality from capital accumulation affecting productivity growth

ρ Probability of dying during period 1 of OLS model

Σ Sum

θ Externality from oil usage affecting capital depreciation

$\tilde{s}$ Endogenous oil stock

$\tilde{x}$ Endogenous depletion rate

$\underline{m}$ Total expenditure

$\underline{T}$ $a_1(1-a_1-a_2)+a_2s+(a_1-s)(\iota(a_2+\gamma)-\theta(1-a_1))$

$\mathit{\Phi}$ Deterministic time trend

φ Externality from oil usage affecting population growth

ς Mortality risk due to fossil fuel extraction

ϑ_{ik} Coefficient on demographic control k in commodity equation i

ϑ_{it} Coefficient on time trend t in commodity equation i

$\mathit{\Upsilon}$ Stone price index

$\mathit{\Xi}_{ij}$ Budget share elasticity for good i with respect to the price of good j

$\mathit{\Xi}_{i}$ Budget share elasticity for good i with respect to total expenditure

ξ Aggregation preferences parameter

ζ Parameter determining the magnitude of spillover affecting oil allocation

* Steady state

^{c} Compensated elasticity

^{SP} Outcomes under choice of the social planner

^{u} Uncompensated elasticity

$_{+1}$ Variable in period 2 of OLS model

$_0$ Initial condition

$_i$ Index of composite commodities

A $a_1(1-a_1-a_2)+a_2s+m(a_1-s)$

a_1 Income share to capital

a_2 Income share to labour

B $a_1(1-a_1-a_2)+a_2s+(m-\theta(1-a_1))(a_1-s)$

b Weighting of period 2 utility in OLS model

C $v(1-a_1-a_2+m)+a_2-m$

c Household consumption

c/k Ratio of consumption to capital

C^i Emissions per unit of good i

c_1 Consumption in period 1 of OLS model

c_2 Consumption in period 2 of OLS model

c_a Average consumption across households

D $C + (v-1)\,\psi\theta$

d_{ik} Demographic translator k on demand for commodity i

d_{ik} Demographic translator k on demand for commodity i

$Dummy$ Indicator variable

E Oil flow

e_{ij} Demand elasticity for good i with respect to the price of good j

e_i Demand elasticity for good i with respect to total expenditure

F $A + a_2\varphi\,(a_1 - s)$

G $A + a_2\varphi\,(a_1 - s) - \theta\,(1 - a_1)\,(a_1 - s)$

g Growth in per capita income

H $C + v\,(1 - a_1 - a_2)\,\varphi - (1a_1)\,\xi\varphi + a_2\varphi$

h Rate of exogenous technological progress

I $\frac{w\Lambda}{(1+w\Lambda)^2}\,(v-1)\,(1 - a_1 - a_2)\,(i + z - wx^*)$

i Time discount rate

J External habit parameter

j Depreciation rate

$Jacobian$ Jacobian matrix

K Capital stock

k Capital per capita

L Surplus ratio

l Stock of human capital of the representative agent

l_a Average stock of human capital in the population

M Ratio of indirect to direct marginal utility of consumption due to habit parameter

m Externality from oil usage affecting productivity growth

N Population

n Exogenous population growth rate

O $\left(1 - a_1 - a_2\left(1 - \frac{s}{a_1}\right)\right)$

o Index of households

P Oil price

Q Output

q Production per capita

R $\frac{(1-a_1)(a_1+a_2)}{a_1}$

r Gross interest rate

S Oil stock

s Proportion of income saved

SC^i Charge per unit of emissions from good i

$share_{i,a}$ Average budget share on commodity i

$share_i$ Budget share on commodity i

SWF_a Social welfare function, unweighted

SWF_b Social welfare function, weighted by family size

T Index of technology

U $v\left(1 - a_1\right) + \left(v - 1\right)\left(\gamma + \iota\left(a_2 + \gamma\right)\right)$

u Proportion of time allocated to training

V Value function

v Utility of consumption preference parameter

W Wage rate

w Utility of energy services preference parameter

X Indirect utility

x Oil depletion as a proportion of stocks

y Lump sum transfer from government

Z Ad valorem oil tax

z Time path of ad valorem oil tax

Z_c Ad valorem consumption tax

z_c Time path of ad valorem consumption tax

Z^B_{EXP} Expenditure tax

Z^G_{EXP} Expenditure tax with adjustment for change in oil stocks

Z_h Ad valorem tax on training

Z_i Ad valorem tax on composite commodity i

$Z_i^{0,VAT}$ Pre reform ad valorem rate of VAT on commodity i

Z_i^0 Total effective pre reform ad valorem tax rate on commodity i

Z_i^c Specific carbon duty on commodity i

Z_i^s Specific duty rate on commodity i

Z_i^T Total duty rate on commodity i

Z_Q Income tax

Z_W Ad valorem tax on wages

Z_x Ad valorem surcharge on oil in production

t Time period

1 PROLOGUE

"Climate change is not....the biggest challenge of our time, it's the biggest challenge of all time" (Sir David King, former UK Government Chief Scientist, remarks to Carbon Trust annual dinner, 29 April 2014)

"This [the problem of human induced climate change] is not science: it is mumbo-jumbo" (Lord Lawson, The Telegraph, Sept 28, 2013)

".....the impacts of climate change can cause lasting damage to capital stocks...current models where this lasting damage is omitted are likely to be deeply misleading."(Lord Stern (2013))

"Climate change, demographics,...energy,.... these issues are all intertwined. We cannot look at one strand in isolation..." (Ban Ki-Moon, remarks to COP-17 High-Level Ministerial Dinner, 7 December, 2011)

[The primary goals of UK energy policy are] ensuring light, power, heat and transport are affordable for households...and reducing carbon emissions in order to mitigate climate change." (Department of Energy and Climate Change (DECC), 2015)

"The challenge for tax design is to achieve social and economic objectives while limiting welfare-reducing side effects." (The Mirrlees Review (2011), Chapter 2)

This thesis is concerned with the economic implications of climate change and fossil fuel dependency, together with associated fiscal policy responses. Stern (2007) cogently argue that emissions of greenhouse gases (GHGs) constitute "the greatest market failure the world has ever seen". They conclude that, if unchecked, the overall costs of climate change – including from declining crop yields, heightened flood damages, and adverse human health effects – would be equivalent to a permanent loss of at least 5 percent of global income.

While Stern's findings have been open to quantitative challenge – not least relating to the low discount rate which the authors apply to the future economic costs, many of which lie decades, even centuries, in the future (Dasgupta (2007), Nordhaus (2007, 2013), Tol and Yohe (2007), Weitzman (2007)) – the basic conclusion, at least, concerning the underlying seriousness of the issue appears sound.[1]

The most recent scientific evidence collated as part of the IPCC Fifth Assessment Report (2014) suggests, for example, that – were global GHG emissions to continue to rise at a rate similar to that observed since the 1950's until now – then there is at least a 66 percent chance that average global surface temperatures will rise by 2.6-4.8 degrees Celsius (C).

At the upper end of this range, such increases are roughly equivalent to the change in average temperatures from the last ice age to today (Stern (2007)).[2] If realised, they would almost certainly result in a radical shift in the physical and human geography of the globe; and serious, albeit difficult to quantify, risks of large-scale shifts in the climate system, such as disruption to oceanic and atmospheric circulations or the irreversible melting of Arctic and Antarctic ice sheets (raising the potential for a 10 metre (or more) rise in sea levels).

From the perspective of an economist, the issue is fundamentally an externality problem: fossil fuel combustion adversely affects future economic development; however, each

[1] The International Panel on Climate Change (IPCC) (2014) estimate that human activity has been the dominant cause of observed warming since the mid-20th century with a probability of more than 95 percent. This is not to suggest complete consensus on this issue. Esteemed physicist Freeman Dyson, for example, argues that such inference is unclear, not least given the uncertain influence of Carbon dioxide (CO_2) on cloud formation (views cited in interview with Quanta Magazine, published 31 March, 2014). Other "climate skeptics" accept the basic pretext that human activity causes global warming, but deemphasise the likely costs associated (see, for example, Lomborg (2007)).

[2] Measures of average surface temperature increases, for example, belie much larger effects on land, and at extreme latitudes.

polluter would prefer others to bear any costs associated with their avoidance – a classic free rider problem. The theoretical response to such issues is described by Pigou (1932): simply set a tax equal to the marginal external cost of each unit of pollution.[3]

A key issue is to determine, in economic terms, how seriously to take the problem. The answer to this question is embodied in the ongoing debate concerning the social cost of carbon (SCC) – the economic damages associated with a small increase in CO2 emissions (conventionally one metric ton) in a given year.[4] However, determining this value is a difficult undertaking. A number of facets of the problem merit particular note at the outset.[5]

First, it is a truly global public bad: a unit of CO2 is equally harmful wherever it is emitted. Important international coordination issues notwithstanding, there is thus considerable merit in guiding the collective action problem, particularly in terms of the overall degree of policy ambition, within a global analytic framework.

Second, the climate problem is long term and persistent. Economic damages arise from the stock (rather than flow) of GHGs. In the case of CO2, for example – by far the most important source of human induced GHG – emissions decay extremely slowly (roughly 1-2 percent a year on average). This means that the problem is fundamentally dynamic: an

[3] This result holds in a first best setting in which prices are otherwise undistorted, for example, by taxation or imperfect competition. Contributions in the public economics sphere have subsequently nuanced the policy insights under less restrictive assumptions (see Jones et al. (2013) for a discussion).

[4] Arguably any external cost is difficult to assess at the margin (as opposed to an average say). Such difficulties have resulted in alternative approaches which involve taking the overall policy objectives on GHGs as given, and then choosing policies which achieves this at least cost (Baumol-Oates (1988)).

[5] Estimates of the SCC vary widely given the technical complexities and divergent views surrounding the appropriate discount rate: Tol (2007), for example, finds a median value of US$15 per tonne (t) CO2, while Stern (2007) puts the figure at US$85 tCO2. By contrast, Nordhaus (2007) suggests a starting value of around US$5 tC02. More recently, the United States (US) government arrived at a central value of around US $35 tCO2 (Interdepartmental Working Group (IWG) (2013)).

optimal response today depends on future policy and economic activity.

Third, and relatedly, most of the costs of climate change fall in the (often quite distant) future.[6] This raises questions concerning the appropriate discount rate, which critically affects the proper level and rate of increase of carbon prices (see Jones et al. (2013) for an overview of these still somewhat controversial issues).[7]

Fourth, policy responses to climate change – not least fiscal incentives for energy conservation and substitution into less polluting technologies – interact, potentially fundamentally, with the exhaustible nature of fossil fuels (which contribute around 85 percent of total global consumed energy).[8] Sinclair (1992), for example, first recognised that energy taxes potentially influence the timing of production choices by profit maximising resource owners, thus emphasising the desirability of a downward sloping tax path.[9]

Fifth, the effects of climate change are likely to be highly heterogeneous both across and within countries. The most adverse effects are expected in developing countries and the most marginalised households (due to their greater exposure to the impacts and weaker adaptive capacity) (Nordhaus (2013), Stern (2007)).[10]

[6] Jaffe and Kerr (2015) argue that cost-benefit analyses based on the aggregation of economic effects fail the Kaldor-Hicks compensation principle, since a comprehensive system of transfer payments across countries and generations is infeasible in practice.

[7] In a notable recent contribution, Giglio et al (2015) find empirical evidence for low long term discount rates - on the order of 2.6 percent per annum - by comparing freehold versus leasehold property values.

[8] Although technological advancements have greatly expanded the recoverable stock, fossil energies remain finite to a first approximation given their slow replenishment rates. The literature relating to resource scarcity and economic development – extending back to the seminal work of Hotelling (1931) and the neoclassical resource-production models of Dasgupta and Heal (1974), Solow (1974) and Stiglitz (1974)) – are thus potentially insightful. These latter studies, in particular, emphasize that consumption over the long run depends on investment returns, the degree of impatience, and the rate of technological progress.

[9] See also Farzin and Tahvonen (1996), Hoel and Kverndokk (1996), Sinclair (1994), Ulph and Ulph (1994)).

[10] Nordhaus (2013), for example, finds that, a global carbon tax could generate discounted benefits of $1.3 trillion in

Importantly, heterogeneities also extend to the economic burden from climate change policies. It is clear that energy intensive, resource dependent economies risk incurring substantial costs from more expensive fossil fuels.[11] Within countries, considerable differences in consumption behaviour exists: low income households, for example, are more financially reliant on basic commodities such as energy. Understanding this later dimension is critical to informing policy design.

The final important dimension concerns the pervasive uncertainty surrounding both the nature of the climatic changes which may take place, and their economic consequences. Such uncertainty may even be "Knightian" since historical climate patterns observations are uninformative in regards to the distribution of future outcomes (Weitzman (2009)).[12] However, the implications of such uncertainty, which includes the possibility of irreversible outcomes, for policy are not yet fully established.[13]

developed countries over the second half of the century, compared to $3.5 trillion in avoided economic damages in developing countries over the same period.

[11] See, for example, International Monetary Fund (IMF) (2008)). These distributional effects are highly sensitive, however, to design choices, including transfer payments and the allocation of pollution rights in any future international carbon trading system.

[12] Pindyck (2013) and Stern (2013) highlight the deterministic form of most climate models (which rely on monte carlo simulation to treat uncertainty). A recent contribution by Hambel et al. (2015), which incorporates uncertainty over both climate and economic variables, represents a valuable contribution to the literature. The implications of potential failures in the axiomatic underpinnings of expected utility theory for climate policy – which could potentially be due to temporary errors in perception – is an emerging research field. Millner et al. (2013), for example, show that the value of climate change abatement increases, potentially substantially, in the presence of probabilistic uncertainty over outcomes where the planner is averse to ambiguity.

[13] The benefits from reduced risk exposure through early action are counterbalanced by the prospect of both better information and technologies in the future (Gollier et al. (2000)). Considerable uncertainty also exists in relation to the costs of mitigating climate change, in part because future technological development is both unpredictable and endogenous to policy choices (Goulder and Mathai (2000), Jaffe and Stavins (1995)). Moreover, the apparent existence of a large "efficiency gap" raises questions about the true returns to investment in currently available energy technologies (Enkvist et al. (2007), Fowlie et al. (2015), Joskow and Maron (1992)).

This thesis seeks to inform several key aspects of this complex and multi-dimensional problem which have hitherto received little attention in the literature; in particular, it studies the implications of potential macro-environmental spillovers, including direct effects on labour and capital markets, and assumptions over the behaviour and preferences of economic agents, for energy taxation and wider fiscal adjustments.

In this context, therefore, it is noteworthy that central analytic tools underpinning appraisals of the economic impacts of climate change are known as integrated assessment models (IAMs) – a name derived from the fact that this class of models attempts to integrate the representation of GHG stock formation with the resulting effects on output, consumption, and other economic variables due to climate change.

They have two main components. First, a welfare function, typically comprising a stream of isoelastic utility over per capita consumption at the global or regional level. Second, a "damage function" which determines the effect of higher temperatures on output.[14]

These damage functions, in particular, have recently come under close scrutiny in an effort to provide better guidance on appropriate climate policy goals; Stern (2013), for example, emphasises the need to broaden the set of environment-economy impacts which are simulated (fossil fuel use is likely to impose multiple social costs on the economy), including direct effects on capital and labour markets.[15]

[14] Research into the macroeconomic effects of pollution extends back to the 1970's (see Forster (1973), Gruver (1976), Keeler et al. (1972)). In contrast to the climate change literature, this literature generally assumes that externalities bear directly on the utility function of the representative agent.

[15] Pindyck (2013) argues that these lack both theoretical and empirical foundations: a common approach has been to model reductions in output levels as a convex function of temperatures (e.g. Nordhaus (2008), Stern (2007)), and to select coefficients such that output losses in the range of 2°C to 4°C are consistent with ex ante beliefs! However, such fundamental questions as to whether higher temperatures might affect levels or rates of change in output, for example, have not yet been fully resolved (Jones et al. (2014)). Fussell (2010) provides a helpful review of leading IAMs.

Turning to the welfare function, and the structure of household preferences, the overwhelming focus of recent research has been on the appropriate discount rate (see Jones et al. (2013) for a discussion). However, several important aspects concerning the role of preferences on economics and policy have so far been the subject of little attention.

As highlighted by Tol (2009), for example, the relevant literature typically presumes that utility is formed over consumption per capita, rather than of a group – thereby failing to consider important concerns from the social choice literature, for example, regarding the implied "tyranny of the individual" (see, for example, Blackorby and Donaldson (1984), Cowell et al. (2010)).[16]

A further almost universal tenant of the neoclassical resource literature is that the resulting stream of utility is additively separable. As such, potentially important insights from the wider macroeconomic literature relating to consumption habits – the idea that historical or wider societal behaviours may affect preferences – have, for the most part, been overlooked (Kennan (1988), Fuhrer (2000), Smets and Wouters (2007)).

Turning to more detailed aspects of policy implementation – despite growing interest in energy taxation to curb fossil fuel usage – relatively little research has been undertaken to date on the distributional consequences of such measures (a key concern, and potential impediment to reform, given the burden of energy costs on many low income households).

Where analysis has been undertaken in the case of the UK, for example, available studies commonly presume that household demand is unaffected by energy tax reforms and rigourous welfare analysis largely (Baiocchi et al. (2010), Dresner and Ekins (2006), Druckman and Jackson (2008), Symons et al. (2002)). This risks over estimating the fiscal base and biasing estimates of the economic costs.

A further important issue is the lack of available analysis into the welfare costs of cor-

[16] Average utilitarian preferences lead to a situation, for example, in which a single person with 100 utils is ranked more favorably than an innumerate number of citizens enjoying 99 utils.

rective indirect energy taxes reform in the UK - arguably the key concern for governments in assessing policy objectives, and in forming implementation choices.

Exploring these issues – which, to the best of my knowledge, are directly addressed in just a single behavioural study for the case of motor fuel excises (Blow and Crawford (1997)) – is thus a key objective of this thesis, and presents a further opportunity for exploring one of its central themes, in particular being the role of preferences in energy taxation choices.

Against this broad research context relating to this important and challenging set of economic and policy issues, let us now turn to a more detailed summary of the key research findings and contributions.

2 SUMMARY OF RESEARCH FINDINGS

Chapters 3 - 5 aim to respond to the hitherto rather narrow set of societal costs and preference forms which have been explored within the existing literature on neoclassical growth with exhaustible resources – thereby exposing a number of new insights on the implications of particular assumptions over the form of the household optimization problem (both in terms of objective function and constraints) for the resulting macroeconomic and policy insights.

Chapter 3 focusses specifically on the effects of climate change on physical capital markets, which have received scant attention in the literature (and are highlighted as a priority area for model development by Stern (2013)). It is well known, for example, that adverse weather conditions cause capital stocks to erode: stresses from heat, cold and rainfall, for example, account for between one third and one half of road maintenance costs (Nemry and Demirel (2012)).

However, it is likely that climate change will increase capital losses. Buildings and infrastructure, for example, are expected to suffer additional damages from coastal flooding, more powerful wind storms, and subsidence due to more intense rainfall or melting permafrost (Field et al. (2014)). In other regions, drought may render capital obsolete: decreased runoff rates in the Colorado river basin of up to 20 percent predicted by mid Century, for example, may threaten the long term viability of the Las Vegas economy (Miller et al. (2011)).[17]

Analysis of such effects are now emerging at the research frontier: Moore and Diaz (2015), for example, recently studied the sensitivity of growth pathways using an IAM fea-

[17] The city depends on the river for 90 percent of its water and is currently suffering extreme water sustainability issues. Implementation of water demand management strategies is a top priority, however opportunities to increase supply appear limited.

turing capital and labour inputs to production (see also Fankhauser and Tol (2005)). However, these contributions ignore potentially important interactions with the exhaustible character of fossil fuel inputs: in particular, more rapid depreciation affects the Hotelling portfolio condition, by lowering net returns to investment.

To the best of my knowledge, only Bretschger and Valente (2011) have studied this linkage in a resource based economy. The authors find that spillovers affecting capital durability influence the level of output but not its growth rate.[18] However, a number of key questions remain substantively open in this context:

- First, how does savings behaviour influence the macroeconomic and policy implications of more rapid environmentally related capital depreciation? I show that the main finding of Bretschger and Valente (2011) rests crucially on assumptions that inter temporal consumption and savings decision making are forward looking. If savings behaviour follows a "Keynesian" rule of thumb, for example, such capital linkages are shown to have negative effects on the time path of output in steady state.

- Second, what is the likely magnitude of any resulting distortions? Although difficult to assess, and ultimately an empirical question, no previous analysis has sought to rigorously appraise the possible size of this potential macro-energy effect. Drawing on a detailed analysis of the available literature, I show that such direct capital channels have non trivial macroeconomic effects, potentially resulting in a fall in output growth, for example, on the order of 0.05 percent for the Keynesian model under plausible parameter values.

- Third, what are the implications for corrective policy? Are any resulting distortions

[18] A handful of studies postulate environmental spillovers affecting capital durability within "AK" production frameworks, effectively simulating standard productivity effects: see, for example, Bretschger and Valente (2011), model 1, Bretschger and Suphaphiphat (2013), and Soretz (2007)).

influenced by the existence and design of wider fiscal policies? The implications of direct effects on physical capital, and the potential for wider fiscal interactions, have not previously been analysed. I show that spillovers affecting capital durability warrant a less steeply declining corrective tax path; and that distortions are substantially exacerbated by the presence of an income tax, but are unaffected by public financing requirements if net investment is exempted from the tax base and revenues are returned "lump sum".

Chapter 4 focuses on the external effects of resource exploitation on demographics. Energy combustion is a major source of air pollutants which are strongly linked to human mortality rates in both the epidemiological and social scientific literature: a recent major study, for example, attributes around 7 percent of global disease to ambient air pollution, around 80 percent of which may be due to energy combustion (Global Energy Assessment (GEA) (2012), Lim et al. (2013)).

Links between the climate externality and mortality rates have also been established with some confidence: more frequent and intense heat waves due to GHG emissions, for example, are expected to increase mortality rates: extreme temperatures caused as many as 70,000 deaths across 16 European countries in 2003 (Robine et al. (2007)). Despite this, growth models featuring exhaustible resources have thus far tended to assume population growth to be exogenous.[19]

Notable exceptions in this context include studies into the relationship between resource scarcity, demographics and technological development (Peretto and Valente (2015), Schäfer (2014a)).[20] In the environmental economics literature, Mariani et al. (2010), Jouvet et al.

[19] Endogenous growth theorists study links between growth and human fertility in models without natural resources (Barro and Becker (1989), Becker, Murphy, and Tamura (1990), Erlich and Lui (1991)).

[20] Peretto and Valente (2015) analyse an infinite horizon Schumpeterian model, in which households have preferences over the number of offspring and finite resources enter into the production process. Their essential insight – that the coexistence

(2010), and Schäfer (2014b) analyse the relationship between pollution, human longevity and economic growth (or health policy).

In contrast, this chapter focuses on the macroeconomic and policy implications of mortality effects (including interactions with wider production externalities), and, in particular, on the role of preferences over the aggregation of welfare across households for these insights. Specifically, it seeks to cast light on the following questions:

- First, what are the implications of potential interactions between capital market and demographic spillovers for economic growth and tax policy? Although Fankhauser and Tol (2005) emphasise their potential importance, these have not previously been studied in an exhaustible resource setting. I show that spillovers affecting mortality have countervailing macroeconomic effects to those arising from capital durability studied in the previous chapter. The former dominate in an optimal growth setting, but are parameter dependent in the Keynesian model.

- Second, how are the macroeconomic and policy implications of demographic spillovers influenced by choices affecting the aggregation of welfare? This question has not previously been considered (see Tol (2009) for a passing reference). I show that if the social planner places positive weight on aggregate (rather than average) felicity levels, mortality spillovers potentially imply policy prescriptions which diverge from the basic downward sloping paths identified in the resource tax literature.

- Third, what are the implications of finite planning horizons for the macroeconomic influence of mortality spillovers? In the first study, to my knowledge, to analyse such

of a stable steady state rate of growth and an asymptotically declining demographic expansion depends on the relationship between capital and resources in the production function – extends Dasgupta and Heal (1974). Schäfer (2014a) highlights the potential for education technologies to improve resource sustainability within a finite horizon model featuring induced technological change and exhaustible resource inputs to the intermediates sector.

effects within an overlapping generations (OLG) model with an exhaustible resource input, an exogenous mortality hazard is shown to unambiguously increase steady state interest and depletion rates, but in an endogenous setting, the effect in capital markets is dependent on interactions between the resulting incentives on the young to save and the Hotelling condition.[21]

Chapter 5 focusses on potential spillovers from energy use to consumption, and their implications for policy and economic development. The contribution of the energy sector to climate change has been widely researched. However, evidence is emerging on counter directional effects: in particular, residential heating and cooling demand is likely to be sensitive to changing climate conditions (see Huang and Scott (2007) for a discussion). In this context, the chapter considers the following question:

- What are the implications of spillovers between climate change and household energy usage for economic growth and tax policy in the United Kingdom (UK)? I show that a potential spillover affecting the division of oil resources from consumption to production has positive implications for output growth and depletion levels due to the faster accumulation of productive capital, provided inter-temporal substitution is sufficiently inelastic. I also characterise previously unexplored implications for differential taxation of resources across usages.

Extending the theme on the importance of preference forms for the transmission of environment-

[21] Kemp and Long (1979) first explored the role of exhaustible resources for inter generational savings, but assumed these to be inessential inputs to production. Agnani et al. (2005), Babu et al. (1997), Howarth (1991), John and Peccecchino (1994), John et al. (1995) assume exogenous survival dynamics within models in which exhaustible resources are required for output. Jouvet et al. (2010) and Mariani et al. (2010) explore the influence of environmental spillovers on longevity and growth, but do not consider natural resources or related production externalities.

economy spillovers and design of appropriate policies, the second part of the chapter analyses the the implications of externalities from fossil fuel usage in the presence of consumption habits. Despite the growing popularity of non separable time preferences within mainstream macroeconomics (Campbell and Cochrane (1999), Fuhrer (2000), Smets and Wouters (2007)), the assumption of time separability has been almost universally maintained in resource economics.

Zhang (2013) studies the influence of internal habits affecting consumption and renewable resource utilitisation. He finds that habits influence the speed of economic adjustment, but not the steady state. By contrast, Schäfer and Valente (2011) analyse consumption habits and bequests within an OLG model featuring exhaustible resources, highlighting the potential for these to generate multiple steady states (see also Schäfer (2014a) for a study of consumption habits, growth and fertility). Against this research context, this chapter considers the following question:

- What are the economic and policy implications of a failure of the time inseparability assumption for productive externalities from exhaustible resource utilization? I show that introducing an external habit of the form adopted by Campbell and Cochrane (1999) causes steady state depletion and interest rates to rise provided the climate change externality is not too large. Consumption externalities are also shown to interact with spillovers to capital durability discussed previously, influencing the appropriate tax policy response.

The aforementioned chapters analyse macroeconomic and policy issues associated with resource exploitation within a highly aggregated framework, featuring a single representative agent. Such approaches are helpful in framing this important global problem.

It is important to recognize, however, that country level policy choices, in particular by the major emitters, will be critical to curbing the costs and risks arising from climate change. In this context, concern for the costs of policies at the national (and potentially even sub-national) level are likely to be key to tax design and implementation choices.

This raises issues surrounding heterogeneity in the burden of climate and energy related policy costs, since taxes on fossil fuels – likely to be essential to curbing utilisation and promoting the developing of substitute technologies – may disproportionately affect certain groups (low income households may be particularly reliant on such goods, for example).

Detailed household level analysis is thus required to assess the economic and welfare costs of more rational taxation of energy goods, and to inform policy makers on appropriate expenditure policy adjustments in order to avoid the most series inequities. However, available evidence on detailed distributional aspects of energy tax reforms in the UK are surprisingly limited (Crawford et al. (2011, 1993), Johnson et al. (1990), and Symons et al. (1994)).

Chapter 6 thus departs from dynamic considerations in tax design, formed over a single representative agent within a general equilibrium framework, to focus, instead, on better understanding the economic and welfare consequences of indirect energy tax reforms in the UK, within a static and partial equilibrium framework featuring heterogeneous agents. Central to the enquiry in this chapter are the following questions:

- What are the likely environmental and revenue effects of imposing carbon taxes on domestic fuels and standardizing their value added tax (VAT) treatment in the UK?
- What are the welfare consequences of such reforms, considering potentially divergent behavioural responses across socioeconomic groups?
- How are these costs influenced by aggregation choices within the social welfare function (SWF)?
- How is the distribution of costs affected by allocation choices over revenues, including adjustments to social security benefits?

Two important features of the analysis presented below distinguish it from the bulk of existing research in this area. First, I model the behavioural responses of UK households to changes in (relative) prices and budgets. Second, I analyse the effects of indirect tax reforms capturing important substitution effects between a broad set of non durable consumption goods. These features are important to robust assessments of the economic and welfare effects of potentially non marginal policy reforms (Banks et al. (1996)).

This chapter contributes to this existing stock of research on the economic and behavioural effects of carbon and VAT reforms using comparable framework in a number of key regards:

- First, it is the only comprehensive behavioural study of carbon taxes to have been conducted since the liberalisation of electricity and natural gas markets, and to analyse tax scenarios which are consistent with current stated government policy guidelines.
- Second, it provides the first money metric estimate of the welfare costs of carbon tax incidence in the UK, and to analyse the implications of different approaches to aggregation within the SWF.
- Third, it is the first analysis of potential interactions between VAT and carbon tax reforms.

In terms of empirical findings, demographic variables are shown to influence consumption substantially. Budget shares to electricity and gas, for example, increase with the age of the household head, while that of gasoline displays the opposite demographic trend. There is also some evidence for declining expenditure shares in natural gas and gasoline from the mid 1990s and early 2000s respectively.

Budget elasticities vary by household for all commodities (emphasising the value of highly disaggregated analysis), and are particularly widely dispersed for electricity (which is an inferior good for more than 25 percent of households in the sample). Among the fuels, natural gas is on average the most price inelastic, with behavioural responses diminishing at higher expenditure levels, particularly for petrol.

Carbon taxes have large predicted effects on fossil fuel demand, reducing aggregate natural gas and gasoline demand by 7-21 percent and 1-4 percent respectively across scenarios. Electricity demand rises by 1-3 percent in the case of the carbon tax scenarios (while VAT reform alone has a downward bearing across all fuels).

However, these aggregate effects belie significant heterogeneity in behaviours across socioeconomic groups: in the case of a carbon tax, for example, the poorest households reduce gas consumption by 5-6 times more than the richest families when expressed in proportionate terms.

Unifying VAT treatment at the standard rate increases sample revenues by around 18 percent, equivalent to additional potential revenue of around £22 billion. The revenue opportunities from carbon taxes are also shown to be quite substantial, at least in the short term: a levy of £50 tCO2, for example, is projected to increase tax revenues £10 billion.

The welfare costs of energy tax reform are found to be material, particularly for scenarios involving both VAT and carbon tax reform, and in the cases of a SWF which are either weighted by family size (highlighting the practical importance of aggregation issues discussed previously), or feature a low degree of inequality aversion.

The detailed behavioural framework adopted has an important bearing on the magnitude of assessed welfare costs, which are generally on the order of 4-18 percent lower compared with estimates based on analysis in which demand is invariant to prices and incomes.

Expenditure measures are shown have strong potential to mitigate these costs. However, these opportunities differ according to both the allocation mechanism adopted, but also, importantly, the form of the SWF (the scope for aggregate welfare gains being generally greater in the weighted utilitarian case).

3 LEAVING LAS VEGAS? CLIMATE CHANGE AND CAPITAL DURABILITY

3.1 Introduction

Stern (2013) emphasises the need to broaden the set of environment-economy interactions analysed, to include the impact of climate change on capital formation, in an effort to improve policy guidance on the desirable extent of greenhouse gas emission reductions. In this context, this chapter analyses key theoretical issues affecting the macroeconomy and tax policy in the presence of linkages between fossil fuel combustion and capital durability due to climate change.

It is intuitive that existing weather conditions affect the operating life of physical capital, including buildings, transport and energy infrastructure. Heat and cold related stresses as well as rainfall degrade road and railway networks (Chinowsky et al. (2015), Jollands et al. (2007), and Nemry and Demirel (2012)). Nemry and Demirel (2012), for example, estimate that 30-50 percent of the cost of maintaining such infrastructures in the European Union (EU) are weather related.

Buildings also degrade more rapidly in the presence of adverse weather conditions. Increased upkeep costs, for example are a familiar pattern for homeowners in temperate zones in winter. Such costs rise markedly following extreme weather events, particularly floods and storms: average annual insured losses from such events between 1990-2010, for example, are estimated to be on the order of $(2008)35 billion (Barthel and Neumeyer (2012)).[22]

However, the assertion here is that weather related capital losses are likely to be af-

[22] However, such statistics are likely to represent only a small fraction of the physical effects due to weak diffusion of insurance services in developing countries, commonly just a few percent of total asset values (Mills (2005)).

fected – generally (but not universally across all asset types) increased – by future climate change related to fossil fuel use. In this context, available analyses by engineers, climate scientists and sector specialists predict that coastal flooding, more powerful wind storms, and subsidence due to more intense rainfall or melting permafrost is likely to damage buildings and infrastructure (Field at al. (2014)).

It is also possible, for example, that drought may even render capital obsolete in some regions over the longer term: one high profile example is the city of Las Vegas which depends on the Colorado river for virtually all its water (and where opportunities to increase supply appear limited). It thus appears conceivable that decreased runoff rates in the Colorado river basin of up to 20 percent predicted by mid Century may threaten the long term viability of sections of the municipality (Miller et al. (2011)).

Analysis of direct linkages between climate change and physical capital is now the subject of emerging research: Moore and Diaz (2015), for example, recently studied the sensitivity of growth pathways to these effects using an IAM featuring capital and labour inputs to production (see also Fankhauser and Tol (2005)).

However, these studies ignore potential interactions with the exhaustible character of fossil fuel inputs: in particular, more rapid depreciation influences the Hotelling portfolio condition. To the best of my knowledge, only Bretschger and Valente (2011) have studied this linkage in a resource based economy. The authors find that spillovers affecting capital durability influence the level of output, but not its growth rate.[23]

This chapter offers new theoretical insights into the relationship between fossil fuel use, the operating life of physical capital, and the time path of resource depletion and output, focussing on the following hitherto unanswered questions: First, how does savings behaviour influence the macroeconomic and policy implications of more rapid environmen-

[23] A handful of studies postulate environmental spillovers affecting capital durability within "AK" production frameworks, effectively simulating standard productivity effects: see, for example, Bretschger and Valente (2011), model 1, Bretschger and Suphaphiphat (2013), Soretz (2007)).

tally related capital depreciation? Second, what is the likely magnitude of any resulting distortions? Third, what are the implications for corrective tax policy? Fourth, are any resulting distortions sensitive to wider fiscal policy design? Finally, to what extent are these findings sensitive to assumptions over the endogeneity of technological development?

It demonstrates that the main finding of Bretschger and Valente (2011), that spillovers affecting capital durability cause level but not growth effects on the time path of output and consumption, rests critically on the assumption that savings adjusts optimally to market incentives: if behaviour is “Keynesian”, for example, capital linkages have negative effects on growth in steady state.[24]

Turning to the second question, no previous study has sought to quantify these effects in the context of a resource based economy, or to undertake a detailed analytic exercise on the possible magnitude of endogenous depreciation rates. Analysis of the available literature indicates that overall depreciation might increase, proportionately, by perhaps 1-10 percent in the long run (within say 20-50 years). This is shown to have non trivial macroeconomic effects: potentially resulting in a fall in output growth, for example, on the order of 0.05 percent for the Keynesian model under plausible parameter values.

The third and fourth questions also remain substantively open. Corrective taxes are shown to fall less rapidly in the presence of a capital spillover. Moreover, the magnitude of any resulting distortions is substantially influenced by the tax treatment of investment: for example, under central assumptions, the output-capital ratio is estimated to increase by an additional 12 percent in the presence of a modest income tax of 20 percent if net investment is exempted from the tax base. Finally, this chapter finds that the key results

[24] While optimal savings choices formed under rational expectations remain a powerful benchmark, both a macro economic and an emerging behaviourist literature – which emphasises the computational complexity implied by dynamic optimizing behaviour – suggests that households may commonly apply simple heuristic approaches in practice: see, for example, Campbell and Mankiw (1989, 1991), Carroll and Summers (1991), Carbone and Hey (1997), Hey and Dardanoni (1988), Thaler (1994), and Winter et al. (2012).

outlined above hold in the presence of fully endogenous technological development.

The structure of the remaining chapter is as follows: Section 3.2 outlines a variant of the basic model due to Sinclair (1992). Section 3.3 extends it to include spillovers from resource depletion to capital depreciation, and analyses the implications for the macroeconomy and policy. Section 3.4 analyses these issues within an optimal growth framework (drawing on Sinclair (1994)), together with the importance of wider policy choices over the taxation of income and expenditure for the size of any resulting distortion. Section 3.5 concludes.

3.2 Fixed savings model with exogenous depreciation

This section adapts a simple growth model due to Sinclair (1992) with exogenous depreciation and an environmental spillover affecting productivity. This serves to both introduce the structure of the basic model, together with the underlying assumptions, and sharpen the subsequent analytic focus on the influence of endogenous depreciation under different assumptions, regarding savings behaviour and technological development.

Central to both Sinclair's (1992, 1994) papers are the assumptions that natural resource stocks are finite, such that the associated price dynamics obey the following "Hotelling rule" (Hotelling (1931)):[25]

[25] The theory is intellectually compelling as a long run description of fossil fuel markets, given their extremely slow replenishment rates. However, empirical evidence for the Hotelling rule is generally inconclusive, being impinged, for example, by a lack of detailed data (particularly relating to marginal production costs) and the challenge of adapting econometric tests to specific market conditions. Krautkraemer (1998) and Slade and Thille (2009) provide excellent surveys of the literature.

A variety of alternative models of price determination have been developed, which also raise theoretical and empirical issues. Cremer and Salehi-Isfahani (1989), for example, argue that domestic investment priorities by resource producers lead to a backward bending supply curve and thus periods of high and low prices. However, this theory rests on unrealistic capital account assumptions and finds mixed empirical support (Dahl and Yücel (1991), Griffin (1985), Salehi-Isfahani (1987)).

Others researchers emphasise the role of anti-competitive behaviour by the Organization of Petroleum Exporting Countries (OPEC): (see Adelman (1982), Gilbert (1978), Salant (1976) for influential early contributions). However, evidence of material price effects from OPEC cooperation is inconclusive, with the exception of a period around the 1980s (Alhaji and Huettner (2000), Almoguera et al. (2011), Dahl and Yücel (1991), Griffin (1985), Griffin and Neilson (1994), Gülen (1996),

$$\hat{P}(t) = r(t) - j \tag{3.1}$$

where $P(.)$ and $r(.)$ represent, respectively, the oil price and (gross of depreciation) rental payment at time t ($\hat{}$ denotes a growth rate); and $j \in (0, 1)$ is the proportion of the capital stock which depreciates in each period (and is assumed time invariant). Assumptions of perfect foresight and zero extraction costs underpin the condition in this form.

Resource stocks evolve according to the following transition equation:

$$E(t) = -\dot{S}(t) = x(t)S(t) \tag{3.2}$$

where $E(.)$, $x(.)$ and $S(.)$ are total inputs to production, the proportion of the stock depleted, and the aggregate stock remaining in the ground at time t respectively ($\dot{}$ signifies the time derivative).

Production, $Q(.)$, is Cobb-Douglas in form, bearing constant returns to scale, such that:

$$Q(t) = T(t)K(t)^{a_1}N(t)^{a_2}E(t)^{1-a_1-a_2} \tag{3.3}$$

where, $T(.)$ is a technology index, and $K(.)$ and $N(.)$ are stocks of capital and labour respectively (the later is assumed to grow at a constant exogenous rate n).[26]

Spilimbergo (2001)).

Modern scholarship has tended to employ structural, rather than reduced form, tests on energy market fundamentals, reflecting concerns over the endogeneity of oil prices to macroeconomic activity. Barsky and Kilian (2002) and Kilian (2009), for example, emphasise the importance of aggregate demand shocks to energy price dynamics. Recent concerns about possible distortions to oil prices arising from financial market activities have found limited support in the literature (Fattou et al. (2013), Killian and Lee (2014)).

[26] The Cobb-Douglas functional form is adopted due to its attractive limiting properties (and analytic tractability): specifically, that resources are an economic necessity (in the sense that absolute exhaustion leads to economic collapse), and physical capital returns fall as produced stocks accumulate relative to resource inputs (Dasgupta and Heal (1974)). A higher degree of substitutability between labour and physical capital likely contravenes laws of thermodynamics (Dasgupta and Heal (1979), p.211), and dismisses resource sustainability issues. However, some researchers argue that natural resources are so fundamental to production that the relationship with physical capital may be complementary (Georgescu-Roegen (1975)). Conclusive empirical evidence to support this point is scant (see Neumayer (2000) for a helpful survey). I thus cautiously

Output can either be consumed or added to the capital stock, with the proportion of output which is invested being determined here by an exogenous savings parameter, s. The equation of motion in capital, assuming (time invariant) depreciation is thus:

$$\dot{K}(t) = sQ(t) - jK(t) \tag{3.4}$$

Although lacking clear micro foundations, this Keynesian assumption may be a reasonable first approximation of the empirical relationship between savings and incomes (Campbell and Mankiw (1989, 1991), Carroll and Summers (1991)):[27] Campbell and Mankiw (1989, 1991), for example, estimate that the effect of predictable changes in aggregate income on total consumption in the US and other Organisation for Economic Cooperation and Development (OECD) countries are accounted for if a substantial proportion (between 1/3 and 1/2 half) of households observe decision rules of this kind. These rather crude papers loosely ascribe these effects to the presence of liquidity constrained consumers. A subsequent behaviourist literature emphasises constraints on rational decision making implied by rational expectations models, potentially leading householders to apply simplified rules of thumb, such as Keynesian fixed propensities, when forming savings choices (Carbone and Hey (1997), Hey and Dardanoni (1988), Thaler (1994), Winter et al. (2012)).

Factor inputs earn their marginal products, reflecting perfectly competitive markets. Gross of depreciation rental rates and oil prices are thus:

$$r(t) = a_1 \frac{Q(t)}{K(t)} \tag{3.5}$$

maintain the assumption of substitutability between capital and energy.

[27] Moreover, posited declines in savings rates in the US since the 1980s do not clearly hold if asset values are included in wealth calculations (see, for example, Juster et al. (2006)).

$$P(t) = (1 - a_1 - a_2)\,\frac{Q(t)}{E(t)} \tag{3.6}$$

Oil consumption is assumed to generate an environmental externality, m, which constrains productivity growth, h, as follows:

$$\hat{T}(t) = h - mx(t) \tag{3.7}$$

where $h \geq 0$, and $m > 0$.

Thus externalities from resource extraction are assumed to limit productivity growth.[28] Following Barbier (1999) and Sinclair (1992, 1994), the magnitude of these effects is calibrated as a proportion of extracted resources in any period.[29] This is designed to facilitate steady state analysis, and simplify calculations by limiting the number of state variables (compared to modelling externalities as a function of pollution stocks, for example).

However, this approach raises two important issues: first, the calibration of m is sensitive to S, and might reasonably be adjusted, for example, in the case of major resource discoveries or new extraction technologies. Second, depletion declines over time, yet a falling time path for m is inconsistent with steady state. This implies, perhaps not unreasonably in the context of climate change, for example, that the damage from a unit of oil

[28] Stern (2007), Nordhaus (2007, 2008), Tol (2002), Weitzman (2009), by contrast, model reductions in output levels as a convex function of temperatures. The empirical literature on this question remains inconclusive. Cross sectional studies have tended to find strong negative relationship between temperatures and per capita output levels (Dell, et al. (2009), Gallup et al. (1999), Masters and McMillan (2001), Sachs (2001, 2003)). However, these are susceptible to bias from omitted economic, social and institutional factors which may be potentially correlated with weather conditions (Acemoglu et al. (2002), Dell et al. (2009, 2014)). The most recent and advanced panel based studies appear to broadly support the formulation adopted here (Bansal and Ochoa (2011a, 2011b) and Dell et al. (2012)).

[29] Note that a wide variety of pollution sources have been modelled in the environment-growth literature, including output (e.g. Keeler et al. (1972), Van der Ploeg and Withagen (1991)), consumption (e.g. Heal (1982)), accumulated capital (e.g. Bretschger and Valente (2011), Stokey (1998)), and even economic depreciation (as in Mäler (1974)). The specification adopted here (appropriately) renders input substitution an important mitigation strategy (infeasible where pollution is a fixed coefficient of output, say).

rises over time (Sinclair (1990)).

In order to study the dynamic effects of taxation, $Z(t)$ denotes an ad valorem levy on $E(.)$ imposed at time t, with time derivative given by: $z(t) = \frac{\dot{Z}(t)}{1+Z(t)}$.

Lemma 3.1: A stable steady state in depletion and interest rates exists if $a_1 > s$***.***

Sketch proof. Steady state expressions for depletion and interest rates are given by (a derivation and formal analysis of stability properties are found at Appendix A):

$$x^* A = (h + a_2 n + j(1 - a_1))(a_1 - s) + zs(1 - a_1) \tag{3.8}$$

$$\frac{r^*}{a_1} A = (h + a_2 n + j(1 - a_1)) - z(1 + m - a_1 - a_2) \tag{3.9}$$

where $A = a_1(1 - a_1 - a_2) + a_2 s + m(a_1 - s)$*. By inspection,* $a_1 > s$*, is sufficient for* $A > 0$*. Figure 1 illustrates the saddle path stability of these points for the case of both a "strong" and a "moderate" climate externality.*[30] ■

This is a dynamic efficiency condition which is hereafter maintained.

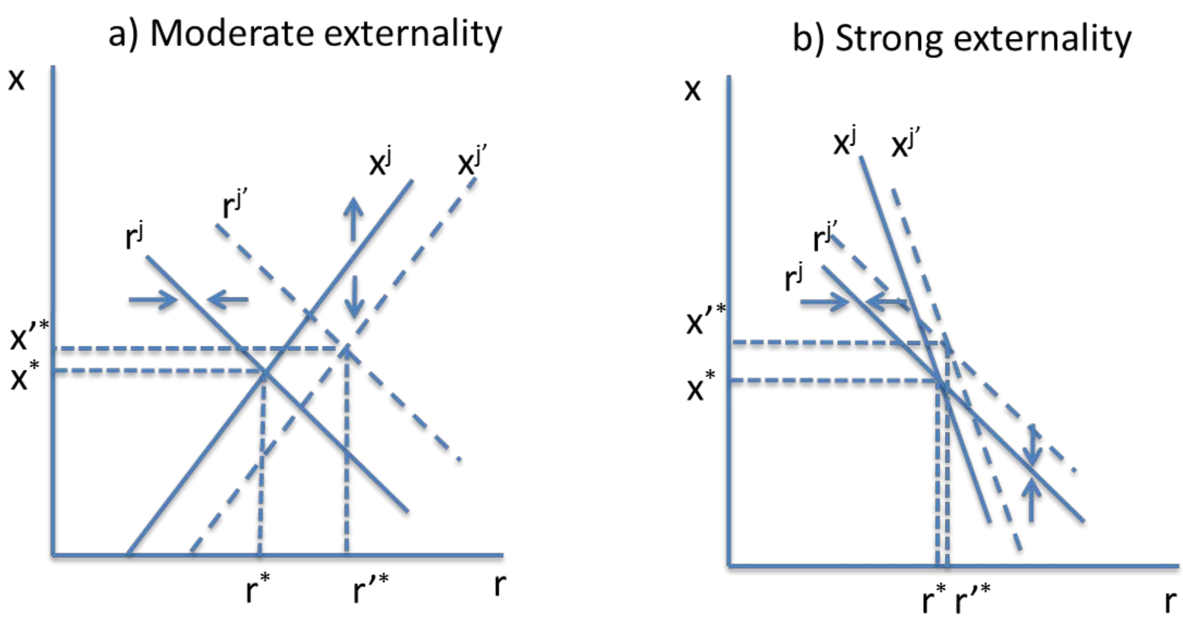
Lemma 3.2: The exogenous capital depreciation term, j***, unambiguously raises steady state depletion and interest rates.***

Sketch proof. By inspection of equations (3.8) and (3.9), $\frac{dx^*}{dj}, \frac{dr^*}{dj} > 0$. ■ This is intuitive: oil inputs to capital replacement raise depletion for any given stationary value of r; while greater capital scarcity drives up interest rates for any given value of x (shown in Figure 1).

Lemma 3.3: i) m ***unambiguously reduces*** x^* ***and, ii) a stationary tax,*** $z(t) = 0$***, is non distortionary.***

[30] The externality is defined as strong (moderate) if $m > (<) a_1 + a_2$. Sinclair (1992) shows that the global warming parameter counterbalances the "Hotelling" effect by which higher interest rates lead to a faster rate of exhaustion (dominating the overall effect in the strong case. However, available evidence suggests this is unlikely to hold (see, for example, Nordhaus (2007)), thus the focus here is principally on the "moderate" externality case, $m < a_1 + a_2$.

Figure 1
Interest and depletion rates with exogenous depreciation



This figure depicts the stationary interest rate and oil market loci (given by equations (A.1) and (A.2)) in x, r space (the arrows denote transitionary forces). Stationary depletion – which rises with r under the "moderate" externality (but is downward sloping in the "strong" case, due to resulting weaknesses in the macroeconomy) – shifts right for $j > 0$ (from x to x'): lower net of depreciation returns reduce stationary values of x for any given gross interest rate (by the Hotelling condition). In addition, j causes the stationary interest rate locus to shift rightwards (from r to r') given higher oil inputs to capital replacement. Steady state interest and depletion rates thus rise unambiguously (from x^*, r^* to x'^*, r'^*).

Sketch proof. By inspection of equation (3.8), $\frac{dx^*}{dm} < 0, \frac{dx^*}{dz} |_{z=0} = 0$. ■

Climate change hampers productivity and promotes resource sustainability. A stationary tax simply captures a proportion of the rents earned by resource owners. However, a rising ad valorem charge (i.e. $z(t) > 0$) accelerates depletion and squeezes output due to lower productivity growth and scarcer resource inputs (this is a key insight of Sinclair (1992)).

Lemma 3.4: Steady state growth increases with s ***and is negatively associated with*** m ***and*** j***.***

Sketch proof. Steady state output growth is given by:[31]

$$A\hat{Q}^* = s\left(\left(h + a_2 n + j\left(1 - a_1\right)\right) - z\left(1 + m - a_1 - a_2\right)\right) - Aj \tag{3.10}$$

$\frac{dQ^*}{ds} > 0, \frac{dQ^*}{dm}, \frac{dQ^*}{dj} < 0$. ■

As is standard in neoclassical resource growth models, productivity growth critically determines output growth along the optimal pathway (Stiglitz (1974)). In this model, a rising tax lowers steady state growth. This also holds for an increase in j which slows capital accumulation. In contrast to the standard Solow model, the savings rate is positively associated with long run growth since higher savings imply slower resource depletion through the Hotelling condition.

3.3 Fixed savings model with endogenous depreciation

This section analyses the potential effects of accelerated depreciation due to climate change. This reflects concerns among engineers, climate scientists and sector specialists, in particular, over possible flooding of coastal and riverine assets from higher sea levels, instability of physical structures built on permafrost, and damage to infrastructure and buildings from heat, precipitation and wind related stresses (or perhaps early obsolesence

[31] This is derived by substituting (3.4) and (3.5) into (3.9).

of capital due to water scarcity).

Let depreciation now depend (for simplicity, linearly) on the proportion of the total oil stock extracted in period t. The equation of motion for capital thus becomes:

$$\dot{K}(t) = sQ(t) - (j + \theta x(t)) K(t) \tag{3.11}$$

where $\theta x(t)$ represents the total proportion of capital which erodes due to spillovers from fossil fuel combustion in period t.

The Hotelling portfolio condition for the evolution of oil input prices is now given by:

$$\hat{P}(t) = r(t) - j - \theta x(t) \tag{3.12}$$

The externality affecting capital durability thus slows long run resource price growth.

Lemma 3.5: Under maintained assumptions, a steady state i) exists, and, ii) is saddle path stable, if: $m > \theta (1 - a_1)$

Sketch proof. Steady state expressions for depletion and interest rates are given by (see Appendix A for details):

$$x^* B = (h + a_2 n + j (1 - a_1)) (a_1 - s) + zs (1 - a_1) \tag{3.13}$$

$$\frac{r^*}{a_1} B = (h + a_2 n + j (1 - a_1)) - z (1 + m - (1 - a_1) \theta - a_1 - a_2) \tag{3.14}$$

where $B = a_1 (1 - a_1 - a_2) + a_2 s + (m - \theta (1 - a_1)) (a_1 - s)$.

i) By inspection, $B > 0$ *under the stated condition; ii) Figure 2 panels a) and b) illustrate the resulting stability of the steady state.*[32] ■

[32] $m > \theta (1 - a_1)$ is also necessary for ii). This is evident from inspection of Figure 2 panel c), which depicts the failure of this ordering. The necessary condition for i) is given by: $\theta (1 - a_1) - m < \frac{a_1(1-a_1-a_2)+a_2 s}{(a_1 - s)}$. This implies a less restrictive upper bound on the magnitude of θ, but nonetheless one which seems highly unlikely to bind. To see this intuitively, consider the most constraining case where m is zero (i.e. environmental spillovers act exclusively through the capital channel). Assuming $a_1 = 0.35$, $a_2 = 0.6$, $s = 0.2$, $x = 0.03$ and total annual depreciation of 7 percent, equilibrium existence requires that the environmental spillover accounts for no greater than around 3/4 of all eroded capital. Drawing on a review of the available literature on potential climate change related capital losses in Appendix A this appears to be a plausible hypothesis.

The stability of the economic system depends on the magnitude of any spillover from resource usage to capital durability relative to that affecting productivity. If the stated condition fails, the additional capital scarcity due to θ is sufficient to overwhelm the downward pressures on marginal product imposed through m. This condition is hereafter assumed to be satisfied.

Proposition 3.1: Under maintained assumptions, steady state depletion and interest rates are reduced by climate change (absent corrective tax policy).

Sketch proof. By inspection of B. ■

Figure 2, panels a) and b) illustrate a fall in the stationary depletion and interest rates (from x^*, r^* to x'^*, r'^* respectively) arising from an increase in climate change damages (through both capital and productivity channels) for the cases where $m > \theta(1-a_1)$.

The overall influence of climate change on steady states in oil and capital markets depends on the relative magnitude of the two spillovers: lower net returns places downward pressure on depletion rates through the Hotelling condition. However, slower capital accumulation raises stationary interest rates, given the fixed proportion of output which is invested and the diminishing factor returns assumption.

That environmental factors influence growth and depletion rates where savings decisions are behavioural or Keynesian in character is an insight not previously found in the literature (in the most closely related papers, Bretschger and Valente (2011) adopt a rational expectations based model of savings, while Moore and Diaz (2015) and Fankhauser and Tol (2005) ignore Hotelling interactions).

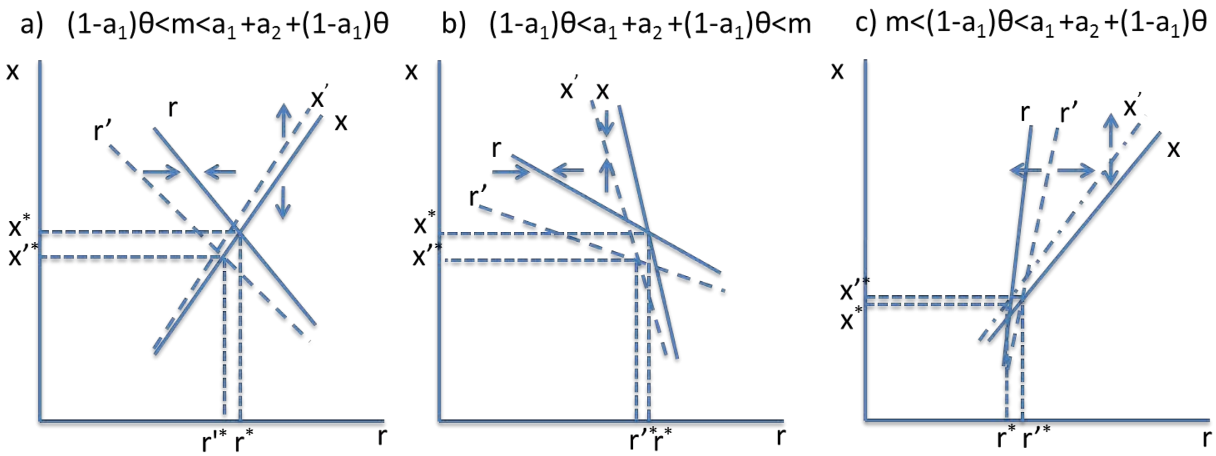
Corollary 3.1: Steady state growth rate is negatively associated with θ.

Sketch proof. The condition for steady state growth is given by:[33]

$$B\hat{Q}^* = (s - \theta(a_1 - s))(h + a_2 n + j(1-a_1)) + sz(1 + m - a_1 - a_2) - Bj \tag{3.15}$$

[33] This is derived by substituting from (3.11) and (3.13) into (3.14). Setting $\theta = 0$, this expression reduces to 3.10.

Figure 2
Interest and depletion rates with endogenous depreciation



This figure illustrates the effect of an increase in climate change – under different relative magnitudes of the productivity and capital depreciation spillovers – on the stationary capital and oil market loci (given by equations (A.3) and (A.4)) in x, r space (where $'$ denotes the influence of more powerful climate externalities). Panels a) and b) show the resulting fall in steady state depletion and interest rates (from x^*, r^* to x'^*, r'^* respectively) for the "strong" and "weak" externality cases (respectively) where $m > \theta(1 - a_1)$. Panel c) demonstrates the "weak" externality case in which the capital effect is large relative to the influence of climate change on productivity, i.e. $m < \theta(1 - a_1)$: here both the stationary interest rate (high depletion causing sufficient capital scarcity to bid up rental returns) and depletion loci are upward sloping, such that climate change increases steady state depletion and rental rates. However, this is a "knife edge" result since these exert horizontal and vertical forces of repulsion respectively (the arrows denoting transitionary forces).

By inspection, $\frac{d\hat{Q}^*}{d\theta} < 0$. ■

The destruction of physical capital implied by $\theta > 0$ has a negative effect on both the level and growth rate of output: since output growth is determined by the rate of capital accumulation, and thus the steady state interest rate.

The influence of the savings rate on steady state output growth is modified by an additional feedback in this model: higher savings lower the interest rate, resulting in more gradual depletion. However, a lower x now further influences the depletion locus through the Hotelling condition.[34]

Corollary 3.2: The corrective tax path is less negatively sloped than in the absence of a spillover affecting capital durability.

Sketch proof. Assuming that oil taxes are constant in the absence of climate change (i.e. $z = 0$ *if* $m = \theta = 0$*), it follows from (3.13) that* $x^* \mid_{z=m=\theta=0} = x^* \mid_{z=z^*(m,\theta>0)}$ *(i.e. the effects of the externality on steady state oil depletion are "corrected") under the following tax path:*[35]

$$z^* = -\frac{(m - \theta(1 - a_1))(a_1 - s)}{s(1 - a_1)} \frac{(h + a_2 n + j(1 - a_1))}{(a_1(1 - a_1 - a_2) + s a_2)} \tag{3.16}$$

Under maintained assumptions: $\frac{dz^*}{d\theta} > 0, z^* < 0$. ■

The capital spillover has a negative effect on the level and growth rate of output, which tempers the oil exhaustion problem, thereby limiting the required incentives for resource producers to defer production (which arise from a downward sloping tax path).

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[34] By inspection, $m > \theta(a_1 - s)$ is sufficient to sustain Sinclair's conclusion that policies to stimulate savings also serve to preserve finite natural resources.

[35] "Corrected" here implies returning the dynamic oil extraction pathway to that which would occur absent the climate change externality.

Discussion and numerical results

Applied analysis into the effects of climate change on capital durability, although still meagre, suggests that depreciation rates could commonly be raised by a substantial amount for a broad class of assets: Appendix A surveys the available literature on the potential extent of such losses, and interprets the relevant insights to parameterize the model using standard depreciation assumptions for the asset class in question.[36] Although naturally subject to considerable uncertainty, the results of this survey suggest that – taking account of the potential to limit capital losses through adaptive investments and behaviour – overall depreciation could increase, proportionately, by perhaps 1-10 percent in the long run (within say 20-50 years).

Table 1 outlines the results of the model under a range of possible parameter choices over m and θ. It assumes that the share of income to capital labour and oil are 0.34, 0.6 and 0.06 respectively. Values of the savings, depreciation, technology and population growth rates are set at 0.2, 0.08, 0.015 and 0.01 respectively. Under these assumptions, the results indicate that accelerated depreciation due to environmental degradation has potentially an important influence on steady state depletion, interest rates and output growth under reasonable parameters.

For instance, annual oil extraction is predicted to be 5.29 per cent in the absence of either productive or capital spillovers. This falls by around 5 percent in the event $m = 0.08$. However, roughly nine-tenths of this reduction is counteracted in the event that $\theta = 0.2$ (consistent with roughly 5 percent of total capital outflows due to environmental factors). Gross interest rates are predicted to be 0.8 percent lower than the baseline for $m = 0.08$ and $\theta = 0$, but just 0.1 percent lower if $\theta = 0.1$. Output growth of 2.58 percent is predicted in the absence of environmental effects, falling to around 2.05 percent in the

[36] Ideally, aggregate changes would be calculated by weighting these changes by the ratio of the value of asset class to the overall stock, a step which has not been attempted here.

event $m = 0.08$ and $\theta = 0$. A positive capital durability effect, $\theta = 0.1$, lowers output by 0.05 of a percentage point.

3.4 Optimal growth model with environment-capital spillovers

I now explore the implications of capital spillovers specified in equation (3.11) within an optimal growth framework (drawing on Sinclair (1994)).[37] The representative agent is assumed to maximise the sum of a discounted, additively time separable sequence of utility over consumption (a requirement which is relaxed in the next chapter), subject to a productive constraint which includes the resource-capital durability spillover (and initial conditions, K_0, S_0, N_0).

This problem is easily expressed by the following (present value) Hamiltonian function:

$$\underset{\{c(t),E(t)\}_{t=0}^{\infty}}{Max} V = \int_0^{\infty} (e^{-it}\frac{c(t)^{1-v}-1}{1-v}+$$
$$\lambda(t)\left(Q(.) - c(t)N(t) - (j+\theta x(t))\, K(t) - \dot{K}(t)\right))dt \tag{3.17}$$

where c is household consumption; v and i represent the individual preference parameters of the household over inter temporal substitution in consumption and impatience

[37] By contrast, environmental quality (or even the stock of natural resources) is sometimes assumed to enter the utility function directly, either as a stock (as in Keeler et al. (1972), Becker (1982), d'Arge and Kogiku (1973), Krautkraemer (1985), and Tahvonen and Kuuluvainen (1993)) or a flow variable (for example, Forster (1973), Gruver (1976), and Smulders and Gradus (1996)) or both (see, for example, Van der Ploeg and Withagen (1991), Bretschger and Valente (2011)). Of itself, the form of preferences has a limited bearing on research insights (Panayotou (2000), Smulders and Gradus (1996)). However, the implicit assumption of additive separability between consumption and environmental quality is less benign: Tahvonen and Kuuluvainen (1993), for example, demonstrate that a (weakly) negative relationship with environmental amenity values is important for the stability and uniqueness of a steady state (see also Heal (1982) and Stokey (1998)). This is an empirical question, for which no evidence - to the best of my knowledge - yet exists. More broadly, consumption is commonly inseparable from leisure in micro data (Browning and Meghir (1991)), but may be a more plausible assumption at a macroeconomic level (see, for example, Mankiw et al. (1985)).

Table 1
Steady state depletion, interest rates and output growth with capital spillovers

		θ				
		0	0.05	0.10	0.15	0.2
m	0	5.29	-	-	-	-
	0.08	5.02	5.14	5.26	-	-
	0.1	4.78	4.89	5.00	-	-
	0.15	4.56	4.66	4.76	4.86	4.97
	0.2	4.36	4.45	4.54	4.63	4.73

(a) Depletion, annual percentage of resource stocks

		θ				
		0	0.05	0.10	0.15	0.2
m	0	15.87	-	-	-	-
	0.08	15.07	15.42	15.78	-	-
	0.1	14.35	14.66	14.99	-	-
	0.15	13.69	13.97	14.27	14.58	14.91
	0.2	13.09	13.35	13.62	13.90	14.20

(b) Gross interest rates, annual percentage

		θ				
		0	0.05	0.10	0.15	0.2
m	0	2.58	-	-	-	-
	0.08	2.05	2.02	2.00	-	-
	0.1	1.56	1.53	1.49	-	-
	0.15	1.13	1.08	1.04	0.99	0.95
	0.2	0.73	0.68	0.63	0.57	0.52

(c) Output growth, annual percentage respectively; and $\lambda(.)$ is the co state variable. All other variables are as defined above.

Lemma 3.6: In an optimal growth framework, θ slows consumption growth, ceteris paribus.

Sketch proof. The Euler equation for consumption is given by (derived formally at Appendix A):

$$r(t) - i - n - j - \theta x(t) = v\hat{c}(t) \tag{3.18}$$

where $\frac{d\hat{c}}{d\theta} < 0$. ■

This interaction between consumption growth and the Hotelling condition, which differs from the model outlines above, rests critically on the assumption that savings behaviour is endogenous to (in this case lower) investment returns.

Proposition 3.2: Steady state depletion, growth and net returns are unaffected by the capital spillover.

Sketch proof. Steady state expressions are given by (see Appendix A for a derivation):

$$Cx^* = (v-1)\left(h - n\left(1 - a_1 - a_2\right)\right) + \left(1 - a_1\right)(i + z) \tag{3.19}$$

$$\begin{aligned}\left(r - j - \theta x^*\right) C = hv + n\left(a_2 + (v-1)\, m\right) - \\ z\left(v\left(1 - a_1 - a_2 + m\right)\right) + i\left(a_2 - m\right)\end{aligned} \tag{3.20}$$

$$\begin{aligned}a_1 Cc^*/k^* = (v - a_1)\left(h - n\left(1 - a_1 - a_2\right)\left(1 + (v-1)\left(1 - a_1\right)\theta\right) - \right. \\ \left.\left(z\left(1 + m - a_1 - a_2 - \left(1 - a_1\right)^2\theta\right) + i\left(1 - a_1\right)\right)\right) + (n + j)\left(1 - a_1\right) C\end{aligned} \tag{3.21}$$

$$g^* C = h - \left(1 - a_1 - a_2\right) n - \left(1 - a_1 - a_2 + m\right)(z + i) \tag{3.22}$$

where $C = v\left(1 - a_1 - a_2 + m\right) + a_2 - m$, *and* c/k *represents the ratio of consumption to capital.*

By inspection, $\frac{dx^*}{d\theta}$, $\frac{d(r^* - j - \theta x^*)}{d\theta}$, $\frac{dg^*}{d\theta} = 0$. ■

As in the case of the fixed savings model, the capital spillover causes the Hotelling line to tilt, such that depletion falls for any given stationary gross interest rate. However, adjustments in savings behaviour (through the output-capital ratio) imply higher gross interest rates for a given rate of depletion and output growth. These Ramsey and Hotelling effects perfectly offset, yielding higher gross interest rates but leaving net returns and growth unaffected (shown in Figure 3).

In terms of environment-economy interactions, resource depletion and growth depend (as in Sinclair (1994)) solely on m as the sign of $(1-v)$): if $v > (<) 1$, which implies a low (high) degree of inter-temporal substitutability, then the negative income effects from lower productivity dominate (are outweighed by) the positive substitution effects due to future consumption becoming more expensive relative to the present.

Appendix A reviews the empirical evidence on potential values of v – equal (under strict assumptions) to the inverse of the elasticity of inter-temporal substitution (EIS) – given its centrality to the model results.[38] It finds that appropriate values of the EIS in the context of aggregate macroeconomic study are markedly lower than 1, perhaps in the range 0.2-0.66 (implying v of 1.5-5).

Lemma 3.7: Stability of the steady state requires that: $\theta(1-a_1) < m$.

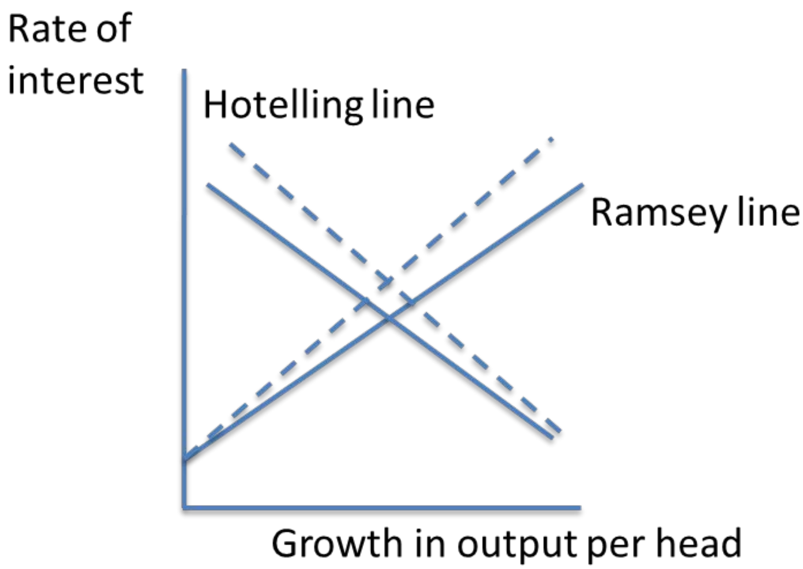
Sketch proof. See Appendix A for details. ■ The supporting argument closely relates to that of Lemma 3.5, ii).

Policy implications: commodity taxation

I now consider the implications of $\theta > 0$ for the optimal taxation of oil. This is undertaken in standard fashion, by comparing the solution to the decentralized problem

[38] The EIS has broad macroeconomic and policy implications, for example, as a determinant of: the magnitude of distortions from capital taxation (King and Rebelo (1990)), the long run importance of national debt burdens and unfunded social security commitments (Hall (1988)), and the effectiveness of monetary policy in smoothing consumption over the business cycle (see, for example, Woodford and Walsh (2005)).

Figure 3
Interest and growth rates with endogenous depreciation



This figure shows (in r, g space) the influence of higher resource related depreciation rates on the steady state time path of output in the optimal growth model with capital spillovers: depletion falls for any given stationary gross interest rate, due to lower net returns (causing the Hotelling line to pivot clockwise). This can be seen by comparing the dotted and solid Hotelling lines (which depict this relationship both with and without the capital spillover respectively). However, this also encourages reduced investment, yielding higher gross interest rates for a given rate of output growth (such that the Ramsey line shifts anti clockwise, from the solid to the dotted locus). These Ramsey and Hotelling effects perfectly offset, yielding higher gross interest rates but leaving net rates of return and growth unaffected.

with the choice of the social planner.

The representative agent behaves as if her oil extraction decisions does not affect the aggregate stock (denoted by $\bar{S}$) when maximising the following function:

$$\underset{\{c(t),E(t)\}_{t=0}^{\infty}}{Max} V = \int_0^{\infty} (e^{-it}\frac{c(t)^{1-v}-1}{1-v}+$$
$$\lambda(t)\left(Q(\bar{S}(t)) - c(t)N(t) - (j+\theta\bar{x}(t))\,K(t) - \dot{K}(t)\right))dt \tag{3.23}$$

where $\bar{x}(t) = \left(\frac{-\underset{o}{\Sigma}\dot{S}_o(t)}{\bar{S}(t)}\right)$.

It follows from the assumption that a large number of such households (indexed by o) exist, that individual resource extraction decisions have no influence on $\bar{x}$ in the limit. From the perspective of the representative agent, at least, individual oil market choices remain optimal (warranting no corrective tax).

Unlike the representative agent, however, the social planner is assumed to factor in the external benefits of leaving an additional unit of oil in the ground, $\tilde{s}$, both in terms of higher aggregate productivity and lower capital depreciation. As such, her constrained optimization problem can be represented as follows:

$$\underset{\{c(t),E(t)\}_{t=0}^{\infty}}{Max} V = \int_0^{\infty} (e^{-it}\frac{c(t)^{1-v}-1}{1-v}+$$
$$\lambda(t)\left(Q(\widetilde{s}(t))) - c(t)N(t) - (j+\theta\widetilde{x}(t))\,K(t) - \dot{K}(t)\right))dt \tag{3.24}$$

where $\tilde{x}(t) = \frac{-\dot{S}(t)}{\widetilde{s}(t)}$.

Corollary 3.3: The optimal tax at steady state falls more slowly for $\theta > 0$.

Sketch proof. The optimal tax is given by (a derivation is fond at Appendix A):

$$z^* = -\frac{x^*\left(m - \theta\left(1 - a_1\left(1 - \frac{c^*/k^*}{r^*}\right)\right)\right)}{(1-a_1-a_2)} \tag{3.25}$$

$\frac{dz^*}{d\theta} = x^*\left(\frac{\left(1-a_1\left(1-\frac{c^*/k^*}{r}\right)\right)}{(1-a_1-a_2)} + \frac{\frac{a_1}{r^*}\left(\frac{d[c^*/k^*]}{d\theta^*} - \frac{d[r^*]}{d\theta^*}\frac{1}{r^*}\right)}{(1-a_1-a_2)}\right) > 0$, *by envelope theorem; and* $z^* < 0$, *since* $m > \theta\left(1 - a_1\left(1 - \frac{c^*/k^*}{r^*}\right)\right) > \theta\left(1 - a_1\right)$.[39] ■

The additional tax term in θ serves to correct the distortion to output levels arising from less durable capital (which reduces incentives to defer current consumption).

Qualitatively, Sinclair's insight that optimal taxes should fall over time is preserved under the stability condition. However, in a transitionary environment from initially low consumption/ high capital ratios, for example, an upward tax prescription may nevertheless apply during a convergence period.

Policy implications: fiscal interactions

This section analyses interactions between spillovers affecting physical capital durability and the taxation of income and investment, demonstrating the important implications of choices over these tax bases for the magnitude of any resulting distortions (see Kaldor (1955) on the pioneering case for an expenditure tax base).

Income taxation

Let us start by introducing a constant tax, $Z_Q \in [0,1]$ on income (with no exemption for net investment). Assuming that household utility depends solely on decisions over private goods,[40] the objective function of the representative household is given by:

$$\underset{\{c(t),E(t)\}_{t=0}^{\infty}}{Max} V = \int_0^{\infty} (e^{-it}\frac{c(t)^{1-v}-1}{1-v} + \lambda(t)((1-Z_Q)\,Q(t) - \\ - c(t)N(t) - (j+\theta x(t))\,K(t) + y(t)N(t) - \dot{K}(t))dt \qquad (3.26)$$

[39] Note $\frac{c^*/k^*}{r^*} = \frac{c(t)N(t)}{a_1 Q(t)} < 1$.

[40] This could arise if public goods provision decision is pre optimised, or, alternatively, could reflect a highly pessimistic view of public services!

where $y(t)N(t)$ represents lump sum redistribution of tax revenues satisfying the following balanced budget condition: $y(t)N(t) = Z(t)E(t) + Z_Q Q(t)$.

Lemma 3.8: An income tax slows the rate of consumption growth, capital accumulation and oil price increases.

Sketch proof. See Appendix A for details. ■

Crucially, the income tax distorts the optimal capital investment programme due to lower net returns to investment, yielding slower consumption, and – by the Hotelling condition – oil price growth, *ceteris paribus.*

The income tax causes the Ramsey curve, together with the stationary interest rate and consumption-capital loci, to pivot anti-clockwise in $r, c/k$ space (due to lower net returns and the effects of scarcer capital). The influence of the income tax on the dynamic system of equations is discussed in Figure 4.

Proposition 3.3: An income tax leaves steady state depletion, output growth and net investment unaffected, but raises gross rental rates.

Sketch proof. This follows by inspection of the following steady state expressions for depletion, interest rates and output growth:

$$Cx^* = (v-1)(h - n(1-a_1-a_2)) + (1-a_1)(i+z) \tag{3.27}$$

$$\begin{aligned}(r(1-Z_Q) - j - \theta x^*) C = hv + n(a_2 + (v-1)m) - \\ z(v(1-a_1-a_2+m)) + i(a_2-m)\end{aligned} \tag{3.28}$$

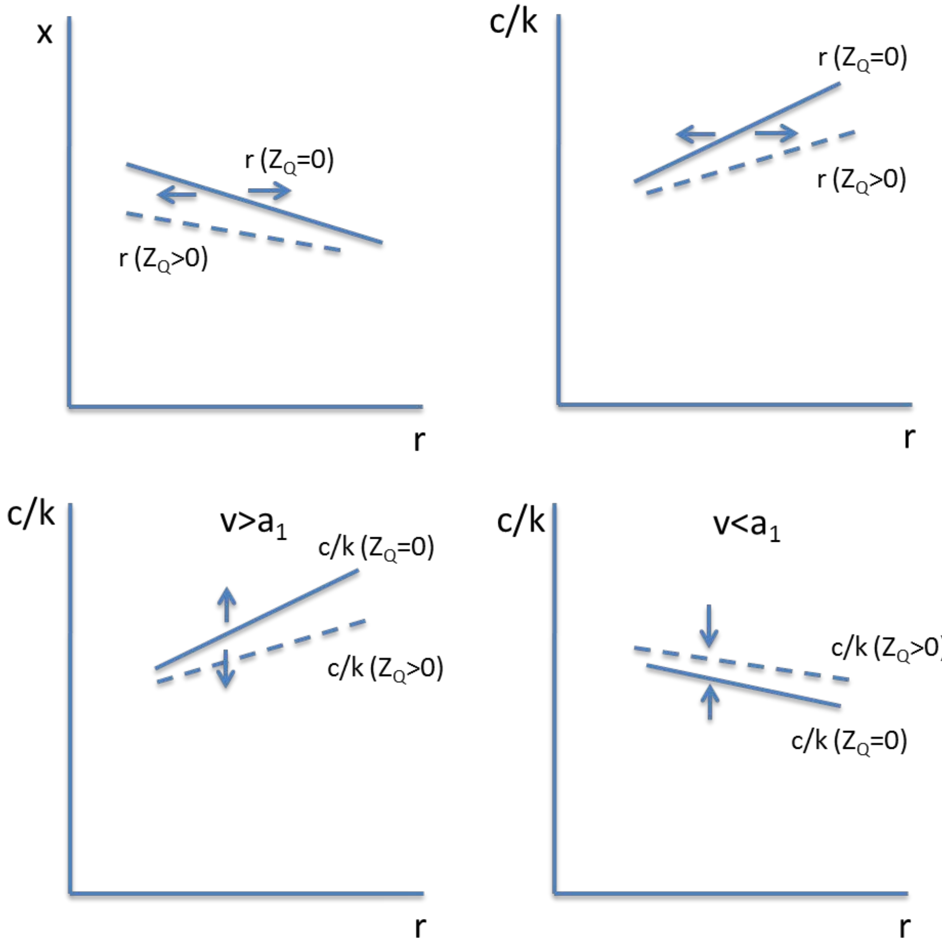
$$g^* C = h - (1-a_1-a_2)n - (1-a_1-a_2+m)(z+i) \tag{3.29}$$

$\frac{dr^*}{dZ_Q} > 0$. *See Appendix A for details.* ■

The adjustment in steady state gross interest rates implies an interaction with changes in consumption levels arising from θ (the possible magnitude of this effect, based on plausible assumptions for the model inputs, are discussed below).

"Brown" expenditure tax

Figure 4
Interest, depletion and consumption-capital loci under an income tax



This figure analyses the dynamics of the model featuring capital spillovers (given algebraically at Appendix A), focussing on the key influences of an income tax:* in particular, Z_Q distorts the transition equation in rental returns causing both a lower depletion rate (in x,r space) and consumption capital ratio (in c/k,r space) for a given stationary value of r. This can be seen by comparing the dotted with the solid lines (which represent the loci with and without the tax respectively) on the upper panels. As highlighted by Sinclair (1990), the slope of the stationary consumption capital ratio (in c/k,r space) depends on the relative concavity of output in capital relative to utility in consumption: in the more probable case of $v > a_1$, such that this locus is upward sloping, the income tax causes the stationary consumption capital ratio to fall for a given gross rate of return (while the opposite holds if inter temporal consumption is highly elastic, $v < a_1$). This is shown in the lower two panels.

*Note that the representation of both the stationary depletion rate and consumption capital ratio (in x,c/k space), for example, are not discussed - being unaffected by Z_Q (while analysis of stationary interest rates in x,r space is restricted to the "stable", "moderate" case in which $a_1 + a_2 + (1 - a_1)\,\theta > m > (1 - a_1)\,\theta$).

Let us now adjust the tax base to include income net of accumulated capital assets to avoid double taxation of investment, denoted by Z_{EXP}^{B} (where superscript B indicates the exemption of changes in resource stocks from the tax base). Maintaining the assumption on public expenditures as in the previous subsection, the Hamiltonian for the representative household is given by:

$$\underset{\{c(t),E(t)\}_{t=0}^{\infty}}{Max} V = \int_0^{\infty} (e^{-it}\frac{c(t)^{1-v}-1}{1-v} + \lambda(t)((1-Z_{EXP}^{B})\,(Q(t)-$$

$$(j+\theta x(t))\,K(t)) + (y(t)-c(t))\,N(t) - \dot{K}(t))dt \tag{3.30}$$

where the revised balanced budget condition is given by:

$y(t)N(t) = Z(t)E(t) + Z_{EXP}^{B}\left(Q(t) - (j+\theta\bar{x}(t))\,K(t) - \dot{K}(t)\right)$.

Lemma 3.9: Consumption growth, capital and oil price transition are invariant to a "brown" expenditure tax, Z_{EXP}^{B}.

Sketch proof. See Appendix A for details. ■

Avoiding double taxation of investment prevents a dynamic distortion in consumption, capital (and thus by the Hotelling condition, oil) markets. The influence of the "brown" expenditure tax on the dynamic system of equations is discussed in Figure 5.

Proposition 3.4: The steady state is unaffected by Z_{EXP}^{B} ***(i.e. there are no interactions with*** θ***).***

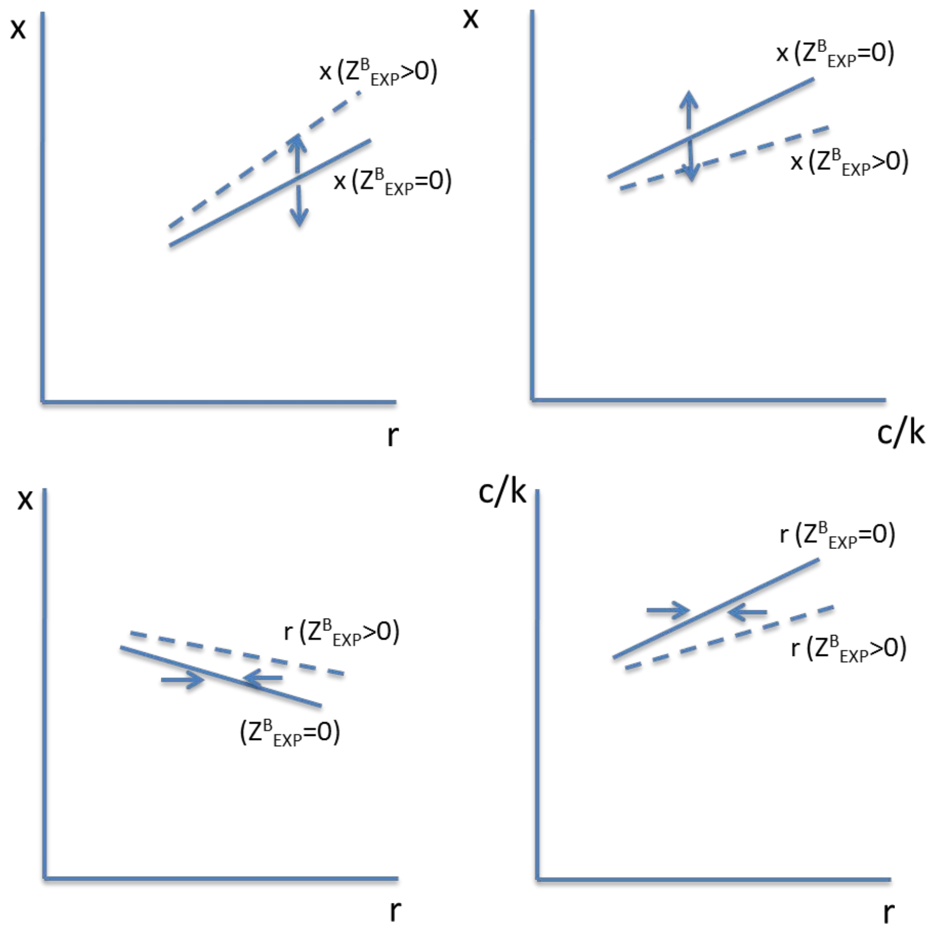
Sketch proof. See Appendix A. Steady state expressions are as given by equations (3.19)-(3.22).

Unlike the income tax case, both gross and net of taxation rates of return are unaffected by the expenditure based levy: the adjustment in the output-capital ratio arising from the external effect to capital durability does not interact with this tax design, since investment is undistorted.

"Green" expenditure tax

An extensive literature advocates comprehensive (including changes in natural resource

Figure 5
Interest, depletion and consumption-capital loci under an expenditure tax



This figure analyses the dynamics of the model featuring capital spillovers (given algebraically at Appendix A), focussing on the key influences of an expenditure tax:* in particular, Z^B_{EXP} now bears additionally on the stationary depletion causing an (anti) clockwise pivot in x, r $(x, c/k)$ space. This can be seen by comparing the dotted with the solid lines (which represent the stationary loci with and without a tax respectively) on the upper panels. The expenditure tax also causes the stationary interest rate locus to pivot (anti) clockwise pivot in $c/k, r$ (x, r) space. This is shown in the lower panels.

*The effect on the stationary consumption capital ratio is similar to the income tax (represented in $c/k, r$ space), although upward sloping under the revised condition$v\left(1 - Z^B_{EXP}\right) > a_1$; while in $x, c/k$ space, transition is qualitatively similar to the base model, but downward sloping if $v(1 - Z^B_{EXP}) > 1$. These instances are not depicted above. Analysis of stationary depletion focuses on the "stable", "moderate" externality case.

stocks) national income accounting (see, for example, Arrow et al. (2003), Dasgupta and Mäler (2000), Hamilton and Clemens (1999), Helm (2015) and World Bank (2011)).

Applying the insights from this literature to the design of a "green" expenditure tax, Z^G_{EXP}, in which the depletion of oil stocks is brought within the base base, is reflected by the following objective function of the householder:

$$\underset{\{c(t),E(t)\}_{t=0}^{\infty}}{Max} V = \int_0^{\infty} (e^{-it}\frac{c(t)^{1-v}-1}{1-v} + \lambda(t)(\left(1-Z^G_{EXP}\right)(Q(t)- \\ \left(j+\theta x(t)\right)K(t) - P(t)\dot{S}(t)) + \left(y(t)-c(t)\right)N(t) - \dot{K}(t))dt \tag{3.31}$$

where the balanced budget condition is given by:

$y(t)N(t) = Z(t)E(t) + Z^G_{EXP}\left(Q(t) - \left(j+\theta\bar{x}(t)\right)K(t) - P(t)\dot{S}(t) - \dot{K}(t)\right)$.

Lemma 3.10: The steady state is unaffected if changes in the value of resource stocks are included in the expenditure tax base, Z^B_{EXP}.

Sketch proof. Since Z^G_{EXP} is assumed constant, the rate of increase in prices due to resource scarcity is unaffected. ■

This follows the key finding of Stiglitz (1976). Importantly, though, the fiscal base is enhanced (since stocks erode), requiring a lower rate to realize a given level of revenue. Moreover, it is also worth noting that a shift from income to expenditure based taxation may raise serious welfare issues during transition, since elimination of the tax distortion affecting household capital investment programmes would likely result in the (potentially large scale) deferral of near term consumption.

Numerical results

The distortions to the output-capital ratio under the tax regimes analysed above are estimated in Table 2 below. The undistorted steady state output-capital ratio is predicted to be 16.7 percent, rising to 18.8 percent in the presence of an income tax. These ratios fall unambiguously with m and thus the productivity of capital, but rise with θ due to the adjustment process described above.

In the case of the expenditure tax, for example, the output-capital ratio falls to 15 percent for $m = 0.08$ and $\theta = 0$, but rises by 1.6 percent if $\theta = 0.1$. In the presence of an income tax, however, the distortion arising from the capital spillover is larger, rising by 1.95 percent to 18.6 percent for $m = 0.08$ and $\theta = 0.1$. Thus the fall in consumption levels due to the capital spillover is exacerbated by the income tax distortion.

Uncertainty and transitional dynamics

The composition of capital losses may be challenging to ascertain: while storm damages to buildings and infrastructure are perhaps readily assessable by households, firms and insurers, the environmental component of these costs is perhaps less transparent. In other cases, the influence of changing environmental conditions on capital durability is likely to become apparent only gradually: for example, it may take time to realise that water infrastructure has become outmoded in the event of changing patterns of rainfall (not least given the natural variability which exists in hydrological patterns).[41]

Lemma 3.11: The resolution of uncertainty surrounding the magnitude of θ ***impacts transitional dynamics if*** j ***is correctly evaluated.***

Sketch proof. Consider the example in which $\theta > (=)0$ *but agents falsely believe* $\tilde{\theta} = (>)0$*, where* ˜ *indicates the agent's perception. The first case would imply that economic depreciation is perceived to be bigger (smaller) than it really is:* $\tilde{j}(t) > (<)j$*. Learning the true composition of capital erosion would leave transition towards the steady state unaffected, since the portfolio condition is efficient:* $\tilde{j}(t) + \tilde{\theta}x(t) = j + \theta x(t)$*.*

However, in the second case, the agent believes capital is accumulating quicker (slower) than it really is: $\tilde{j}(t) + \tilde{\theta}x(t) < (>)j + \theta x(t)$*. This implies that oil prices rise too*

[41] I here assume, for simplicity, that all other economic parameters are fully observable.

quickly (slowly) in transition, as the net marginal product is over (under) estimated: $\hat{P}\left(\tilde{j},\tilde{\theta},t\right) > (<) \hat{P}\left(j,\theta,t\right)$ *On resolution of this uncertainty, oil prices to jump up (down) and then rise at a slower (faster) rate, with output effects being inversely related to prices.* ■

If aggregate depreciation is observed correctly but excessively attributed to standard "wear and tear", resolution of uncertainty does not influence the Hotelling portfolio condition. However, if learning about environmentally related depreciation is such that overall capital outflows are temporarily misperceived, an adjustment in price and output dynamics takes place through the arbitrage condition.

Extension I: non separability of capital and productivity

Environmental externalities such as climate change are widely expected to bear more heavily on less developed countries (that is, in a neoclassical sense, those with smaller capital stocks). This raises the possibility of further indirect linkages between environmental spillovers from fossil fuel use and technological progress. Reflecting this, consider the following representation of technology growth:

$$\hat{T}(t) = h - (m + \psi\theta)\, x(t) \tag{3.32}$$

where ψ determines the extent of any linkages between between capital decumulation, productivity growth and external effects due to environmental factors. The Hotelling condition is again given by equation (3.12).

Corollary 3.4: θ influences steady state depletion and growth rates if productivity depends on capital stocks as the sign of $1 - v$.

Sketch proof. This is evident from the following steady expressions (see Appendix A for details):

$$Dx^{*} = (v - 1)\left(h - n\left(1 - a_1 - a_2\right)\right) + \left(1 - a_1\right)(i + z) \tag{3.33}$$

$$(r - j - \theta x^*) D = hv + n(a_2 + (v-1)m) - z(v(1 - a_1 - a_2 + m)) + i(a_2 - m) \tag{3.34}$$

$$a_1 Dc^*/k^* = (v - a_1)(h - n(1 - a_1 - a_2)(1 + (v-1)(1 - a_1)\theta) - \left(z\left(1 + m - a_1 - a_2 - (1-a_1)^2\theta\right) + i(1 - a_1)\right)) + (n + j)(1 - a_1) D \tag{3.35}$$

$$g^* D = h - (1 - a_1 - a_2) n - (1 - a_1 - a_2 + m + \psi\theta)(z + i) \tag{3.36}$$

where $D = C + (v-1)\psi\theta$.

By inspection of (3.33) and (3.36), $\frac{dx^*}{d\psi} > 0$ *if and only if* $1 - v > 0$. ■

Clearly, the finding that – when savings decisions are endogenous to interest rates – capital spillovers generate level but not growth effects on output depends on the assumption that productivity growth is independent of capital accumulation (the effects of ψ being thus qualitatively similar to m).

Corollary 3.5: θ ***The optimal tax falls more rapidly than in the baseline model for*** $\psi, \theta > 0$***.***

Sketch proof. This is evident by inspection of the following expression for the optimal tax:

$$z^* = -\frac{x^*\left(m - \theta\left(1 - a_1\left(1 - \frac{c^*/k^*}{r^*}\right) - \psi\right)\right)}{(1 - a_1 - a_2)} \tag{3.37}$$

By inspection, $\frac{dz^*}{d\psi} > 0$ *if and only if* $\theta > 0$*. It follows from Corollary 3.3 that* $z^* < 0$*.* ■

Thus for $\psi, \theta > 0$, the optimal tax falls more rapidly than in the absence of the indirect capital spillover, due to the additional productivity drag arising from a unit of oil consumption. This tax policy prescription is not restricted to the steady state.

The finding modifies the quantitative conclusions of Sinclair (1994), but supports qualitatively the insight that the optimal tax be falling over time. It thus emphasises the importance of understanding the precise nature of interactions between the environment and the economy in seeking to determine policy.

Extension II: endogenous human capital formation

A further modelling priority emphasised by Stern (2013) concerns the potential importance of interactions between climate change and learning. This reflects emerging empirical evidence linking, for example, heat stresses with reduced productivity and cognitive development (Barbier (1999), Dunne et al. (2013), Hancock et al. (2007), Kjellstrom et al. (2009, 2013)).[42]

A number of previous studies have explored the effects of exhaustible resource degradation on productivity and learning using fully endogenous growth models (see, for example, Barbier (1999), Scholz and Ziemes (1999), Shou (2000, 2002)).

I here extend Lucas (1988) and Shou (2000) to analyse the case in which both the returns to training and the durability of capital are reduced by resource exploitation. Following Lucas, I incorporate human capital as a determinant of productivity, with knowledge growth a function of the , under the following production function:

$$Q(t) = AK(t)^{a_1} \left(u(t)N(t)l(t)\right)^{a_2} E(t)^{1-a_1-a_2} l_o(t)^{\gamma} \tag{3.38}$$

where $u(.)$ is the proportion of time spent working, $l(.)$ represents human capital, and $l_a(.) = \frac{\int^{\infty} oN(o)do}{\int^{\infty} N(o)do}$ denotes the average stock of human capital. $\gamma > 0$ reflects the assumed positive. All other terms are as previously defined.

Human capital is assumed to increase with investment in training, but is also affected by resource depletion as follows:

[42] In a recent contribution, however, Zivin et al. (2015) found temperature increases have adverse effects on cognitive development which are confined to mathematics over the short run (attributing the absence of a persistent influence to adaptive behaviour).

$$\hat{l}(t) = \Omega\left(1 - u(t)\right) - \iota x(t) \tag{3.39}$$

where $\iota > 0$.

Corollary 3.6: Under endogenous human capital formation, i) steady state depletion falls with θ ***in a Keynesian model, but is unaffected within a fully optimized framework; and, ii) the stability the steady state depends on the magnitude of capital relative to learning related spillovers:*** $\iota\left(a_2 + \gamma\right) > \left(1 - a_1\right)\theta$***.***

Sketch proof. See Appendix A for details. ■

Assumptions over savings choices continue to critically determine the macroeconomic influence of environmental spillovers affecting capital durability, while the stability of the steady state depends on the relative magnitude of capital and productivity related externalities. This finding closely parallels Propositions 3.1 and 3.2.

Corollary 3.7: With endogenous human capital formation, i) the oil tax is less downward sloping for $\theta > 0$***, and, ii) in the case of endogenous savings decisions, optimal policy also requires both a wage tax and a subsidy to human capital accumulation.***

Sketch proof. See Appendix A for details. ■

Optimal policy requires a corrective tax similar to that described in Lemma 3.7. However, the representative agent also fails to take account of the effect of her training decision on average skill levels. This is corrected through a wage tax and subsidy to human capital accumulation (this finding is similar to García-Castrillo and Sanso (2000), Gomes (2003) in models without resources and environmental spillovers).

3.5 Concluding remarks

Climate change is likely to increase the wear and tear to buildings and infrastructure. Stern (2013) highlights the need to consider such effects as part of efforts to improve guidance for policy makers on the appropriate extent of GHG emissions reductions.

However, analysis undertaken thus far has tended to ignore potential interactions with the exhaustible character of fossil fuel inputs (Fankhauser and Tol (2005), Moore and Diaz (2015)). This chapter extends Bretschger and Valente (2011) – the only study to date of this linkage in a resource based economy – by offering a number of new theoretical insights into the relationship between fossil fuel use, the operating life of physical capital, and the time path of output and resource depletion.

First, it shows the sensitivity of Bretschger and Valente's finding to assumptions over savings behaviour, and considers the implications of such spillovers for tax policy. Second, it is the first study which attempts to quantitatively assess the magnitude of these effects within a resource based model. Finally, it demonstrates the implications for optimal commodity taxation, and analyses the importance of wider fiscal choices by government to the magnitude of the resulting distortions

In the Keynesian model of Sinclair (1992), links between oil combustion and capital durability are found to negatively affect both the level and the growth rate of output in the steady state, thereby tempering the downward pressure on steady state depletion arising from climate change. Moreover, stability of the economic system requires a restriction on the magnitude of the capital spillover relative to the productivity effect. Numerical results indicate that accelerated depreciation due to environmental degradation could have macroeconomic significance under plausible parameter values.

Extending Sinclair (1994), however, I find that capital spillovers cause level effects: adjustments in savings behaviour (through the output-capital ratio) offset the Hotelling effects, leaving net returns and growth unaffected. In addition, the magnitude of such distortions are show to be sensitive to wider fiscal policy design, rising (potentially materially) in the presence of an income tax but invariant where net investment is exempted from the fiscal base (assuming that revenues are recycled in lump sum fashion).

The optimal tax also falls more slowly at steady state for $\theta > 0$ in order to correct the distortion to consumption levels: the capital spillover reduces the oil exhaustion problem, thereby limiting the required incentives for resource producers to defer production (which arise from a downward sloping tax path). Qualitatively, Sinclair's insight that optimal taxes should fall over time, however, is preserved under the required stability condition.

4 DEATH AND TAXES! MACROECONOMIC, FAMILY SIZE AND RESOURCE POLLUTION

4.1 Introduction

This chapter analyses the macroeconomic and policy implications of higher mortality rates associated with fossil fuel combustion, highlighting, in particular, new insights into the sensitivity of the resulting effects to preferences over the aggregation of welfare within a family or society.

The issue of air pollution – around 80 percent of which is estimated to be due to energy combustion (GEA (2012)) – came into ever sharper focus during 2015, for example, following the US corporate scandal involving excessive nitrous oxide emissions from diesel cars produced by Volkswagen (and the latest “red alerts” over smog levels in China, which prompted mass closure of schools and the imposition of vehicle restrictions).

In terms of managing the health consequences, a prime area of concern relates to the emission of particulate matters (PMs), which are known to cause cardio vascular and respiratory illnesses and cancers in the US (see Pope and Dockery (2006) for a review of the epidemiological literature).[43] This issue is still more prescient – though less widely studied – in developing countries where PM concentrations are commonly many fold higher than in advanced countries (particularly in urban areas).

[43] 2 major “longitudinal” studies in the US, in which participants were monitored for an extended period, are particularly noteworthy, due to the richness of the data (Dockery et al. (1993), Pope et al. (1995)). In regression analysis of mortality on a wide range of socioeconomic and health related variables, Dockery et al. (1993), for example, conclude that the positive relationship between air pollution and mortality rates is most severe for PMs with a diameter of less than 10 micrometres. Nevertheless, even such expansive studies may suffer from mismeasurement of accumulated exposure to air pollution over the life time of participants. Chay and Greenstone 2003(a,b) limit this concern by focusing on infant mortality: exploiting exogenous variation in pollution levels in the US arising from the 1981-82 recession, and regulations embodied in the 1970 Clean Air Act, they find that a one percent reduction in PM concentrations results in a 0.35-0.5 percent decline in infant mortality.

The World Bank (2007), for example, estimates that air pollution causes 500,000 deaths annually in China.[44] In a compelling study, Chen et al. (2013) find that differences in PM levels across sub regions of China account for a five and a half year difference in life expectancy.[45] Globally, ambient particle pollution from fossil fuel combustion accounts for approximately 3.2 million premature deaths, equivalent to about 3 per cent of the global burden of disease (Lim et al. (2013)).[46]

In addition, changing climatic conditions – due, in major part, to energy use – have also been linked to adverse health outcomes. More frequent and intense heat waves due to higher GHG concentrations have been shown to increase mortality rates in the US and Europe (Christidis et al. (2012), Honda et al. (2014), Robine et al. (2007), Whitman et al. (1997)): the extremely hot summer of 2003, for example may have caused as many as 70,000 deaths across 16 European countries.[47]

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[44] In a study of the health effects of PMs in Dehli, World Bank (1997) find that a 100- microgram (a roughly 30 percent average) increase in PMs raises death rates by around 2.3 percent.

[45] This result appears particularly robust given the large exogenous variation in air pollution which arises from differences in publicly funded heating services between adjacent administrative districts (restrictions on migration also limit concerns over the mismeasurement of pollution exposure).

[46] In contrast, links between pollution and human fecundity rates are less clearly established. Despite declining birth rates, particularly in advanced countries since the 1960s, an underlying trend has not been clearly established, given difficulties of controlling for wider factors including smoking, obesity, trends towards child rearing later in life and issues measuring female fecundity (Carlsen et al. (1992), Merzenich et al. (2010)). Robust links between pollution and male fertility, for example, are limited to high exposure occupational groups (such as those working closely with pesticides and certain chemicals), and a number of now largely banned substances such as Polychlorinated biphenyls. Among adult females clear-cut evidence is also generally lacking, but is strongest for heavy metal contaminants (Mendola et al. (2008), Hauser et al. (2008)). Barreca et al. (2015) find that temperature shocks influence historical birth rates in the US, potentially with persistent effects.

[47] Recent studies point to a similar effect in developing countries (Burgess et al. (2011), McMichael et al. (2008) and Pudpong and Hajat (2011)). However, their magnitude appears sensitive to possible harvesting effects (higher vulnerability due, for example, to mild preceding winters), and may be concentrated among non working age people (Deschênes and Moretti (2009), Fouillet et al. (2008), Rocklov et al. (2009), Stafoggia et al. (2009)). Questions also remain as to the extent to which technologies and improved health services can mitigate such risks: Barreca et al. (2013), for example, highlight

Climate change is also projected to alter the incidence of vector borne diseases such as malaria and dengue fever (IPCC (2014)). These effects are highly uncertain, but potentially large in magnitude: Hales et al. (2002), for example, estimate that an additional 1.5-2.5 billion people could be exposed to a greater than 50 per cent risk of dengue fever by the 2080's as a result of climate change and population growth (absent changes in health care).[48]

Recently, scholarship has increasing focussed on links between climate change, resource scarcity and shifting migration patterns (Carraro (2015), Ghimire et al. (2015)).[49] Although researchers and development specialists generally emphasise the importance of economic and social factors, extreme weather events, reduced agricultural productivity, sea level rise and other forms of slow onset environmental degradation have the potential to fuel migratory patterns and increase the probability of civil conflict (Bilsborrow (1992), Morrissey (2009)).[50]

Despite the evidence above, growth studies featuring exhaustible resources have tended

substantial declines in temperature related mortality due to diffusion of air conditioning (although this exacerbates CO2 emissions unless powered by renewables).

[48] Drawing on a range of studies for Africa, IPCC (2007), for example, conclude that climate change will be associated with geographical expansions of the areas suitable for malaria transmission in some regions (and possibly also over longer seasons), while contractions may occur in other parts of the continent.

[49] Desmet et al. (2015) simulate the welfare effects of potential sea level rise using a theoretical macro model incorporating linkages between geographical location, population density and productivity.

[50] Some indications of future trends are beginning to emerge: low lying islands such as Tuvalu have already begun discussions with Australia and New Zealand regarding relocation of entire populations in the face of predicted sea level rise. However, the extent of these effects are extremely uncertain, with the number of predicted climate migrants potentially ranging from 25 million to 1 billion by mid century (Laczko and Aghazarm (2009); Myers and Kent (1995)). Moreover, analysis of the macroeconomic effects is confounded by the likelihood that population movements may often be localized (Foresight (2011)).

to assume demographics trends to be exogenous. Notable exceptions include studies of interactions between resource scarcity, demographics and technological development (Peretto and Valente (2015) and Schäfer (2014a)).[51] In the environmental economics literature, Mariani et al. (2010) and Schäfer, (2014b) analyse the relationship between pollution, human longevity and growth.[52]

In contrast, this chapter contributes to an understanding of feedbacks between pollution, mortality and the macro economy, focussing, in particular, on the implications of societal choices over welfare aggregation (the neoclassical exhaustible resource literature typically assumes that utility is formed over consumption per capita, rather than of a group).[53] This issue has important implications outlined below (Chapter 6 examines the empirical consequences of different approaches to welfare aggregation in the context of UK energy tax reform).

In Section 4.2, I show that spillovers affecting mortality have countervailing macroeconomic effects to those arising from capital durability, which have not previously been studied in an exhaustible resource setting: the former dominate in an optimal growth setting, but are parameter dependent in the Keynesian model. The insights for resource

[51] Peretto and Valente (2015) analyse an infinite horizon Schumpeterian model, in which households have preferences over the number of offspring and finite resources enter into the production process. Their essential insight – that the coexistence of stable steady state growth and an asymptotically declining demographic expansion depends on the relationship between capital and resources in the production function – extends Dasgupta and Heal (1974). Schäfer (2014a) highlights the potential for education technologies to improve resource sustainability within a finite horizon model featuring induced technological change and exhaustible resource inputs to the intermediates sector.

[52] Mariani et al. (2010), for example, highlight the potential for a non linear relationship between pollution and human longevity to help explain observed bimodalities in the distribution of environmental quality and life expectancy across countries. Jouvet et al. (2010) analyse issues relating to the coordination of health and pollution related policies, within a similar finite horizon model in which overcrowding also generates a congestion externality.

[53] As such, it does not fully consider important lessons from the social choice literature regarding the potential "tyranny of the individual" (see, for example, Blackorby and Donaldson (1984), Cowell et al. (2010)).

depletion are not previously uncovered by Fankhauser and Tol (2005) in a study using a Ramsey model with labour and capital inputs.

In another previously uncharted area of research (Tol (2009) makes a passing reference but offers no analysis), Section 4.3 characterises the implications of demographic spillovers for resource taxation under different assumptions over utilitarian preferences: it shows that optimal tax prescriptions, for example, may diverge from the basic downward sloping paths identified in the resource tax literature, if the social planner places positive weight on aggregate (rather than average) felicity levels.

Section 4.4 explores the relationship between mortality from energy use, resource sustainability and the macroeconomy under the assumption that families are no longer infinitely lived: employing a framework in which environmental factors influence generational survival changes, this spillover is shown to have potentially ambiguous effects on the steady state which depend on interactions between the resulting incentives on the young to save and Hotelling condition. Section 5.4 offers concluding remarks.

4.2 Fixed savings model with mortality effects

Reflecting the linkages between fossil fuel usage and mortality rates outlined above, this section extends Sinclair (1992) by postulating the following relationship between population growth and oil market activity:

$$\hat{N}(t) = n - \varphi x(t) \tag{4.1}$$

where $n > \varphi x(t) \geq 0$ captures the magnitude of the spillover from the resource to labour market (for simplicity, capital depreciation is suppressed, all other aspects of the model are as set out in Section 3.3).

Lemma 4.1: φ ***unambiguously lowers steady state growth, depletion and growth rates.***

Sketch proof. This follows by inspection of the following steady state expressions (see Appendix B for a derivation):

$$x^* F = (h + a_2 n)(a_1 - s) + zs(1 - a_1) \tag{4.2}$$

$$\frac{r^*}{a_1} F = (h + a_2 n) - z(1 + m + a_2 \varphi - a_1 - a_2) \tag{4.3}$$

$$F \hat{Q}^* = s(h + a_2 n - z(1 + m + a_2 \varphi - a_1 - a_2)) \tag{4.4}$$

where $F = A + a_2 \varphi (a_1 - s)$.[54]

By inspection: $\frac{dx^*}{d\varphi}, \frac{dr^*}{d\varphi}, \frac{d\hat{Q}^*}{d\varphi} < 0$. ■

By slowing the rate of expansion of the labour supply, φ exacerbates the productive distortions from climate change, reducing steady state oil depletion and interest rates (assuming a zero tax trend for simplicity) by a greater degree than in the baseline model.[55] Figure 6 illustrates these effects.

Corollary 4.1: For $\varphi > 0$, a corrective tax path is more negatively sloped than in the baseline model.

Sketch proof. Assuming that oil taxes are constant in the absence of climate change (i.e. $z = 0$ if $m = \theta = 0$), it follows from (4.2) that $x^* |_{z=m=\theta=0} = x^* |_{z=z^*(m,\psi>0)}$ (i.e. the effects of the externality on steady state oil depletion are "corrected") if:

$$z^* = -\frac{(m + a_2 \psi)(a_1 - s)}{s(1 - a_1)} \frac{(h + a_2 n)}{(a_1(1 - a_1 - a_2) + s a_2)} \tag{4.5}$$

By inspection $\frac{dz^*}{d\varphi} < 0$, $z^* < 0$. ■

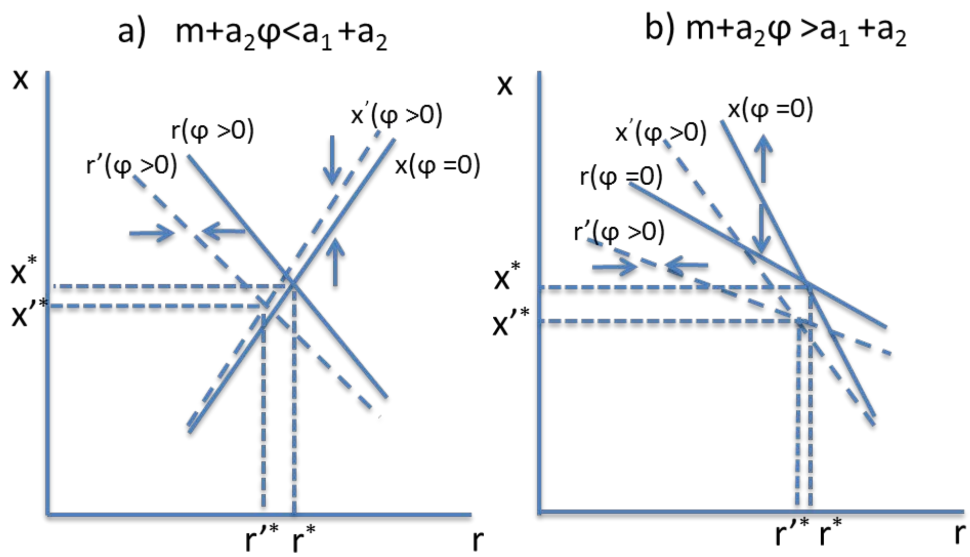
The additional mortality spillover sharpens the incentives for resource producers to defer production, warranting a more steeply downward sloping tax path.

---

[54] As before, equilibrium existence thus requires the dynamic efficiency condition: $a_1 > s$.

[55] Equation (4.3) relates closely to the effects of temperature change on interest rates through demographic changes identified by Fankhauser and Tol (2005). However, since their model does not include exhaustible energy inputs, the insights for resource sustainability are not previously uncovered.

Figure 6
Oil and capital market loci with mortality effects



This figure depicts the stationary interest rate and oil market loci in the “Keynesian” model featuring mortality spillovers (algebraic expressions are found at Appendix B) in x, r space (the arrows denote transitionary forces). Similar to the effects of m, ψ causes stationary depletion to pivot anti clockwise (where x and x' represent the locus with and without the mortality effect respectively), due to the resulting weaknesses in the macroeconomy (potentially overwhelming the Hotelling effect such that this slopes downward). In addition, ψ causes stationary interest rates to pivot anti clockwise (where r and r' again represent the locus with and without the mortality effect respectively) through the additional drag of x on output growth (in x, r space). Steady state interest and depletion rates thus fall unambiguously (from x^*, r^* to x'^*, r'^*).

Interacting capital and labour effects

As emphasised by Stern (2013) and Fankhauser and Tol (2005), spillovers from fossil fuel combustion are likely to have multi-channelled effects on the macro economy. I therefore consider a model variant in which both φ and $\theta > 0$ (such that capital accumulates as in equation (3.11)).

Corollary 4.2: At a stable steady state, the combined impact of climate change on depletion and output growth through productivity and mortality spillovers dominate any capital effects.

Sketch proof. Steady state expressions for oil and capital markets are given by:

$$x^* G = (h + a_2 n)(a_1 - s) + zs(1 - a_1) \tag{4.6}$$

$$\frac{r^*}{a_1} G = (h + a_2 n) - z(1 + m - (1 - a_1)\theta + a_2\varphi - a_1 - a_2) \tag{4.7}$$

where $G = F - \theta(1 - a_1)(a_1 - s)$. ■

By inspection, $\frac{dx^*}{d\theta} > 0, \frac{dx^*}{d\varphi} < 0$, *with* $G\ (m, \varphi > 0) > G\ (m, \varphi = 0)$ *if and only if:* $m + a_2\varphi > \theta(1 - a_1)$. *This condition is also necessary and sufficient for saddle path stability, since the stationary depletion locus is otherwise upward sloping, yielding knife-edge properties (see Lemma 3.5).*

In this Keynesian set up, the influence of the mortality (and productivity) channel partly offset that of less durable capital on output growth. It follows from previous analysis that, within an optimal growth framework, the former effects would dominate the level effect arising from θ.

4.3 Optimal growth model with mortality effects

This section analyses mortality effects using a model in which savings behaviour is optimized. Unlike in the previous chapter, this extension proves to have qualitatively similar findings in terms of the external effects on the macroeconomy as compared to the fixed savings variant (but provides an important building block for subsequent analysis).

Specifically, I present new insights on the implications of household preferences over the aggregation of welfare, for the economic and policy consequences of mortality spillovers, which have not previously been studied in neoclassical growth literature with exhaustible resources. To see this, I start by modify assumptions over the preferences of the representative agent.

Unlike the basic set up in Chapter 3, in which the representative agent aims to maximise per capita utility, she is assumed here to place positive weight on aggregate welfare across the family. This approach reflects well known ethical issues arising from SWFs based on average utilitarian preferences which is sometimes referred to by social choice theorists as the "tyranny of the individual".[56]

The objective function is thus given by (once again suppressing physical capital erosion):

$$\underset{\{c(t),E(t)\}_{t=0}^{\infty}}{Max} V = \int_0^{\infty} (\left(\frac{c(t)^{1-v} - 1}{1-v} \right)^{\xi} (N(t))^{1-\xi} + \lambda(t) \left(Q(.) - c(t)N(t) - \dot{K}(t) \right))dt \tag{4.8}$$

where $\xi \in [0, 1]$. Evidently, this reduces to the basic model specification in Section 3.4 in the case where $\xi = 1$ (and $j = 0$).

Lemma 4.2: The mortality effect, φ, slows consumption growth for positive weight on aggregate utility levels for $0 \leq \xi < 1$, ceteris paribus.

Sketch proof. The Keynes-Ramsey rule derived from (4.8) is given by:

$$r(t) - i - \xi (n - \varphi x(t)) = v\hat{c}(t) \tag{4.9}$$

[56] Little empirical research on aggregation preferences has been undertaken thus far. Cowell et al. (2010), for example, undertake an experimental enquiry into preferences over income transfers. Their results suggest that, of the sample for whom a clear aggregation preference could be discerned, $\xi = 1(0)$ for about 60 (40) percent of respondents respectively.

By inspection, $\frac{d\hat{c}}{d\psi} > 0$ *if and only if* $0 \leq \xi < 1$. ■

The oil related spillover to labour markets increases consumption growth, since total consumption is shared among smaller families (an effect which increases with ξ, $\frac{d^2\hat{c}}{d\psi d\xi} > 0$). However, if the representative agent concerns herself only with the aggregate level of consumption (i.e. $\xi = 0$), consumption growth is invariant to the spillover.

These effects on the dynamics of the economy are illustrated in Figure 7 (see Appendix B for algebraic expressions): φ causes the stationary depletion locus to pivot anti-clockwise (in x, c/k space), due to lower oil demand; and the stationary rental growth locus to pivot anti-clockwise through the additional drag of x on output growth (in x, r space).

Under the revised objective function, the stationary consumption-capital ratio now rises (falls) with depletion rates if $v > \xi$ ($v < \xi$): an increase in x causes both consumption and capital to be shared among smaller families, but the effect on consumption is disproportionately small (large) with a low (high) willingness to substitute between future and current populations.

Lemma 4.3: The sufficient and necessary conditions for existence of a steady state are respectively: i) $v > 1$***, and ii)*** $(1-v)\,m+((1-a_1)\,\xi - a_2 - v\,(1-a_1-a_2))\,\psi < v\,(1-a_1-a_2)+a_2$***.***

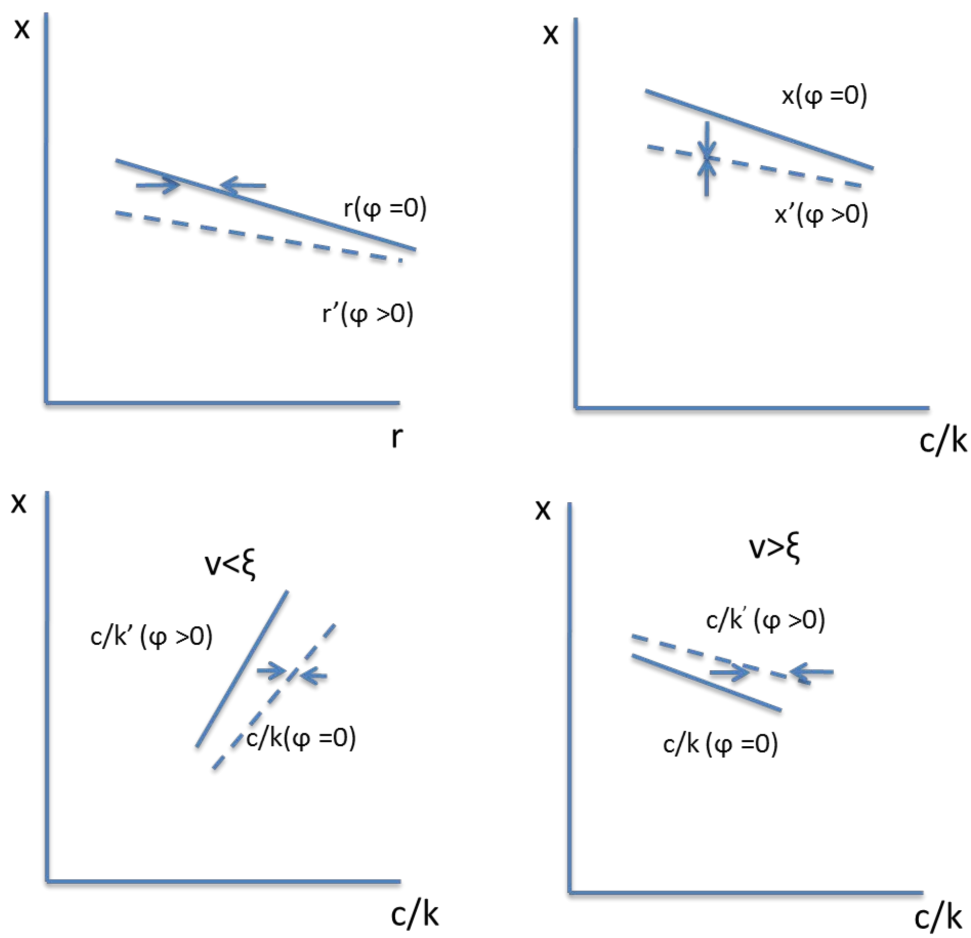
Proposition 4.1: i) Steady state depletion (and growth) declines with φ ***if*** $\xi > \frac{a_2+v(1-a_1-a_2)}{(1-a_1)}$***, and, ii) increases unambiguously with*** ξ ***(for*** $\varphi > 0$***).***

Sketch proof. Steady state expressions for depletion, interest rates, the consumption-capital (per capita) ratio and output growth are given by (see also Appendix B*):*

$$Hx^* = (v-1)\,h - ((1-a_1-a_2)\,v - (1-a_1)\,\xi + a_2)\,n + (1-a_1)\,(i+z) \tag{4.10}$$

$$\begin{aligned} r^*H = {} & hv + n\,(a_2\xi + (v-\xi)\,m) \\ & - zv\,(1-a_1-a_2+m+\varphi) + i\,(a_2-m-\varphi) \end{aligned} \tag{4.11}$$

Figure 7
Optimal growth with mortality effects



This figure analyses the dynamics of the model featuring capital spillovers (given algebraically at Appendix B), focussing on the effect of the mortality and aggregation parameters:* similar to the Keynesian model variant, ψ causes both the stationary depletion (in x,r) and interest rate (in $x, c/k$) loci to pivot anti clockwise through lower oil demand and weaker productivity growth (from x to x' and r to r') respectively (c/k acting as a close proxy for r). This is shown in the upper panels. However, the stationary consumption-capital ratio now rises (falls) (in $x, c/k$ space) with depletion rates if $v > \xi$ ($v < \xi$): an increase in x causes both consumption and capital to be shared among smaller families, but the effect on consumption is disproportionately small (large) with a low (high) willingness to substitute between future and current populations. This is shown in the lower panels.

*The effects on the stationary interest rate and consumption capital ratio (in $r, c/k$ space) are qualitatively similar to the base model and, as such, are not depicted here. Analysis of the depletion locus (in x,r and x,c/k space) focuses on the "moderate" externality case.

$$
\begin{aligned}
a_1 Hc^*/k^* = (v - a_1)\,(h - n\,(1 - a_1 - a_2) - \\
&(1 + m - a_1 - a_2 + \varphi\,(1 - a_1 - a_2))\,z) + \\
&(1 - a_1)\,((m + a_2\varphi - a_1 - a_2)\,i + n(\xi\,(a_2 - m) \\
&v\,(1 + m + a_2\varphi - a_1 - a_2) - (1 - \xi)\,(a_1 + a_2\varphi)))
\end{aligned} \tag{4.12}
$$

$$
\begin{aligned}
Hg^* = h\,(1 - (v - \xi)\,\varphi) - (1 - a_1 - a_2 - (v - 1)\,\varphi)\,n - \\
(1 - a_1 - a_2 + m + a_2\varphi)\,(z + i)
\end{aligned} \tag{4.13}
$$

where $H = C + v\,(1 - a_1 - a_2)\,\varphi - (1 - a_1)\,\xi\varphi + a_2\varphi$..

Lemma 4.3 follows by inspection of H.

$H\frac{dx^*}{d\psi} = x^*\,((1 - a_1)\,\xi - a_2 - v\,(1 - a_1 - a_2)) > 0$ *if and only if:*

$((1 - a_1)\,\xi - a_2 - v\,(1 - a_1 - a_2)) > 0$. $H\frac{dx^*}{d\xi} = ((1 - a_1)\,n + \varphi x) > 0$. *This demonstrates Proposition 4.1.* ■

A larger weighting on aggregate utility in the preferences of the representative householder reduces the level of steady state depletion, given the greater relative value placed on future welfare due to population growth.

Corollary 4.3: The impact of climate change on resource sustainability depends on the sign of: $\frac{((1-a_1)\xi - a_2)\varphi + m}{(m + (1 - a_1 - a_2)\varphi)} - v$.

Sketch proof. Evaluating $x^* \mid_{m=0,\varphi=0} - x^* \mid_{m>0,\varphi>0} > 0 = 0$ *yields the stated condition.*
■

For the case in which $\xi = 1$, φ=0, this result reinforces the original finding of Sinclair (1994), that the influence of global warming on steady state depletion depends on whether or not v exceeds unity: if the willingness of households to substitute consumption across time periods exceeds (is less than) 1, then the income effects associated with the productive externality dominate (are dominated by) the substitution incentives (since the externality raises the cost of consumption today relative to the future), reducing (increasing) steady state depletion.

However, where the representative agent has positive utility over aggregate family consumption levels (i.e. $0 < \xi < 1$), this condition holds for inter-temporal preferences with less than unitary elasticity (since the substitution incentives are diminished through the effects of aggregation).[57] Thus, in this revised set up, the production externalities limit growth (but alleviate resource sustainability issues) under less restrictive assumptions regarding the EIS.

Policy implications

I now consider the implications of mortality effects for tax policy. This is once again undertaken by comparing the solution to the decentralized problem with the choice of the social planner.

When maximising her utility, the representative agent behaves as if her oil extraction decisions does not affect the aggregate stock or the proportion of the stock extracted (denoted by $\bar{S}$), given by the following Hamiltonian function:

$$\underset{\{c(t),E(t)\}_{t=0}^{\infty}}{Max} V = \int_0^{\infty} (\left(\frac{c(t)^{1-v}-1}{1-v}\right)^{\xi} (N(t,\bar{x}))^{1-\xi} + \\ \lambda(t)\left(Q(\bar{S}(t)) - c(t)N(t) - \dot{K}(t)\right) + \mu(t)\left(n - \psi\bar{x}(t)\right)N(t))dt \qquad (4.14)$$

where $\mu(.)$ denotes the co state variable in population. The private household thus ignores the influence of her oil market activity on productivity and health as part of individually optimizing behaviour.

By contrast, the optimization problem of the social planner is given by:

[57] Differentiating (4.13) with respect to ψ confirms that this condition also applies to steady state growth as one would expect.

$$\underset{\{c(t),E(t)\}_{t=0}^{\infty}}{Max} V = \int_0^{\infty} (\left(\frac{c(t)^{1-v} - 1}{1-v}\right)^{\xi} (N(t,\widetilde{x}))^{1-\xi} +$$

$$\lambda(t)\left(Q(\tilde{s}(t)) - c(t)N(t) - \dot{K}(t)\right) + \mu(t)\left(n - \psi\widetilde{x}(t)\right)N(t))dt$$

The social planner thus internalizes the effects of extraction decisions on both productivity and mortality rates.

Corollary 4.4:* For** $v > 1 > \xi$**,** $\psi > 0 > \hat{N} - i$ ***the slope of the corrective oil tax trajectory rises over time, becoming upward sloping for $t > \bar{t} = \frac{m(v-1)}{\varphi(1-\xi)\left(i-\hat{N}(t)\right)}\left(\frac{r^*}{c^*/k^*}\right)$.

Sketch proof. The optimal tax is given by (see Appendix B for a derivation):

$$z^* = \frac{-\left(m + \frac{t\varphi(1-\xi)}{(1-v)}\left(\frac{c^*/k^*}{r^*}\right)\left(i - \hat{N}(t)\right)\right)x}{(1 - a_1 - a_2)} \tag{4.15}$$

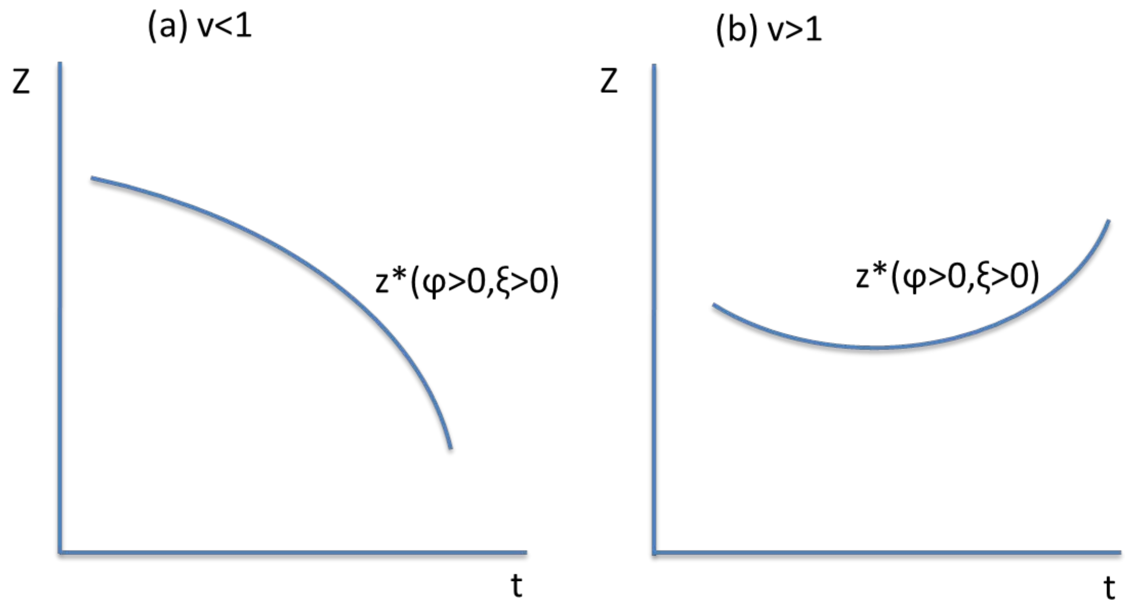
By inspection, under stated assumptions:[58] $\frac{dz^*}{dt} > 0$, $z^* > 0$ *if and only if* $t > \bar{t}$. ■

Intuitively, equation (4.15) reduces to the basic tax prescription of Sinclair (1994) if either $\psi = 0$, or the social planner cares only about average societal income, i.e. $\xi = 1$ (which is unaffected by the spillover). However for $\varphi > 0, \xi \neq 1$, a number of important differences arise.

The mortality spillover causes current consumption to fall because the positive substitution effects are outweighed by the negative income effects, warranting a tax which falls less rapidly than in the baseline model (the case supporting the assumption of $v > 1$ is outlined previously). The tax trend is no longer time invariant, even for a steady state, because the corrective component relating to the mortality spillover increases (in absolute value) over time due to population growth. These effects (including in the more improbable case of $v < 1$) are discussed in Figure 8.

[58] As discussed in Chapter 3, $v \in \{1.5, 5\}$; i and is commonly thought to be in the range 3-4 percent per annum, while annual global population growth currently averages around 1-1.5 percent (exceeding 3 for a very limited number of low income countries, in which i may itself be higher due to lower life expectancy).

Figure 8
Optimal taxation with mortality effects & an aggregate utilitarian SWF



This figure shows the optimal oil tax path in the presence of mortality spillovers for different values of the EIS. For $\upsilon > 1$, $\varphi > 0$ (shown in the right hand panel) causes a substitution of present for future consumption. This warrants a tax which falls less rapidly than in the baseline model. The tax trend is no longer time invariant, even for a steady state, because the corrective component relating to the mortality spillover increases (in absolute value) over time due to population growth. For $\upsilon < 1$, $\varphi > 0$ the optimal tax falls more rapidly than in the case of $\psi = 0$: current consumption rises due to the dominance of the substitution effects. The corrective component relating to the mortality spillover becomes more powerful over time due to population growth, leading to an increasingly negative tax prescription over time, $\frac{dz^*}{dt} < 0$.

The finding modifies a central insight from the optimal exhaustible resource tax literature that tax paths be downward sloping (see, for example, Farzin and Tahvonen (1996), Hoel and Kverndokk (1996), Sinclair (1994) and Ulph and Ulph (1994)).[59]

4.4 OLG model with mortality hazard

A key assumption underpinning the analysis above is that families are infinitely lived. This section departs from this standpoint by exploring the influence of mortality spillovers on the macroeconomy within an OLG framework, where these influence the probability of surviving into old age.

Existing studies of finite horizon models of growth with exhaustible resources assume exogenous survival dynamics (Agnani et al. (2005), Babu et al. (1997), Howarth (1991), John and Peccecchino (1994), John et al. (1995)).[60] This is the first study to my knowledge to explore the implications of externality effects affecting production within an OLG model which incorporates exhaustible resource inputs.

A basic variant of the model (modifying an earlier study by Sinclair (1990)) in which survival rates are exogenous is first presented as a benchmark, before endogenizing this

---

[59] Within a finite horizon setting, Schäfer (2014b) posits a hump-shaped optimal output tax, with revenues employed to finance abatement activities, because diverting resources away from production has adverse powerful effects on fertility at low levels of output (but abatement expenditures confer relatively greater benefits at higher levels of development). Formally speaking, this is a constrained optimal tax prescription since demographic choices are not endogenously formed. As such, this represents a possible area for further work (discussed further in Chapter 7). Implicitly, I assume that child rearing taxes are infeasible. Jouvet et al. (2010), for example, analyse a second best pollution tax arising from limitations to inter generational transfers.

[60] Kemp and Long (1979) first explored the role of exhaustible resources for inter generational savings, but assumed these to be inessential inputs to production. Jouvet et al. (2010), Mariani et al. (2010) and Schäfer (2014b) explore the influence of environmental spillovers affecting longevity and growth, but do not consider natural resource inputs. Schäfer (2014a) explores interactions between induced technological change, population dynamics and exhaustible resource utilization.

probability as a function of resource extraction decisions.

OLG model with exogenous survival probability

Households are assumed to live for 2 periods, young and old. A single good is either consumed or invested. Consumption in old age is sustained by investments from wage income earned in youth (for simplicity each individual is endowed with one unit of labour), which earns a known rate of return.

The representative household is thus assumed to solve the following utility maximization problem:

$$\underset{c_1,c_2}{Max} E_1 U = (1-b)\, log c_1 + (1-\rho)\, b log c_2 + \lambda\left(\left(W - c_1 - \frac{PS}{N}\right)(1+r_{+1}) - c_2\right) \quad (4.16)$$

Preferences over consumption in periods 1 and 2 (denoted by c_1 and c_2 respectively) are here assumed to be Cobb-Douglas; b weights preferences over these two periods; W is the wage rate earned on labour supplied in the first period; and, r_{+1} represents interest earned on savings in the successive period.

Finally, ρ indicates the probability of not surviving until old age. It has the effect of depressing savings since it reduces the expected value of deferred consumption (savings can only be enjoyed by survivors!). Natural resources are assumed to be endowed to the generation of old people, thus requiring the young to purchase oil out of their first periods budget constraint at a cost per capita of $\frac{PS}{N}$. Oil prices thus affect the supply of capital in the successive period.

Production depends on the labour of the young, and capital and exhaustible natural resources supplied by the old, and is given (in intensive form) by:

$$q_t = T_t k_t^{a_1} \left(\frac{x_t S_{t-1}}{N}\right)^{a_2} \quad (4.17)$$

where q_t represents output per head in time t. S_{t-1} are oil reserves in period $t-1$. x_t represents the proportion of oil stocks extracted in period t. T_t is a productivity term, which is assumed to evolve according to an exogenous rate of technological progress, h, net of a productivity drag due to climate change, m, given by:

$$\frac{T_+}{T} = (1+h)(1-x)^m \tag{4.18}$$

All factor inputs earn their respective marginal products. Once again, natural resource prices are assumed to obey the Hotelling portfolio equilibrium such that:

$$1 + r_+ = \frac{P_+}{P} \tag{4.19}$$

where $\frac{P_+}{P}$ is the rate of oil price growth.

Lemma 4.4: With an exogenous hazard risk, existence of a steady state requires that $a_2 < \bar{a}_2 = b(1-\rho)(1-a_1-a_2)\frac{x_t}{(1-x_t)}$***.***

Proposition 4.2: An exogenous mortality hazard unambiguously increases steady state interest and depletion rates.

Sketch proof. The stationary "Hotelling" and "Savings" curve are given by (see Appendix B for further details):

$$(1-x^*) = \left(\frac{(1-\rho)^{1-a_1-a_2}(1+h)}{(1+r_{+1})^{1-a_1}}\right)^{\frac{1}{1-a_1-a_2-m}} \tag{4.20}$$

$$r^* = \frac{a_1\left[(1-\rho)^{1-a_1-a_2}(1+h)(1-x^*)^{a_2}\right]^{\frac{1}{1-a_1}}}{\left(b(1-\rho)(1-a_1-a_2) - a_2\frac{(1-x_t^*)}{x_t^*}\right)} \tag{4.21}$$

By inspection, $r^* < 0$ *if* $a_2 > \bar{a}_2$; $\frac{dx^*}{d\rho}, \frac{dr^*}{d\rho} > 0$. ■

The savings rate is downward sloping, a higher value of x implies slower output growth: a faster rate of decline in scarce inputs acts in a similar way to a decline in technical progress. The Hotelling curve bends backwards if $m > 1 - a_1 - a_2$, due to the negative interaction with the non oil economy (in the absence of a productivity spillover, i.e. $m = 0$, there is an unambiguously positive, but concave, link between oil depletion and the rate of interest).

ρ cause a leftward shift in the stationary Hotelling locus, due to the effects of scarcer savings operating through the arbitrage condition; together with a rightward shift in the savings curve, since the expectation of a lower survival rate depresses savings (thereby increasing rental payments for a given depletion rate). These effects are shown in Figure 9, panel a)). The restriction on a_2 ensures that purchasing oil stocks does not takes up all the savings of youths.

OLG model with endogenous survival probability

I now extend the previous model by considering the implications on growth, as well as oil and capital markets, when mortality is exogenous to oil extraction. As such, the probability of survival into old age is assumed to be:

$$n = \rho - \varsigma x \tag{4.22}$$

where ςx indicates the additional influence of oil usage on mortality rates.

It follows that the revised household optimization problem reflects this adjustment expectation of survival into old age:

$$\underset{c_1, c_2}{Max} E_1 U = (1-b)\, log c_1 + (1-\rho-\varsigma x)\, b log c_2 + \lambda \left(\left(W - c_1 - \frac{PS}{N} \right) (1 + r_{+1}) - c_2 \right) \tag{4.23}$$

Thus mortality risk lowers savings according to the following expression $W - c_t = (1-\rho-\varsigma x)\, bW$. This creates an additional source of endogeneity between interest and extraction rates.

***Lemma 4.5:* With an endogenous hazard risk, existence of a steady state requires that** $a_2 < \bar{\bar{a}}_2 = b(1-\rho-\varsigma x)(1-a_1-a_2)\frac{x_t}{(1-x_t)} < \bar{a}_2$**.**

***Lemma 4.6:* The mortality spillover,** $\varsigma > 0$**, increases steady state interest but the impact on interest rates is ambiguous.**

Sketch proof. The stationary "Hotelling" and "Savings" curve are (now implicitly) given by:

$$(1-x^*) = \left(\frac{(1-\rho-\varsigma x^*)^{1-a_1-a_2}(1+h)}{\left(1+r^*_{+1}\right)^{1-a_1}}\right)^{\frac{1}{1-a_1-a_2-m}} \tag{4.24}$$

$$r^* = \frac{a_1\left((1-\rho-\varsigma x^*)^{1-a_1-a_2}(1+h)/(1+r)^{a_2+m}\right)^{\frac{1}{1-a_1-a_1-m}}}{\left(b(1-\rho-\varsigma x^*)(1-a_1-a_2)-a_2\frac{(1-x_t^*)}{x_t^*}\right)} \tag{4.25}$$

By inspection, applying envelope theorem, $\frac{dx^*}{d\varsigma} > 0$*; while* $\frac{dr^*}{d\varsigma}$ *depends on the sign of:*

$$-\left(b(1-\rho-\varsigma x^*)(1-a_1-a_2)-a_2\frac{(1-x_t^*)}{x_t^*}\right)+b(1-\rho-\varsigma x^*)\left((1-\rho-\varsigma x^*)^{1-a_1-a_2}\frac{(1+h)}{(1+r)^{a_2+m}}\right)^{\frac{a_1+a_2+m}{1-a_1-a_1-m}}.$$

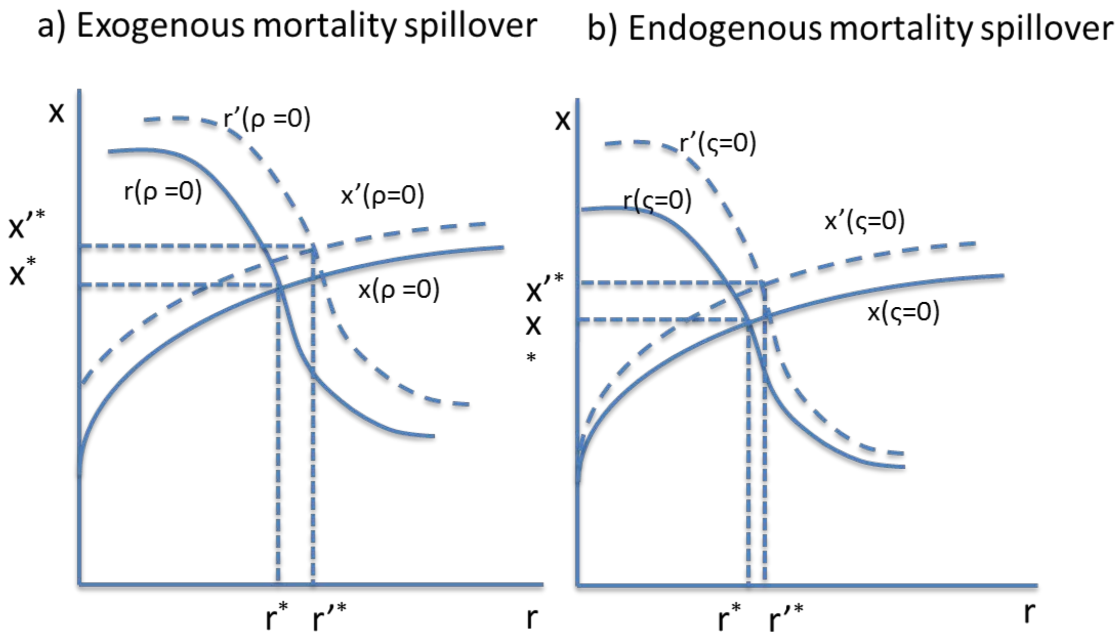
■

The endogenous component of the hazard rate effects an anti-clockwise pivot in the stationary Hotelling curve (see Figure 9, panel b): as x increases, the mortality spillover reduces savings, increasing rental prices and thus depletion rates through the Hotelling effect. It also causes an anti-clockwise pivot in the savings curve, as lower savings rates fall with higher depletion levels. If this later term in the condition stated above is sufficently powerful, then downward pressure on savings due to reduced life chances from pollution result in rental rates being bid up as x increases (see Figure (9), panel b)).

4.5 Concluding remarks

There is growing evidence on the links between global, and particularly local, air pollution and demographic factors such as mortality. Despite this, economic models of growth featuring exhaustible resource inputs to production have thus far tended to assume demo-

Figure 9
Mortality hazard and steady states in oil and capital markets



This figure illustrates the influence of exogenous and endogenous mortality spillovers on steady states in oil and capital markets within the finite horizon model. In the exogenous cause, shown in the left hand panel, ρ causes a leftward parallel shift in the stationary Hotelling locus (from x to x'), due to the effects of scarcer savings operating through the arbitrage condition; and a rightward shift in the savings curve (from r to r'), since the expectation of a lower survival rate depresses savings (thereby increasing rental payments for a given depletion rate). Steady state interest and depletion rates unambiguously rise with ρ. In the endogenous cause, shown in the right hand panel, ς results in an anti-clockwise pivot in the stationary Hotelling curve, since the mortality spillover has more powerful effects in reducing savings (and thus increasing interest rates) through the Hotelling effect; and an anti-clockwise pivot in the savings curve, as savings rates fall disproportionately with higher depletion levels. In this case, steady state depletion increases but the outcome for interest rates is ambiguous.

graphic factors are exogenous to extraction choices.

This chapter analyses the implications of higher mortality rates, associated with fossil fuel combustion, for the macroeconomy and policy. It offers new insights into the sensitivity of the resulting effects to the form of household preferences, including with regard to the aggregation of welfare over family members.

Slower population growth imposes downward pressures on macroeconomic performance in this class of model, warranting a more steeply downward sloping tax path under descriptive analysis. However, these effects are unlikely to take place in isolation (as noted by Fankhauser and Tol (2005)).

I show that spillovers affecting mortality have countervailing macroeconomic effects to those arising from capital durability, which have not previously been studied in an exhaustible resource setting: the former dominate in an optimal growth setting, but are parameter dependent in the Keynesian model.

Turning to issues relating to the aggregation of welfare, I show that climate change lowers growth (but alleviates resource sustainability issues) – even if inter-temporal substitution preferences are moderately elastic – where substantial weight is placed on the welfare of the family rather than the individual, modifying a core finding of Sinclair (1994).

This is also shown to have a potentially powerful on policy tax prescription, warranting a tax which falls less rapidly than in the baseline model under maintained assumptions. Moreover, the optimal tax trend is 'u' shaped, rather than declining monotonically (as pollution affects more people over time).

To the best of my knowledge, this is the first study which characterises the implications of demographic spillovers for resource taxation. It thus offers a rare exception to an existing exhaustible resource tax literature, which typically emphasis that tax paths ultimately be downward sloping.

Within a finite horizon model, I find that environmental effects bearing on generational survival changes have potentially ambiguous effects on steady state interest rates which depends on the resulting incentives on the young to save and the Hotelling condition.

5 A CHANGING CLIMATE FOR CONSUMPTION? MACROECONOMICS AND POLICY IN THE PRESENCE OF RESOURCE-DEMAND SPILLOVERS

5.1 Introduction

This chapter analyses the macroeconomic and policy implications of intra temporal externalities from resource utilization affecting household energy consumption. Research has focused on the impacts of the energy sector on climate change. However, recent contributions have highlighted the potential countervailing effects of changing weather conditions on residential energy demand in the US and, to a lesser extent, Europe (Amato et al. (2005), Rosenthal et al. (1995), Ruth and Lin (2006), Scott et al. (1994)).

This body of research consistently demonstrates two key sensitivities: first, fewer cold winter days reduce heating related demand. Second, more frequent and intense hot summer spells are likely to boost air conditioning usage. The balance of these factors depends substantively on geography, with savings from lower heating requirements expected to dominate in higher latitude regions and increases in cooling related energy usage greater in hotter regions (Huang and Scott (2007)).[61]

Macroeconomists have sought to incorporate these insights into increasingly complex models (Aaheim et al. (2009), Bosello et al. (2007), Eboli et al. (2010), Isaac and van Vuuren (2009), Nordhaus (1991) and Tol (2002)). However, such allocative shocks have rarely been examined in isolation, rendering it difficult to identify and interpret their effects. Moreover, insights for corrective tax policy have not hitherto been analysed.

In this context, Section 5.2 simulates the potential macroeconomic influence of climate

[61] Observed temperature increases are themselves increasing in the distance from the equator: warming in the polar regions has hitherto warmed 6-8 times faster than equatorial zones (IPCC (2014)).

change arising from shifting patterns of residential energy demand in the UK, and characterises previously unexplored implications for differential taxation of resources across usages. It demonstrates that a spillover which shifts the division of oil resources from consumption to production has negative implications for output and depletion levels but no growth effects (although these are likely in transition). It further offers a theoretical argument for differential energy taxation (by end usage) on efficiency grounds (practical examples of such tax treatments have hitherto been grounded in a distributional rationale).

The analysis thus far has assumed that utility inter temporally separable (i.e. preferences are independent of past consumption choices). This approach has been entirely standard in the macro literature until quite recently. However, economists have increasingly explored the plausibility that historical consumption behaviour influences present day demand (Campbell and Cochrane (1999) and Constantinides (1990)).[62]

In particular, macroeconomic models which relax this assumption appear better able to explain, for example, the cyclical co movement of labour supply and consumption (Barro and King (1984)), the lack of volatility in wages (Kennan (1988)), the influence of nominal interest rates on real activity (Fuhrer (2000), Smets and Wouters (2007)), or the apparent willingness of households to take on risk (Constantinides (1990), Campbell and Cochrane (1999)).

However, to date, only a very limited number of studies have relaxed time inseparability assumptions in exhaustible resource based growth models. Krautkraemer (1985) and Manning (1978) are early examples of modelling time dependence – by including resource stock arguments to the utility function – and finding that consumption is shifted to the

[62] Nevertheless, it is important to recognize that empirical evidence on habit persistence is mixed (with many studies simply calibrating analytic models to historical data). Dunn and Singleton (1986), for example, find limited evidence of external habits in monthly consumption data. This contrasts with the results of Constantinides and Ferson (1991) and Heaton (1995) at quarterly frequencies. Micro economic studies have also yielded inconclusive empirical findings (see, for example, Alessie and Teppa (2010), Browning and Collado (2007), Dynan (2000), Guariglia and Rossi (2002) and Ravina (2005)).

future if cumulative resource exploitation lowers the marginal utility of consumption.

A further branch of literature explores the influence of time dependent discount rates for optimal renewable resource extraction choices (Hepburn et al. (2010), Zhang (2013));[63] Ikefuji (2008) studies interactions between consumption habits, growth and optimal pollution abatement activities and finds. The author finds that faster habit formation reduces the marginal abatement cost (and growth rates) and thus optimal environmental policy.

However, research into the effects of consumption habits on growth and exhaustible resource depletion has thus far been rather scarce. Valente (2011) analyse interactions between consumption habits and bequests within an OLG model featuring exhaustible resources. They show that the initial stock of habit, determines whether this preference form results in level rather than permanent growth effects (see also Schäfer and Valente (2011), discussed above)).[64]

In light of this, Section 5.3 explores the potential influence of consumption habits on the macroeconomic and policy implications of production externalities due to climate change and (together with potential spillovers to capital durability discussed previously). I find, for example, that introducing external habits raises depletion, provided the negative influences of capital thinning and the productivity spillover do not outweigh upward pressures

[63] Hepburn et al. (2010) explore the influence of hyperbolic discounting on fisheries, highlighting that high near term discount rates generate the potential for stock collapse. By contrast, Zhang (2013) analyses renewable resources using an application of the Uzawa (1968) framework, which implies heavier discounting as consumption levels rise (while necessary for system stability, this approach is questionable from an intuitive perspective) (see also Maeda and Nagaya (2010) for an analyse of interactions between the Hotelling condition, the EIS, and switching points to a backstop under time dependent discount rates).

[64] Specifically, if the stock of habits is below a threshold then bequests are operative such that stronger habits have level effects on output and increase long run resource usage (by inducing temporarily greater willingness to accumulate capital, and input substitution). By contrast, if initial habits exceed this level, then there are growth effects: bequests shut down and growth is faster, and extraction time profile flatter. Zhang (2013) finds that habits influence the speed of economic adjustment, but not the steady state using a model featuring renewable resource inputs.

due to technology and impatience.

5.2 Climate change and consumption of energy services

This section models potential spillovers from resource usage to the allocative behaviour of the household, reflecting the potential for environmental externalities to influence demand for energy intensive services, for example by reducing heating requirements as a result of milder winters, or increasing the need for air conditioning due to hotter summers (see Appendix 5 for a survey of the literature on the potential magnitude of these effects).

To explore these issues, I adapt once more the basic neoclassical growth model with exhaustible resources, such that energy is consumed by the representative householder – to provide heating services, for example – subject to the following Cobb-Douglas utility function:

$$\underset{\{c(t),E(t),\chi(t)\}_{t=0}^{\infty}}{Max} V = \int_0^{\infty} (e^{-it} \left(\frac{c(t)^{1-v} - 1}{1-v} + \frac{\left(\left(1-\chi\left(x\left(t\right)\right)\right) E\left(t\right)\right)^{1-w}}{1-w} \right) + \lambda(t) \left(Q(.) - c(t)N(t) - \dot{K}(t) \right))dt \tag{5.1}$$

where w is the preference parameter over directly consumed energy services; $1 - \chi(.)$ determines the proportion of oil allocated to consumption, which is subject to the following postulated relationship:

$$\chi\left(x\left(t\right)\right) = \zeta x(t) \tag{5.2}$$

$\zeta x(t) > (<) 1$ determines the magnitude and sign of the allocative shift; and the revised production function is given by: $Q(.) = A(t)K(t)^{a_1}N(t)^{a_2}\left(\chi\left(x\left(t\right)\right)E\left(t\right)\right)^{(1-a_1-a_2)}$. All other terms are as previously defined.

Optimal oil allocation – the balance between resources used in consumption and production – satisfies the following condition:

$$\chi^* \left(x\left(t\right)\right) e^{-it} \left(\left(1 - \chi^* \left(x\left(t\right)\right)\right) E(t)\right)^{-w} = \lambda(t) \left(1 - a_1 - a_2\right) \frac{Q(t)}{E(t)} \tag{5.3}$$

which determines that, at the margin, the utility from oil allocated to consumption is equal to its shadow value in production.

Lemma 5.1: An interior solution requires that $z = -i$.

Differentiating condition (5.3) with respect to time, and substituting for the time path of the marginal product of oil, yields the following expression for the growth rate of oil allocated to production:

$$\hat{\chi} \left(1 + w\Lambda\left(x\left(t\right)\right)\right) = z + i \tag{5.4}$$

where $\Lambda\left(x\left(t\right)\right) = \frac{\chi(x(t))}{1-\chi(x(t))}$ *represents the ratio of oil used in production to consumption in the presence of the allocative spillover. The stated condition holds by inspection.*■

If this knife-edge condition fails, the ratio of oil used in production and consumption is not stable over time ($\frac{d\Lambda(x^*)}{dt} \neq 0$), leading to either economic collapse, or the production only representation outlined previously.

Lemma 5.2: Under stated assumptions, allocation of oil to the householder affects depletion rates as the sign of $1 - v$***. Furthermore, this condition also determines the influence of the preference parameter,*** w***.***

Sketch proof. Steady state depletion, interest rates, consumption-capital and output growth are given by (see Appendix D for further details):

$$\begin{aligned} I\left(\Lambda\left(x^*\right)\right) x^* = {} & (v-1)\left(h - n\left(1 - a_1 - a_2\right)\right) + \\ & \left(\frac{w\Lambda\left(x^*\right)\left(1-a_1\right) + \left(v\left(1-a_1-a_2\right)+a_2\right)}{\left(1 + w\Lambda\left(x^*\right)\right)}\right)(i+z) \end{aligned} \tag{5.5}$$

$$I\left(\Lambda\left(x^{*}\right)\right) r^{*}=vh+n\left(a_{2}+\left(v-1\right) m\right)+i\left(a_{2}-m\left(\frac{w\Lambda\left(x^{*}\right)}{1+w\Lambda\left(x^{*}\right)}\right)\right)-$$
$$vz\left(\frac{\left(1-a_{1}-a_{2}+m\right) w\Lambda\left(x^{*}\right)-\left(1-a_{1}-a_{2}\right)}{\left(1+w\Lambda\left(x^{*}\right)\right)}\right) \tag{5.6}$$

$$a_{1} I\left(\Lambda\left(x^{*}\right)\right) c^{*}/k^{*}=nI\left(\Lambda\left(x^{*}\right)\right)+\left(v-a_{1}\right)\left[h-n\left(1-a_{1}-a_{2}\right)-\right.$$
$$\left.\left(z\left(\frac{\left(1-a_{1}-a_{2}+m\right) w\Lambda\left(x^{*}\right)-\left(1-a_{1}-a_{2}\right)}{\left(1+w\Lambda\left(x^{*}\right)\right)}\right)+i\left(1-a_{1}\right)\right)\right] \tag{5.7}$$

$$g^{*} I\left(\Lambda\left(x^{*}\right)\right)=h-\left(1-a_{1}-a_{2}\right) n-$$
$$w\left(\frac{\Lambda\left(x^{*}\right)\left(1-a_{1}-a_{2}+m\right)+\left(v-1\right)\left(1-a_{1}-a_{2}\right)}{\left(1+w\Lambda\left(x^{*}\right)\right)}\right)\left(z+i\right) \tag{5.8}$$

where:

$$I\left(\Lambda\left(x^{*}\right)\right)=\left(v\left(1-a_{1}-a_{2}\right)+a_{2}+\left(v-1\right) m\right)+$$
$$\frac{w}{\left(1+w\Lambda\left(x^{*}\right)\right)}\left(v-1\right)\left(1-a_{1}-a_{2}\right)$$

$U\left(\Lambda\left(x^{*}\right)\right) \frac{-dx^{*}}{d\Lambda^{*}}=\frac{w\Lambda}{(1+w\Lambda)^{2}}\left(v-1\right)\left(1-a_{1}-a_{2}\right)\left(i+z-wx^{*}\right)>0$ *if* $v<1$. *Under maintained assumptions,* $I\left(\Lambda\left(x^{*}\right)\right)=-\frac{(v-1)(1-a_{1}-a_{2})}{\left(1+w\Lambda\left(x^{*}\right)\right)^{2}}\left(\left(1+\left(w-1\right)\Lambda\left(x^{*}\right)\right)-w\frac{d\Lambda}{dx^{*}}\frac{dx^{*}}{dw}\right) x^{*}$. *The second part of the result follows by envelope theorem.* ■

Thus depletion rates fall with the allocation of oil resources to consumption due to the slower accumulation of productive capital. Moreover, for an increase in w, marginally utility falls more rapidly with higher oil consumption, raising incentives for the householder to preserve scant resources, thereby increasing the scale of the adjustment.

It follows that a shift in energy allocation away from household consumption has the potential to raise depletion and output growth: a 4 percent fall in the share of demand by households, for example – which, as evidenced by the literature survey at Appendix 5 represents an indicative order of potential magnitude for the UK by around mid century

– corresponds with a 5 percent reduction in depletion rates for plausible assumptions over preferences and income shares to resources.[65] [66]

Tax policy under a consumption spillover

Macroeconomic simulations of such allocative shifts in energy demand have not hitherto formally characterised the policy implications for energy taxation. I make an efficiency based argument here for differential taxation of energy across consumptive and productive usages. However, and importantly, any welfare gains should be appraised against the potential costs in terms of revenue leakage and additional complexity in tax administration.

To illustrate this, consider the following revised decision of the representative household, assuming the imposition of the optimal oil excise, is given by:

$$\underset{\{c(t),E(t),\chi(t)\}_{t=0}^{\infty}}{Max} V = \int_0^{\infty} (e^{-it} \left(\frac{c(t)^{1-v}}{1-v} + \frac{\left(\left(1-\chi\left(\bar{x}\right)\right) E\left(t\right)\right)^{1-w}}{1-w} \right) +$$

$$\lambda(t) \left(Q(\bar{S}, \bar{x}, Z_{\chi}) - \left(c(t) - y(t)\right) N(t) - \dot{K}(t) \right))dt \tag{5.9}$$

where $Q(., Z_{\chi}) = A(t)K(t)^{a_1}N(t)^{a_2}\left(\chi\left(\bar{x}\right)\left(1 - Z_{\chi}(t)\right) E\left(t\right)\right)$; Z_x represents an ad valorem surcharge on oil used in production; and the redistribution of revenues satisfies a balanced budget constraint given by: $y(t)N(t) = Z_x(t)\chi\left(.\right) E\left(t\right)$.

Lemma 5.3: Optimal policy warrants an additional levy on energy used in

---

[65] Specifically, $v = w = 1.5$, $a_1 = 0.34$, $a_2 = 0.6$ $\chi = 0.25$, $h = 2\%$, $n = 1\%$.

[66] Simulations which incorporate the influence of climate change on household energy demand into macroeconomic models without exhaustible resource inputs to production identify long terms output effects on the order of a few tenths of one percent of Gross Domestic Product (GDP) in magnitude (Aaheim et al. (2009), Bosello et al. (2009, 2007), Eboli et al. (2010), Jorgensen et al. (2009)). The sign of such effects often differ across regions, being negative for hotter regions (see, for example, Aaheim et al. (2009); Eboli et al. (2010)), and is disputed for some important economies such as the US (contrast the findings, for example, of Eboli et al. (2010) with those of Jorgensen et al. (2004)).

production, Z_χ to correct the distortion to the intra temporal allocation of oil resources, given by: $Z(t)_\chi = 1 - \frac{((1-\chi(x^*))E(t))^{-w}}{((1-\chi(\bar{x}))E(t))^{-w}}$**.**

Sketch proof. See Appendix D. ■

Optimal tax policy thus warrants an additional measure to correct the distortion to the intra temporal resource allocation. Such differential taxes on energy have been employed across a wide range of countries: in the UK, for example, diesel for agricultural uses has been subject to preferential excise treatment; while residential use of kerosene is more lightly taxed than aviation fuel in many developing countries.

However, these policies were originally designed with the objective of pursuing redistributive goals. Such arguments are generally considered weak in advanced countries where well developed social security systems offer alternative mechanisms for their achievement, which may be preferred both in theory and practice.

By contrast, this analysis presents an efficiency based rationale.[67] However, one should be mindful of the potential costs in terms of revenue leakage and additional complexity in tax administration. One key issue in this latter regard, concerns the risk of tax leakage from imperfect market discrimination.

Practical efforts to mitigate these risks have sometimes relied on colouration of fuels for particular usages, which can, in theory at least, be monitored. However, such responses are inevitably imperfect and costly to implement, particularly in countries with weak tax administration.

Consumption tax rates: numerical results

Appendix D summarizes currently available evidence concerning the potential responsiveness of energy demand to climatic conditions, and draws inference for potential correc-

[67] Diamond and Mirrlees (1971a, b), for example, show that, under certain key assumptions, it is preferable to tax final consumers, since it avoids distorting production decisions (which serve to erode the tax base). Such theories have had a profound influence on the evolution of modern tax systems, including growing international preferences for implementing a VAT. However, taxing externalities lies outside the general prescription that levies not be imposed on business inputs.

tive tax policies in the UK. These studies differ importantly in terms of their projections.

However, in broad terms, they project that climate change has the potential to impact residential heating demand in the range +2% to -10% by mid century (and suggest that industrial energy demand in invariant to temperature changes).

Equating $1 - \chi$ with the share of total energy use by households in the UK at 28 percent (DECC (2012)), Table 3 below provides a simple range of numerical results for the corrective tax on energy used in production under different assumptions over the size of the allocative shift and the preference parameter w. In the case of $w = 1$, for example, it suggests, for example, that a 4 percent shift in oil resources towards consumption implies an extra 3.1 percent ad valorem charge on oil allocated to production.

5.3 Environment, the macroeconomy and consumption habits

Despite the increasing popularity of inter-temporally non separable preference forms in modern macro theory, the classical separability assumption has typically been retained in the neoclassical exhaustible resource modelling.

A number of studies explore the implications of time dependent discount rates (Hepburn et al. (2010), Maeda and Nagaya (2010), Zhang (2013). However, research into the effects of consumption habits on growth and exhaustible resource depletion has thus far been rather scant (Valente (2011), Zhang (2013)).

This section analyses interactions between habit formation and the sustainability of growth in the presence of exhaustible resources, and considers the implications for both the macroeconomy and the design of corrective tax policy (together with possible interactions with other climate related externalities).

The representative agent is thus assumed here to have isoelastic preferences over consumption relative to average consumption levels in the preceding period as follows:

Table 2
Steady state gross interest rates with endogenous depreciation

		θ				
		0	0.05	0.10	0.15	0.2
m	0	16.67	-	-	-	-
	0.08	15.00	15.74	16.60	-	-
	0.1	13.75	14.32	14.97	-	-
	0.15	12.78	13.23	13.74	14.30	14.93
	0.2	12.00	12.37	12.78	13.23	13.72

(a) Expenditure tax

		θ				
		0	0.05	0.10	0.15	0.2
m	0	18.83	-	-	-	-
	0.08	16.75	17.61	18.60	-	-
	0.1	15.19	15.84	16.58	-	-
	0.15	13.97	14.49	15.06	15.07	15.70
	0.2	13.00	13.42	13.88	14.38	14.94

(b) Income tax

Table 3
Ad valorem corrective tax rates under consumption spillovers

This table provides a simple range of numerical results for the corrective tax on energy used in production tax under different assumptions over the magnitude of the spillover and the preference parameter w.

		$(1-\chi^*)\,/\,(1-\bar{\chi})$						
		0.90	.92	0.94	0.96	0.98	1.00	1.02
w	1	9.8	6.6	3.8	1.6	0.8	0	-0.8
	2	20.6	13.6	7.7	3.1	1.6	0	-1.6
	3	32.5	21.1	11.8	4.7	2.4	0	-2.4

$$\underset{\{c(t),E(t)\}_{t=0}^{\infty}}{Max} V = \sum_{0}^{\infty} (e^{-it} \frac{(c(t) - J(t))^{1-v} - 1}{1-v} +$$

$$\lambda(t) \left(Q(.) - c(t)N(t) - \dot{K}(t) \right)) \tag{5.10}$$

where $J(t) = \alpha c_a(t-1)$ (where c_a indicates the average consumption rate across all households). This is subject to initial conditions in both capital, labour and the stock of external habits:$K(0)$, $N(0)$, and $J(0)$.

Following Campbell and Cochrane (1999), I define the surplus ratio: $L(t) = \frac{(c(t)-J(t))}{c(t)} \leq 1$. Thus marginal utility in period t is given by:

$$U(C(t)) = e^{-it} (c(t) - J(t))^{-v} = e^{-it} L(t)^{-v} c(t)^{-v} \tag{5.11}$$

Differentiating (5.11) with respect to time and substituting for marginal utility and the shadow value of capital, yields the following consumption Euler:

$$\frac{v}{L(t)} \hat{c}(t) = r(t) - i - n \tag{5.12}$$

Thus incorporating external habits slows consumption growth (relative to the case in which $\alpha = 0$). Combining with the transition equation in physical capital, yields the following expression for the ratio of consumption to capital:

$$\hat{c}(t) - \hat{k}(t) = c(t)/k(t) + (n(v - L(t)) + L(t)r(t) - L(t)i)/v - r(t)/a_1 \tag{5.13}$$

Proposition 5.1: In the absence of an oil tax, the habit parameter increases steady state depletion and interest rates if $m < a_2$***.***

Sketch proof. Solving the revised system of equations involving the new consumption-capital transition given by 5.13 yields the following steady states expressions in interest rates, depletion, consumption-capital ratio, output growth and the surplus ratio:[68]

[68] By inspection these expressions reduce to the baseline case where $L = 1$, corresponding with the absence of preferences over a habit stock (L^* is naturally falling in the strength of the habit stock).

$$
\begin{aligned}
\left(C-\left(1-L^{*}\right)\left(a_{2}-m\right)\right) r^{*} = {} & vh+n\left(a_{2}+\left(v-L^{*}\right) m\right) \\
& +iL^{*}\left(a_{2}-m\right)-vz\left(1-a_{1}-a_{2}+m\right)
\end{aligned} \tag{5.14}
$$

$$
\begin{aligned}
& \left(C-\left(1-L^{*}\right)\left(a_{2}-m\right)\right) x^{*} = \\
& \qquad \left(v-L^{*}\right)\left(h-n\left(1-a_{1}-a_{2}\right)\right)+\left(1-a_{1}\right) L^{*}(i+z)
\end{aligned} \tag{5.15}
$$

$$
\begin{aligned}
& a_{1}\left(C-\left(1-L^{*}\right)\left(a_{2}-m\right)\right) c^{*}/k^{*} = \left(v-L^{*} a_{1}\right) = \\
& \quad \left(h-n\left(1-a_{1}-a_{2}\right)-\left(z+iL^{*}\left(1-a_{1}\right)\right)\right) + \\
& \qquad (n+j)\left(1-a_{1}\right)\left(C-\left(1-L^{*}\right)\left(a_{2}-m\right)\right)
\end{aligned} \tag{5.16}
$$

$$
\left(C-\left(1-L^{*}\right)\left(a_{2}-m\right)\right) g^{*} = L^{*}\left(h-\left(1-a_{1}-a_{2}\right) n-\left(1-a_{1}-a_{2}+m\right)(z+i)\right) \tag{5.17}
$$

$$
L^{*} = \left(1-\frac{\alpha}{1+g^{*}}\right) \tag{5.18}
$$

$\frac{dr^{*}}{d\alpha} > 0, \frac{dx^{*}}{d\alpha} > 0$ *under the stated conditions.* ■

α encourages households to defer consumption, given the positive influence on welfare (utility being formed over the difference rather than the level of the good demand). However, a higher growth rate strengthens the climate change externality, rendering consumption in the future more expensive relative to today. The overall influence on depletion and rental returns in the real economy therefore depends on the relative size of the two effects.

Tax policy under habit formation

This subsection examines the tax policy implications of external habit formation by comparing the consumption choices of the representative household with those of the social planner. The former is assumed to maximise the following:

$$\underset{\{c(t),E(t)\}_{t=0}^{\infty}}{Max} V = \sum_{0}^{\infty}(e^{-it}\frac{\left(c(t) - \bar{J}(t)\right)^{1-v} - 1}{1-v}+$$

$$\lambda(t)\left(\left(1 - Z_Q\right)Q(.) - N(t)\left(c(t)\left(1 - Z_c\right) + y(t)\right) - \dot{K}(t)\right)) \qquad (5.19)$$

where $\bar{J}(t) = \alpha c_a(t-1)$ indicates the external stock is considered invariant to her consumption decision, and Z_c is an ad valorem consumption tax, obeying the following intra temporal budget constraint: $Z(t)c(t)N(t) + Z(t)P(t) = y(t)N(t)$.

Differentiating the consumption first order condition with respect to time yields the following Euler equation:

$$\frac{v}{L(t)}\hat{c}(t) = \left(1 - Z_Q\right)r(t) - i - n - z_c(t) \qquad (5.20)$$

where $z_c(t) = \frac{\dot{Z}_c(t)}{1+Z_c(t)}$.

The social planner is assumed to maximise the following:

$$\underset{\{c(t),E(t)\}_{t=0}^{\infty}}{Max} V = \sum_{0}^{\infty}(e^{-it}\frac{\left(c(t) - \tilde{J}(t)\right)^{1-v} - 1}{1-v}+$$

$$\lambda(t)\left(\left(1 - Z_Q\right)Q(.) - c(t)N(t) - \dot{K}(t)\right)) \qquad (5.21)$$

where $\tilde{J}(t) = \alpha c_a(t-1)$ is an endogenously determined state variable.

Differentiating (5.21) with respect to $c(t)$ yields:

$$e^{-it}\left(c(t)^{SP} - J(t)^{SP}\right)^{-v} -$$

$$\alpha e^{-i(t+1)}\left(c(t+1)^{SP} - J(t+1)^{SP}\right)^{-v} = \lambda(t)^{SP}N(t) \qquad (5.22)$$

where the term $\alpha e^{-it+1}\left(c^{SP}(t+1) - J^{SP}(t+1)\right)^{-v}$ captures the negative influence on utility in period $t+1$.

Differentiating with respect to time and substituting from (5.20) gives the following consumption Euler for the social planner:

$$-i - v\hat{c}(t)\left(\frac{1}{L(t)^{SP}} + \frac{\alpha e^{-i}M(t)}{L(t+1)^{SP}\,(1+g(t))}\right) + \hat{\lambda}^{SP}(t) + n \tag{5.23}$$

where $M(t) = \frac{\left(c(t+1)^{SP} - J(t+1)^{SP}\right)^{-v}}{\left(c(t)^{SP} - J(t)^{SP}\right)^{-v}}$ is the ratio of indirect (due to the habit) and direct marginal effects on utility from consumption in period t.

Restricting attention to taxation on the balanced growth path, employing (5.18) and the marginal productivity of capital condition, this can be expressed:

$$\frac{v}{L^{SP}(t)}\left(\frac{\left(1+g^{SP}(t)\right) + \alpha e^{i}M(t)}{\left(1+g^{SP}(t)\right)}\right)\hat{c}^{SP}(t) = r(t)^{SP} - i - n \tag{5.24}$$

Lemma 5.5 The optimal consumption tax is increasing in the habit parameter.

Sketch proof. The optimal consumption tax path, at steady state, is calculated by equating (5.20) with (5.24), given by:

$$z_c^{*} = \left(\frac{\alpha e^{-i}M(t)}{\left(1+g^{SP}(t)\right) + \alpha e^{i}M(t)}\right)\left(r^{SP}(t) - i - n\right) \tag{5.25}$$

which is positive by inspection, and increasing in the habit parameter (provided $m < a_2$).

■ The householder has an excessively smooth consumption profile from the perspective of the social planner, by failing to capture the negative influence of her decision on marginal utility of other households as a result of a lower surplus ratio. The optimal consumption tax is thus rising to correct for this incentive.

Habit formation and spillovers affecting capital durability

Lemma 5.6 The optimal consumption tax is increasing in the habit parameter is falling in θ.

Sketch proof. This is evident by inspect of the following optimal tax expressions:

$$z_c^{*} = \left(\frac{\alpha e^{-i}M(t)}{\left(1+g^{SP}(t)\right) + \alpha e^{i}M(t)}\right)\left(r^{SP}(t) - i - n - \theta x^{SP}\right) \tag{5.26}$$

■ The prescribed consumption tax path is thus less steeply sloped, and the optimal capital tax rate reduced, in the presence of an environmental-resource impact to capital durability, due to the additional externality bearing on the consumption path and net returns.

5.4 Concluding remarks

The first part of this chapter analyses the macroeconomic and policy implications of intra temporal externalities from resource utilization affecting consumption markets. In contrast to the more standard approach of exploring the contributions of the energy sector to climate change, it analyses counter directional effects: in particular, the influence of changing weather conditions on residential heating and cooling demand.

I simulate the potential macroeconomic influence of climate change arising from shifting patterns of residential heating and cooling demand in the UK, and characterises previously unexplored implications for differential taxation of resources across usages: a shift in energy allocation away from household consumption due to climate change raises depletion and output growth and potentially warrants a surcharge on oil allocated to production.

Extending the theme on the importance of preference forms for the transmission of environment-economy spillovers, the second part of the chapter analyses the macroeconomic and policy implications of potential interactions between consumption habits and wider externalities from fossil fuel usage.

Despite the growing popularity of non separable time preferences within mainstream macroeconomics, research into the effects of consumption habits on growth and exhaustible resource depletion has thus far been rather scarce.

Introducing an external habit of the form adopted by Campbell and Cochrane (1999) causes steady state depletion and interest rates to rise provided the climate change externality is not too large.

Once again, the tax policy insights are sensitive to the form of economy-environment externality: in particular the prescribed consumption tax path is less steeply sloped in the presence of an environmental-resource impact to capital durability, which lowers net returns.

6 THE DISTRIBUTIONAL CONSEQUENCES OF ENERGY TAX REFORM IN THE UK

6.1 Introduction

The analysis above has thus far explored economic and policy issues arising from different possible macro linkages between exhaustible resource and the economy – under particular assumptions, including over the structure of preferences and the determinants of savings behaviour – within a dynamic, general equilibrium framework featuring a single representative agent.

Such approaches are helpful in framing this important global problem. However, we need to recognize that national level policy choices, in particular by the major emitters, will be critical to limiting the costs and risks associated with climate change. Concerns about the distributional consequences of more rational taxation of energy within countries rise to the fore in this context.

This chapter focuses on heterogeneity in the burden of climate and energy policy costs for the case of the UK.[69] It offers detailed appraisal of the economic and welfare consequences of potential indirect energy tax reforms within a static and partial equilibrium framework, in which behaviour differs across households. In particular, it seeks to address the following key questions:

What are the likely economic and revenue effects of imposing carbon taxes on all domestic fuels and standardizing their VAT treatment in the UK (domestic fuels are subject to a reduced rate of VAT, and direct carbon taxation on households is currently limited

[69] This chapter is a substantially revised and extended version of Jones (2012). It builds on this previous study in a number of key regards, including by: i) formally modelling the influence of socioeconomic variables on demand behaviour, ii) improving the underlying estimation techniques (based on less restrictive exogeneity assumptions) and robustness tests, and, iii) analysing the implications for welfare, including the influence of different preference forms in the SWF.

to electricity)?[70] What are the welfare consequences of such reforms, considering potentially divergent behavioural responses across socioeconomic groups? How are these costs influenced by any weighting over family size within the SWF, as well as allocative choices by government over any resulting revenues?[71]

From an efficiency perspective, the case for such reforms is compelling: the current reduced rate of VAT – 5 percent as compared to the standard rate of 20 percent – encourages economically costly substitution between domestic fuels and other commodities; while the absence of broad based carbon pricing generates incentives for excessive pollution ((Crawford et al. (2011), HM Treasury (1993)).[72]

However, the distributional consequences associated with indirect taxation of basic commodities, such as energy, are potentially more concerning; in particular, higher resulting prices may threaten the welfare of vulnerable groups. This is because lower income households are commonly more financially reliant on these goods, and may have more limited substitution possibilities than wealthier households (particularly in the short term).

In this context, relatively little analysis has been undertaken into how the burden of energy tax reforms in the UK – considering potentially important differences in behaviour –

[70] IFS highlight the substantial gaps which exist between the 2015 election policy statements and the fiscal adjustment targets of the major parties; and emphasise that VAT rates would likely need to rise to meet current deficit reduction goals, despite recent election promises to the contrary (similar statements were made prior to rate rises in the 2010-2015 Parliament) (Crawford et al. (2015)).

[71] Fullerton (2011) identifies 6 different economic channels through which energy taxes could impact the distribution of incomes and consumption, including, for example, higher product prices, shifting returns to factors of production and the incidence of resulting environmental benefits. This study is concerned narrowly with the direct economic and welfare costs of carbon and energy tax reforms.

[72] Despite mounting evidence on the economic risks from climate change, only electricity – which is covered by the EU Emissions Trading Scheme – is subject to a formal carbon charge in the household sector. The Climate Change Act (2008) sets ambitious targets for the UK to reduce GHG emissions by at least 34 percent by 2020 compared with 1990 levels.

might be shared across households and socioeconomic groups. Detailed micro level analysis is therefore needed to assess the distributional implications of more rational taxation of energy goods on vulnerable social groups, and to inform policy makers on appropriate expenditure policy adjustments for limiting the most serious inequities.

Existing research to data has typically assumed that UK household demand is unaffected by energy tax reforms (Baiocchi et al. (2010), Dresner and Ekins (2006), Druckman and Jackson (2008), Symons et al. (2002)). This risks over estimating the fiscal base and biasing welfare losses (an issue shown to be quantitatively important here). Pearson and Smith (1991) and Sterner (2007) analyse energy demand and tax revenues using average own price and expenditure elasticities, thereby failing to capture important behavioural differences across households which may critically influence tax incidence.

Heterogeneity in energy consumption behaviour has been studied in the context of UK space heating demand (Jamasb and Meier (2010), Meier and Reddanz (2010)) and transportation (Blow and Crawford (1997), Santos and Catchesides (2005)) within single equation estimation frameworks. However, by ignoring the influence of a broad set of cross price effects, these studies are unsuited to analysing the welfare effects of non marginal tax changes of the sort discussed below (Banks et al. (1996)).

Among the existing literature which captures such interactions, only Symons et al. (1994) and Jones (2012) have analysed the effects of carbon tax in the UK. However, market and technological conditions have evolved greatly in the 20 years since the former study was conducted, and the policy insights are weakened by the rather implausible tax rates simulated (around 10 times higher in real terms than current policy guidelines).

Jones (2012) is a more recent, but nascent, contribution on this topic; in particular, it does not formally model the influence of socioeconomic variables, or the implications of tax reform, on energy demand; or the implications for aggregate welfare. Moreover, the underlying estimation techniques impose highly restrictive exogeneity assumptions, and the specification and identification strategy is not subject to formal testing.

This chapter contributes to the rather limited stock of existing behavioural research into the distributional effects of energy tax reform in the UK in a number of key regards. First, it is the first behavioural study of carbon taxes, which analyses a broad set of cross price effects, to have been conducted since the liberalisation of electricity and natural gas markets.[73] Second, it is the first research to produce money metric estimates of the welfare consequences of such reforms, and to analyse the implications of different approaches to the aggregation within the SWF.[74] Finally, it provides insights into hitherto unexplored interactions between VAT and carbon tax changes.

The structure of this chapter is as follows. Section 6.2 presents a structural non linear demand model, originally due to Banks et al. (1997). Section 6.3 outlines the data sources and estimation approach. Section 6.4 presents the key findings in terms of the economic and welfare effects of VAT and carbon tax reform in the UK. Section 6.5 concludes.

6.2 A non linear model of structural demand

Analysing the distributional consequences of energy taxes requires a robust representation of consumer behaviour, which properly characterises the impact of income and relative price changes on consumption. However, these behavioural characteristics are likely to vary widely across households, rendering it important to capture their entire distribution when seeking to assess the incidence of energy and other indirect tax reforms.

[73] Johnson et al. (1990) and Symons et al. (1994) draw on data series ending in 1986. Marked changes in household energy usage and technologies have taken place since this time, including, for example, substantial efficiency gains in traditional appliance and the mass diffusion of information technologies.

[74] Money metric welfare estimates have been undertaken by Brännlund and Nordstrom (2004), Bureau (2011), Cornwell and Creedy (1997), Parshardes et al. (2014), Romero-Jordán and Sanz-Sanz (2009), Tiezzi (2005) and West and Williams (2004) for Sweden, France, Australia, Spain, Italy, Cyprus and the US respectively. Blow and Crawford (1997) analyse money metric welfare losses in UK gasoline markets only.

The standard analytic approach is to take the preferences of households as the primitive, and then analyze the consequences for behaviour (and the consistency of any econometric results with classical theory). In this context, I here extend a model first developed by Banks et al. (1997), itself an extension of the Almost Ideal Demand System (AIDS) of Deaton and Muellbauer (1980a), which has a number of attractive features

In particular, it is consistent with the axioms of choice, can be readily estimated at high degrees of disaggregation, allows the slope of the Engel curves to vary at different points in the expenditure range (such that goods may be luxuries at some income levels and necessities at others),[75] and, importantly, is shown to fit the data well. The structure of the model is outlined below.

Log indirect utility function is of the form:

$$\log X(\mathbf{p},\mathbf{z},\underline{m}) = \left(\left(\frac{(\log \underline{m} - \log(\Upsilon(\mathbf{p})))}{\Delta(\mathbf{p})}\right)^{-1} + \omega(\mathbf{p})\right)^{-1} \tag{6.1}$$

where $\underline{m}$ represents total household expenditure, $\mathbf{p}$ and $\mathbf{d}$ are vectors of prices and other controls respectively; $\Upsilon(\mathbf{p})$ is a continuously differentiable homogeneous function of degree one facing consumers in prices; $\Delta(\mathbf{p})$ and $\omega(\mathbf{p})$ are continuously differentiable homogeneous functions of degree zero.[76]

Extending Deaton and Muellbauer (1980a), the functions $\Upsilon(\mathbf{p})$ and $\Delta(\mathbf{p})$ take the following flexible form given by:

[75] This is shown to be empirically desirable below (see also Hausman et al. (1995); Banks et al. (1997)).

[76] Homothetic preferences imply that budget shares depend only on relative prices. However, Boppart (2014), for example, demonstrates that expenditure shares on goods are lower among rich compared to poor households in the US. He develops a model in which the marginal propensity to consume goods and services differs across the income spectrum, such that inequality affects the aggregate demand structure. This approach is used to explain the structural phenomenon of declining consumption shares to, and prices of, goods relative to services with the balanced output growth and stable interest rates which form the basis of Kaldor's stylized facts.

$$\log(\Upsilon(\mathbf{p},\mathbf{d})) = \alpha_0 + \sum_k \vartheta_{ik} d_{ik} + \sum_k \vartheta_{it} \Phi_{it} + \sum_i \alpha_i \log p_i + \frac{1}{2} \sum_i \sum_j \gamma_{ij} \log p_j \log p_i \quad (6.2)$$

where d_{ik} and Φ_{it} are demographic translators bearing on demand for good i (these controls have the interpretation of determining subsistence budget share requirements) and deterministic time trends respectively (note that prices are assumed to be homogeneous across households and are therefore not indexed by o).[77]

$\Delta(\mathbf{p})$ is the Cobb-Douglas price aggregator given by:

$$\Delta(\mathbf{p}) = \prod_i p^{\Delta_i^o} \quad (6.3)$$

where: $\Delta_i^o = \Delta_i^o + \Delta_i^{o,d} Dummy$, with $Dummy^o$ taking the form of an indicator variable, such as the presence of children in the family;[78]

$\omega(\mathbf{p})$ is assumed to take the form:

$$\omega(\mathbf{p}) = \sum_i \omega_i^o \log p_i \quad (6.4)$$

Differentiating $X(\mathbf{p}, \underline{m}^o, \mathbf{d})$ with respect to m^o, p_i, and substituting for the derivatives of the price aggregates, yields the following budget share equation for household o on good i, denoted by $share_i^o$:[79]

[77] The function $\Upsilon(\mathbf{p})$ is commonly approximated by a Stone index given by: $\sum_i share_i \log p_i$, where $share_i^o$ represent the expenditure share on good i. This index has the potential to introduce measurement error; for example it is not invariant to changes in the price units. A Laspeyres price index which replaces $share_i$ by $share_{i,a}$, the sample average budget share, is preferred (Moschini (1995)). However, in practice, these choices were not found to influence the parameter estimates materially (with a Laspeyres index employed).

[78] Demographic interactions with prices, for example, were not revealed by the data (unlike, for example, West and Williams (2004) in a study of US gasoline demand). D^o permits the expenditure reaction functions to vary according to household characteristics.

[79] These are derived from the indirect utility function using Roy's identity as follows: $share_i^o = \frac{p_i x_i^o}{\underline{m}^o} =$

The following budget share equation is thus estimated below:

$$share\,(\mathbf{p},\underline{m},\mathbf{z})_i^o=\alpha_i^o+\sum_k\vartheta_{ik}d_{ik}^o+\sum_k\vartheta_{it}\Phi_{it}+\sum_j\gamma_{ij}\log p_j+$$

$$\Delta_i^h\frac{(\log\underline{m}^o-log(\Upsilon(\mathbf{p})))}{\Upsilon\,(\mathbf{p},\mathbf{z})}+\frac{\omega_i^o}{\Delta(\mathbf{p})}\frac{\left(\log\underline{m}^h-\log(\Upsilon(\mathbf{p}))\right)^2}{\Upsilon\,(\mathbf{p},\mathbf{z})} \tag{6.5}$$

subject to these constraints which are derived (respectively) from the theoretical restrictions of adding up, symmetry and homogeneity:

$$\sum_i\gamma_{ij}=0,\sum_i\alpha_i=1,\sum_i\vartheta_{ik}=0,\sum_i\vartheta_{it}=0,\sum_i\Delta_i=0,\sum_i\omega_i{=}0 \tag{6.6}$$

$$\gamma_{ij}=\gamma_{ji} \tag{6.7}$$

$$\sum_j\gamma_{ij}=0 \tag{6.8}$$

Price and expenditure elasticities are derived by differentiating the budget share equation (for good i, say) with respect to $\log m^o$ and $\log p_j$ respectively (and substituting for $b'(\mathbf{p})$), yielding:

$$\Xi_i^o=\frac{\partial\delta share_i^o}{\partial\log\underline{m}^h}=\Delta_i+2\frac{\omega_i^o}{\Delta(\mathbf{p})}(log\underline{m}^o-log(\Upsilon(\mathbf{p}))) \tag{6.9}$$

$$\Xi_{ij}^o=\frac{\partial share_i^o}{\partial\log p_j}=\gamma_{ij}-\Xi_i^o\left(\alpha_j+\sum_k\gamma_{jk}\log p_k\right)-\frac{\omega_i^h\Delta_j}{\Delta(\mathbf{p})}\frac{(\log\underline{m}^o-log(\Upsilon(\mathbf{p}))^2}{\Upsilon\,(\mathbf{p},\mathbf{z})} \tag{6.10}$$

Price and income elasticity equations are related to the budget share equations as follows:

$\frac{p_i}{\underline{m}^o}\left(\frac{-\frac{\delta\log X(\mathbf{p},\underline{m}^o)}{\delta p_i}}{\frac{\delta\log X(\mathbf{p},\underline{m}^o)}{\delta\underline{m}^o}}\right)$.

$$e_i^o = \frac{\delta x_i^o}{\delta \underline{m}^o}\frac{\underline{m}^o}{x_i^h} = \frac{1}{w_i^o}\frac{\delta share_i^o}{\delta \log \underline{m}^o} + 1 = \frac{\Xi_i^o}{share_i^h} + 1 \tag{6.11}$$

$$e_{ij}^{o,u} = \frac{\delta x_i^o}{\delta p_j}\frac{p_j}{x_i^h} = \frac{1}{share_i^o}\frac{\delta share_i^o}{\delta \log p_j} - \delta_{ij} = \frac{\Xi_{ij}^o}{share_i^h} - \delta_{ij} \tag{6.12}$$

where δ_{ij} represents the Kronecker delta (equal to1 if $i = j$ and 0 otherwise).

Exploiting the Slutsky decomposition, compensated demand elasticities are given by:

$$e_{ij}^{o,c} = e_{ij}^{h,u} + \frac{e_i^o}{share_i^o} \tag{6.13}$$

I employ a Compensating Variation (CV) measure of welfare (which represents the amount of money a household would require to maintain pre reform levels of utility at post tax prices), given by:

$$CV^o = C(\mathbf{p}^1, U_0^o) - C(\mathbf{p}^0, U_0^o) \tag{6.14}$$

Banks et al. (1996) emphasise the importance of incorporating substitution effects into assessments of non marginal tax reforms of the sort analysed below. The authors show that a second order Taylor expansion of $C(\mathbf{p}^1, U_0^o)$ around $(\mathbf{p}^0, U_0^o)$ yields the following expression for CV:

$$\begin{aligned} C(\mathbf{p}^1, U_0^o) \approx C(\mathbf{p}^0, U_0^o) + \sum_j \frac{\delta C(\mathbf{p}^0, U_0^o)}{\delta p_j^0}\left(p_j^1 - p_j^0\right) + \\ \sum_j \sum_k \frac{\delta^2 C(\mathbf{p}^0, U_0^o)}{\delta p_j p_k}\left(p_j^1 - p_j^0\right)\left(p_k^1 - p_k^0\right) \end{aligned} \tag{6.15}$$

This can be re expressed in terms of observable variables as follows:

$$CV^o \approx k^o - \sum_j \sum_k \frac{\delta^2 C(\mathbf{p}^0, U_0^o)}{\delta p_j p_k}\frac{\left(p_j^1 - p_j^0\right)}{p_j^0}\left(1 + \sum_k e_{jk}^{o,c}\frac{(p_k^1 - p_k^0)}{p_k^0}\right) \tag{6.16}$$

where k^o is some transfer to household o satisfying, in aggregate, the government's revenue neutrality constraint, given by:

$$\sum_o y^o \leq \sum_o \sum_i Z_i^1 p_i^1 x_i^o - \sum_o \sum_i Z_i^0 p_i^0 x_i^o \tag{6.17}$$

6.3 Data and estimation

This chapter employs repeated cross sectional data on approximately 50,000 households drawn from the UK Family Expenditure Survey (FES) between 1986 and 2009.[80] This well known data source details household expenditures on around 50 different goods and services, including food products, fuels, and other regular domestic purchases. An extended discussion of the survey methodology, descriptive trends in the data, and estimation strategy is found at Appendix D.

The data have been aggregated into 7 commodity groups summarised in Table 4. These have been selected to make sense from a functional perspective (by grouping goods which have similar uses together), but also to reflect both different indirect tax treatments (in order to be relevant for tax and revenue analysis) and a detailed focus on energy products and policies.

This raises the potential for bias arising from "zero expenditures" (Blundell and Robin (1999), Keen (1986)). However, current options for resolving this issue in a system of equations remain limited: simply removing zero observations risks introducing selection bias; while censoring is technically extremely complex.[81]

[80] From 2001, the FES was combined with the National Food Survey and renamed the 'Expenditure and Food Survey' (EFS), before being renamed the 'Living Costs and Food Survey' (LCF) in 2009. The FES, EFS and LCF are hereafter used synonymously. Data on historical UK monthly temperatures are taken from the Met Office website: www.metoffice.gov.uk.

[81] I have sought to balance the risks associated through my choice of aggregation, which yields zero expenditures in less than 2 percent of the observations for most commodity groups, rising to around 15 percent for gas and gasoline. The parameter estimates are found to be fairly stable across the conditional and unconditional distributions.

Table 4
Description of commodity bundles

This table outlines the composite commodities which form the basis of the analysis, the individual goods over which these groupings are formed, together with their respective tax treatments, average sample expenditure shares and log prices.

Commodity Group	Individual commodities	Tax treatment	Average share of (non housing) budget, 2008	Weighted average log price
Food, non VAT	bread, cereals, beef, pork, lamb, fish, butter, oil, cheese, eggs, milk, coffee, tea, vegetables, chicken	Zero rate VAT.	0.20	5.78
Food, VAT	canteen, biscuits, soft drinks, confectionery	Standard rate VAT	0.11	6.29
Electricity		Reduced rate VAT	0.05	6.20
Gas		Reduced rate VAT	0.04	6.44
Gasoline	Gasoline, Diesel	VAT+Excise	0.07	6.55
General consumer	Consumer goods, pet care, telephone, domestic services, fees & subscriptions, chemicals, personal services, maintenance, tax & insurance,*men's clothing, women's clothing, footwear	Standard rate VAT	0.31	6.15
Leisure goods and services	Audio visual, records. toys, garden, entertainment, TV licence**	Standard rate VAT	0.22	6.50

*Insurance services are exempt from VAT, but subject to a 5 percent insurance premium tax (raised to 20 percent in 2015).

**TV licenses are exempt from VAT.

Endogeneity is an ubiquitous issue in applied economics given the potential for simultaneity bias, as well as measurement and/ or specification error. Empirical tests, presented below, clearly warrant estimation by Instrumental Variables (IV). However, non linear IV estimates of the complex range of economic and demographic factors bearing on household energy demand behaviour analysed below proved both slow to compile and somewhat unstable (the preferred demand specification has on the order of five hundred estimated parameters).

In light of this, I employ an iterated linear least squares estimator (ILLE) – which exploits the fact that the model outlined above is linear conditional on parameters – that is asymptotically equivalent to a non linear three stage least squares (3SLS) estimator and computationally highly attractive (see Blundell and Robin (1999), Lewbel and Pendakur (2009)).[82] The basic approach is as follows: let $\boldsymbol{\theta}$ be matrix all the parameters in the budget share equation (6.5) such that $\mathbf{share}^o = f(\boldsymbol{\theta}^\mathbf{o})$.

Given the observations on $\mathbf{share^o}$, I derive estimates, $\hat{\boldsymbol{\theta}}$, for the system of equations using linear 3SLS (employing an instrument vector $\mathbf{q}$, satisfying the moment conditions $E\left(\varepsilon'\mathbf{q}\right) = \mathbf{0}$). Predicted budget shares are generated, and the process repeated, taking the share estimates as data, to obtain a revised parameter vector $\hat{\hat{\boldsymbol{\theta}}} = \Theta\left(\hat{\mathbf{s}}\right)$. Further iterations take place until convergence to a fixed point, defined by $\hat{\hat{\boldsymbol{\theta}}} = \Theta_i\left[f(\mathbf{share}, \mathbf{p}, \hat{\hat{\boldsymbol{\theta}}})\right]$, is achieved.[83]

[82] Blundell and Robin (1999) formally derive a variant of this estimator. The near equivalence of the ILLE and Generalized Method of Moments (GMM) estimates is confirmed in Appendix D using a sample of available data. The ILLE is asymptotically consistent in the presence of heteroskedastic and non normal errors (and efficiency losses arising from heteroskedastic and non normal errors are shown to be small).

[83] Note that maintained assumptions on Jacobian symmetry require cross equation restrictions at each iteration. In practice, a high degree of convergence is achieved to high degree (10^{-6}) after five or six iterations.

6.4 Results

Determinants of demand

This section analyses empirical estimates of the relationship between prices, total expenditure and demographic controls for individual commodities, focussing on energy products.

Table 5 presents the key price and expenditure coefficients derived using both ordinary least squares (OLS) and ILLE estimators (this is for ease of reference given the complexity of the overall demand system in this study). Full sets of regression outputs, together with analysis of the predicted errors, are found at Appendix D. Following Banks et al. (1997) and Blundell and Robin (1999), I employ household income (and power transformations of) as an instrument for expenditure. Wu-Hausman tests clearly indicate a preference for the IV based estimates (Table 6 summarises the results of the key identification tests).

Table 5
Comparing key parameter estimates: OLS vs ILLE

This table shows IV and OLS price and expenditure estimates.

	Food (non VAT)		Food (VAT)		Electricity		Gas		Gasoline		Consumer	
	IV	OLS	IV	OLS	IV	OLS	IV	OLS	IV	OLS	IV	OLS
Log expenditure	-0.08	-0.11	-0.02	-0.02	-0.01	-0.03	-0.01	-0.02	-0.05	-0.03	-0.04	0.04
Log expenditure squared	0.02	-0.01	-0.02	-0.00	0.02	0.00	0.00	-0.00	-0.01	-0.01	-0.03	-0.00
Log price food (non VAT)	0.02	0.02	0.03	0.03	0.03	0.02	0.00	0.01	-0.02	-0.02	-0.07	-0.09
Log price food (VAT)	0.03	0.03	-0.08	-0.04	-0.02	-0.01	0.01	0.00	-0.01	-0.02	0.09	0.07
Log price electricity	0.03	0.02	-0.02	-0.01	-0.00	-0.01	0.00	0.01	0.00	0.01	0.00	0.00
Log price gas	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.01	0.01	-0.03	-0.02
Log price gasoline	-0.02	-0.02	-0.01	-0.02	0.00	0.01	0.01	0.01	0.04	0.03	-0.04	-0.05
Log price consumer	-0.07	-0.09	0.09	0.07	0.00	0.00	-0.03	-0.02	-0.04	-0.05	0.17	0.19
Constant	0.13	0.17	0.16	0.11	0.04	0.04	0.01	0.00	-0.04	-0.02	0.30	0.36

Table 6
Summary of identification tests

This table summarises the results of a number of key robustness checks. The data clearly support the case for IV estimation. The instruments for expenditure – household income (and power transformations of) – are highly informative; and Sargan tests do not appear to raise serious exogeneity issues.

	Food (non VAT)	Food (VAT)	Elect -tricity	Gas	Petrol	Cons -umer	Leisure
Wu Hausman (t-stat)	10.92	-13.94	4.31	-1.34	4.89	4.90	4.71
Sargan $\chi(1)^2$ (p-val)	3.24 (.07)	1.20 (.27)	2.78 (.09)	1.70 (.19)	1.31 (.25)	3.11 (.08)	1.28 (.26)
$\underline{m}^3$ (t-Test)	-.53	-.13	-.51	1.04	.35	1.05	1.12
Homogeneity (t-stat)	-.43	-.47	-.28	.05	.23	.80	.12
Instr. relevance (F-stat)	2999.9						
Symmetry LR $\chi(15)^2$ (p-val)	1						

*Prices and demographic variables (excluding interactions with expenditure) are assumed exogenous.

**Squared terms are significant in all equations except for food (non VAT); and tests on higher order expenditure terms are insignificant.

***Homogeneity holds regardless of whether symmetry is imposed (the reported t-statistics are for the unrestricted model). Symmetry is hereafter imposed to ensure consistency with micro theory and to simplify the subsequent behavioural analysis.

Various demographic variables significantly determine energy consumption, reinforcing the merits of the disaggregated approach adopted here. Budget shares to electricity and gas generally increase with the age of the household head, while that of gasoline observes the opposite trend.[84] Car ownership unsurprisingly has a significant upward bearing on gasoline demand, but has negative partial effects on domestic fuels (indicating larger heating bills among less mobile households). Interestingly, the presence of children interacts significantly with expenditure, reducing the slope of the Engel curve for domestic fuels (implying, perhaps not unreasonably, that fuels are a less essential good in a family setting).[85]

[84] Meier and Rehdanz (2010), for example, find that space heating expenditures increase with household size, average household age and number of children.

[85] There are also some discernible trends, for example, towards declining expenditure shares in natural gas and gasoline

Behavioural responses are most easily expressed in terms of elasticities: Table 7 summarises both expenditure and (uncompensated) own price elasticity estimates (fuller information regarding the distribution of elasticities is found at Appendix D). For domestic fuels, average expenditure responses are around the centre of the range of short run estimates identified in the wider literature, and slightly towards the upper end of the distribution of values in the case of gasoline (Espey and Espey (2004), Steinbuks (2011)).

However, the responses identified are widely dispersed (once again emphasising the value of this form of micro behavioural analysis). Average expenditure elasticities fall for petrol and gas as total expenditure rises. In the case of electricity, however, these have an inverted 's' shape, with an inflection point at total non housing related expenditure of around £25,000 per annum (and is inferior for more than 25 percent of households in the sample).[86] This rather interesting finding may relate to housing differences (controls are imposed for the number of rooms but not size, for example).

Fuel is on average inelastically demanded (with values toward the upper end (in absolute terms) of the short run price elasticities identified elsewhere in the literature (Espey and Espey (2004), Steinbuks (2011)). Gas and petrol become less price elastic among higher spending households. Price elasticities also observe rather different degrees of dispersion across energy products, varying considerably less for electricity than gasoline, for example (also compared to Blow and Crawford (1997)).

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from the mid 1990s and early 2000s respectively. This may reflect improvements in residential insulation and vehicle efficiency (as well as greater use of public transport and improved communications technologies).

[86] Baker et al. (1989) uncover a similar finding. The concept of a household production function in which high energy prices cause low wage families to devote more time to cooking and other energy intensive domestic activities may be relevant in this context (Becker (1965)).

Table 7
Expenditure and uncompensated own price elasticities

This table outlines average, median and inter quartile values for both expenditure and (uncompensated) own price elasticity estimates (denoted by superscripts w, 50, and 25/75 respectively).* All the fuels are necessary goods on average, with gasoline being the most expenditure elastic. However, all these values are highly dispersed, particularly in the case of electricity. Weighted own fuel price elasticities are all negative and imply price inelastic demand (particularly for gasoline).

	$e_i^{(w)}$	$e_i^{(75)}$	$e_i^{(50)}$	$e_i^{(25)}$	$e_{ii}^{u(w)}$	$e_{ii}^{u(75)}$	$e_{ij}^{u(50)}$	$e_{ij}^{u(25)}$
Food (non VAT)	0.38	0.53	0.34	0.02	-1.28	-1.21	-1.29	-1.45
Food (VAT)	1.10	1.36	1.12	0.95	-1.77	-1.55	-1.88	-2.57
Electricity	0.26	0.43	0.15	-0.22	-1.00	-0.99	-1.00	-1.01
Gas	0.57	0.64	0.46	0.23	-0.91	-0.80	-0.90	-0.95
Gasoline	0.63	0.79	0.61	0.29	-0.66	-0.39	-0.61	-0.75
Consumer	1.07	1.21	1.09	0.99	-0.51	-0.32	-0.50	-0.62
Leisure	1.78	2.98	2.02	1.56	-1.61	-1.43	-1.80	-2.55

*Averages are weighted by contribution of household to total expenditure on a given commodity.

Carbon tax and VAT reform: energy usage and revenues

This section simulates the effects of comprehensive VAT rate reform (in particular, the elimination of reduced and zero ratings on food and fuel), and the imposition of carbon taxes on gasoline and natural gas of £25 and £50 tCO2).[87] These tax reforms – discussed in detail in Appendix D – are modelled both independently and in combination (raising previously unaddressed questions regarding potential interaction effects).

Carbon taxes have potentially large predicted effects on aggregate fossil fuel demand, particularly for natural gas and to a lesser extent gasoline (detailed results are presented in Figure 10). These results are not readily comparable with Symons et al. (1994), the only other published study of this kind, given the widely divergent policy reform scenarios which are modelled (the tax rates are 4-10 fold higher than in this analysis).[88]

These increases are less marked when implemented in conjunction with VAT rate reform (due to both the fall in relative prices and real incomes), emphasising the merits of analysing interactions between indirect taxes. The impacts of VAT reform identified here are not dissimilar to the average reduction in domestic fuel demand of 4 percent projected by Johnson et al. (1990) arising from standardizing VAT at 15 percent, but are someway smaller than the 5.8 percent average reduction identified by Crawford and Smith (1993) in the case of a uniform 17.5 tax rate.

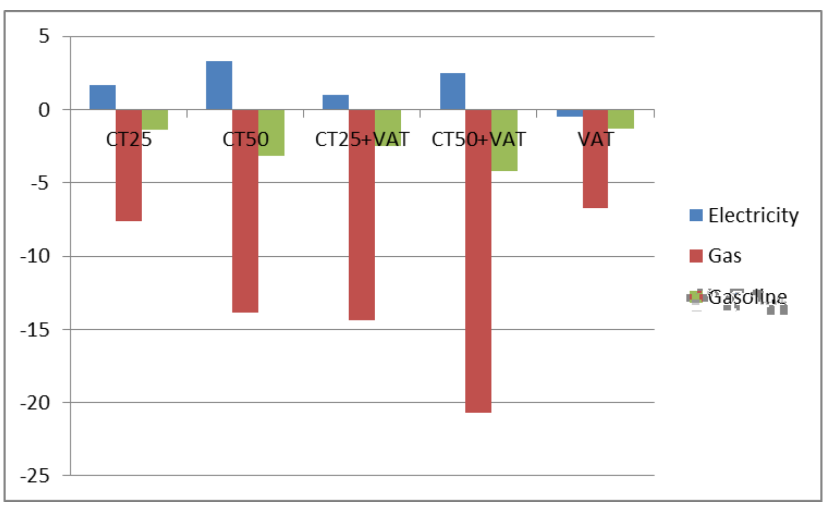
In terms of the distribution of behavioural responses, carbon taxes are predicted to result in much larger proportionate reductions among lower spending households for gas

[87] The gradual elimination of such anomalous treatment has been government policy since the early 1990s (HM Treasury (1993)). Note that VAT reform is simulated for 2008 at the then applicable general rate of 17.5 percent. The simulated carbon prices reflect government estimates of the levels currently required to achieve its objective of reducing emissions in the household sector (DECC (2009)).

[88] The authors predict a 24 percent reduction in gasoline related GHG emissions from a carbon tax levy of around £250 tCO2. Johnson et al. (1990) find that an excise on motor fuels alone, roughly equivalent to a carbon tax of £150 tCO2 in real value terms, reduces gasoline demand by 9 percent on average.

Figure 10
Percentage change in aggregate fuel demand by policy scenario

This figure summarises the percentage change in total sample demand for each fuel across policy scenarios under the assumption that all revenues are fully retained by the authorities. Carbon taxes (denoted in the subsequent figures by CT) have large predicted effects on fossil fuel demand, with aggregate reductions on the order of 7-21 percent and 1-4 percent for natural gas and gasoline respectively across scenarios. Electricity demand rises by approximately 1-3 percent in the case of the carbon tax scenarios. VAT reform in the absence of carbon taxes is predicted here to have more modest effects (although having important revenue benefits), reducing demand for electricity, gas and gasoline by around 0.3, 6.1 and 1.3 percent respectively.



and petrol (detailed results are presented in Table 8). This later finding appears to support Blow and Crawford (1997) – who find that that the lowest income quintile is roughly twice as price elastic (in an uncompensated sense) as the upper most – as compared to Johnson et al. (1990), who identify broadly homogeneous behavioural responses under a simulated increase in fuel excise duties.

Electricity demand, by contrast, adjusts to a greater degree among higher spending households across scenarios (a result which is not previously uncovered by studies on domestic fuels combined (Johnson et at (1990), Symons et al.(1994)).[89] VAT reform and carbon price reform combined appears to slightly widen the distribution of predicted behaviours: for example, demand reductions are relatively larger among lower spending households for gas and petrol under the combined policy reforms.

These potential tax changes are also shown to have substantial revenue raising potential, ranging from on the order of £(2008)5 to £(2008)30 billion across scenarios (shown in Figure 11): in a rare example of a revenue forecast based on such sophisticated behavioural analysis is rare, carbon taxes alone are predicted to have the potential to raise £(2008)5-10 billion.[90] This represents a considerable sum indeed (equivalent to between one-quarter and one-half of the total annual receipts from motor fuel excises, for example).

Welfare implications of energy tax reforms

I analyse aggregate welfare effects under two different possible specifications of the SWF:

[89] This could be associated with the prevalence of powerful negative income effects among poorer households, and strong cross price effects with both fuels and food. However, to some extent this type of result is a peril of such non linear models (similar anomalies are also found by Johnson et al. (1990) in analysis of VAT reform, for example).

[90] Dresner and Ekins (2006), for example, project revenues of around £1.2 billion annual from a tax of £10 tCO2 in the UK, assuming demand is invariant to prices and incomes. Estimate revenues of £(2008)22 billion from VAT reform closely parallels the result of Crawford et al. (2011).

Table 8
Distribution of percentage demand changes by expenditure decile

This table summarises the distribution of behavioural responses across expenditure deciles for three scenarios. A number of trends are apparent: in the case of the £25 tCO2 carbon tax, proportionate demand reductions are larger among lower spending households for gas and petrol: for example, the highest decile group lowers gas consumption by 1.6 percent, compared to 10.7 percent for the lowest. Electricity demand, by contrast, adjusts more among higher spending households across scenarios. This behavioural pattern appears to be reinforced when carbon taxes are implemented in conjunction with VAT reform.

Expenditure decile	Electricity	Gas	Petrol
Decile 1	0.5	-11.1	-4.8
Decile 2	0.9	-10.5	-4.3
Decile 3	1.1	-10.1	-3.9
Decile 4	1.5	-9.3	-3.7
Decile 5	1.6	-8.7	-3.5
Decile 6	1.9	-8.5	-3.1
Decile 7	1.9	-7.8	-3.1
Decile 8	2.3	-6.6	-2.9
Decile 9	3.0	-5.5	-2.5
Decile 10	4.1	-3.8	-1.3
Aggregate Sample	1.7	-7.6	-1.4

(a) Carbon tax £25 tCO2

Expenditure decile	Electricity	Gas	Petrol
Decile 1	-7.0	-20.1	-5.2
Decile 2	-4.2	-19.2	-4.8
Decile 3	-2.9	-18.5	-4.5
Decile 4	-0.7	-17.2	-4.3
Decile 5	0.1	-16.3	-4.2
Decile 6	2.2	-15.8	-3.9
Decile 7	2.7	-14.7	-3.9
Decile 8	5.0	-12.7	-3.7
Decile 9	9.6	-10.9	-3.4
Decile 10	17.5	-8.1	-2.4
Aggregate Sample	1.0	-14.4	-2.5

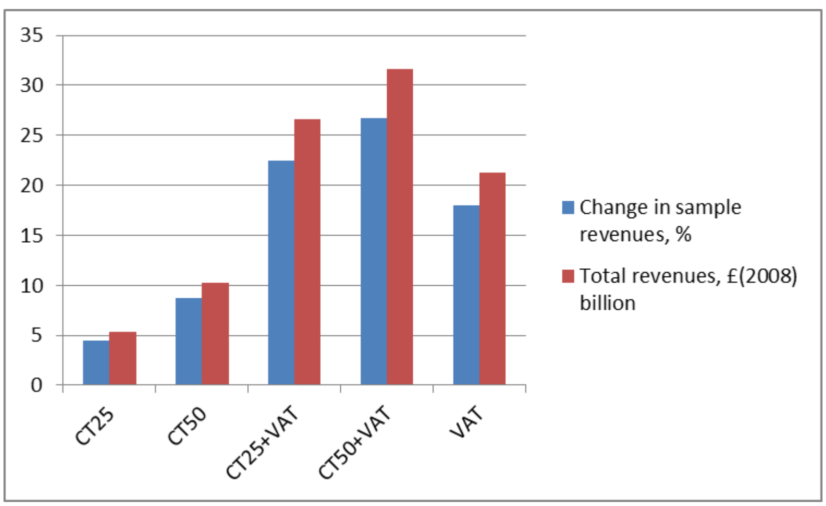
(b) Carbon tax £25 tCO2 + VAT

Expenditure decile	Electricity	Gas	Petrol
Decile 1	-7.5	-9.6	-0.5
Decile 2	-5.0	-9.1	-0.6
Decile 3	-3.9	-8.8	-0.7
Decile 4	-2.0	-8.1	-0.8
Decile 5	-1.3	-7.7	-0.8
Decile 6	0.5	-7.4	-0.9
Decile 7	0.9	-6.9	-0.9
Decile 8	2.9	-5.8	-0.9
Decile 9	6.9	-5.0	-1.0
Decile 10	13.8	-3.5	-1.3
Aggregate Sample	-0.4	-6.7	-1.3

(c) VAT only

Figure 11
Revenue effects by policy scenario

This table 11 summarises the implications of each scenario for total sample revenues under each scenario, and draws inference for the Exchequer. The removal of reduced and zero rates of VAT on domestic fuel and food, increases sample revenues by around 21 percent. Given that combined fuel excise and VAT receipts totalled around £105 billion in 2008 (HM Treasury (2009)), this represents additional potential revenue of around £22 billion in that year.* It also highlights the important revenue earning potential of carbon taxes: a levy of £50 tCO2, for example, is projected to increase sample tax revenues by around 10 percent, equivalent to around £10.5 billion in that year.



*This assumes the sample is representative of the collective tax base (an issue discussed further in Appendix D).

a) an unweighted utilitarian function given by $SWF_a = \sum_o \frac{C_o^{1-v}-1}{1-v}$; and, b) a function in which aggregate welfare is weighted by the number of household members, N_o, such that $SWF_b = \sum_o \left(N_o \frac{C_h^{1-v}-1}{1-v} \right)$. The results are shown in Table 9 for each policy scenario under plausible values of inequality aversion, v.

As outlined previously, a key feature of this analysis, is its detailed behavioural framework, which provides a robust foundation for the appraisal of welfare implications. This is highlighted by a comparison of such estimated effects with those derived under a model in which demand is invariant to prices. These findings are materially different – commonly higher by on the order of 4-18 percent higher – to those presented above (shown in Appendix D).

Table 9 shows the welfare losses in the event that revenues are fully retained by the government (a choice which is difficult to discount given the current fiscal situation in the UK), and their sensitivity to assumptions over both the form of the SWF and parameter choices over v. These are found to be potentially substantial, particularly for scenarios involving both VAT and carbon tax reform, and in the cases of either a weighted SWF and/or a low degree of inequality aversion.

The welfare consequences of energy tax reforms are affected by the choice of government over the allocation of revenues (explored in Table 10):[91] in particular, the opportunities to curb aggregate welfare losses differ according to the allocation mechanism adopted, but also, importantly, with the form of the SWF (the scope for aggregate welfare gains being generally greater where this is weighted by family size).

Turning to indirect tax incidence questions in more detail, Table 11 analyses the distri-

[91] The implications of revenue choices for carbon tax incidence has been a recent focus in the literature, but have assumed demand is invariant to after tax prices (see Mathur and Morris (2014), Dinan (2012) for leading examples undertaken for the US). Symons et al. (1994) analyse the potential impact of carbon tax receipts for the distribution of expenditure in the UK.

Table 9
Aggregate welfare losses by policy scenario, percentage

This table summarizes the percentage welfare losses under each policy scenario and SWF. Across tax reform scenarios, the aggregate utility effects have the potential to be substantial: for the case of logarithmic utility ($v = 1$) and an unweighted SWF, carbon taxes result in between a 0.18 and 0.36 percent reduction in total welfare. This rises to between 0.96 and and 1.13 percent when implemented in conjunction with VAT reform. The welfare implications are highly sensitive to both the form of the SWF and the inequality aversion parameter. In the case of the former, aggregate losses are roughly 2-2.5 fold higher across scenarios if household welfare is weighted by the size of the family (compared to the unweighted case). A higher value of v reduces the aggregate welfare costs across tax reforms and SWFs – because although the total demand reductions are among highest in aggregate terms at higher consumption levels, the effects are outweighed by lower marginal utility – falling by more than 95 percent if $v = 3$ as compared to the case of logarithmic utility.

v	1	2	3
CT25	-0.184	-0.008	-0.000
CT50	-0.361	-0.015	-0.000
CT25+VAT	-0.957	-0.048	-0.002
CT50+VAT	-1.128	-0.055	-0.002
VAT	-0.774	-0.039	-0.001

(a) Unweighted: SWF_a

v	1	2	3
CT25	-0.420	-0.013	-0.000
CT50	-0.827	-0.026	-0.001
CT25+VAT	-2.146	-0.082	-0.002
CT50+VAT	-2.537	-0.095	-0.003
VAT	-1.730	-0.067	-0.002

(b) Weighted: SWF_b

Table 10
Aggregate welfare losses by revenue recycling scenario, percentage

This table summarizes the effects of full revenue recycling – through lump sum transfers and upticks in child and unemployment benefit respectively – for the cases of the carbon tax of £25 tCO2 (implemented both with and without VAT reform) and VAT reform, under the posited forms of SWF given by SWF_a and SWF_b. It confirms that such expenditure measures have strong potential to limit aggregate welfare costs. In the case of the unweighted SWF, SWF_a, unemployment benefit is the most effective mechanism among those considered (abstracting from any labour market effects), yielding aggregate welfare gains; while lump sum transfers to households are preferred to child benefit increases (across scenarios and degrees of inequality aversion). In the case of the weighted SWF, SWF_b, the scope for Dalton improving indirect tax reform appears more prevalent, with significant opportunities across all the revenue recycling options analysed.

v	1	2	3
No Recycling	-0.184	-0.008	-0.000
Lump Sum	0.057	0.011	0.001
Child benefit	-0.029	-0.001	0.000
Unemployment benefit	0.154	0.020	0.001

(a) Carbon tax £25, SWF_a

v	1	2	3
No Recycling	-0.420	-0.013	-0.000
Lump Sum	0.028	0.013	0.001
Child benefit	0.125	0.008	0.000
Unemployment benefit	0.044	0.020	0.001

(b) Carbon tax £25, SWF_b

v	1	2	3
No Recycling	-0.957	-0.048	-0.002
Lump Sum	0.263	0.040	0.002
Child benefit	-0.208	-0.021	-0.001
Unemployment benefit	0.559	0.055	0.002

(c) Carbon tax £25 +VAT, SWF_a

v	1	2	3
No Recycling	-2.146	-0.082	-0.002
Lump Sum	0.137	0.048	0.003
Child benefit	0.505	0.008	-0.000
Unemployment benefit	-0.024	0.046	0.002

(d) Carbon tax £25 +VAT, SWF_b

v	1	2	3
No Recycling	-0.774	-0.039	-0.001
Lump Sum	0.203	0.032	0.002
Child benefit	-0.168	-0.017	-0.001
Unemployment benefit	0.473	0.048	0.002

(e) VAT, SWF_a

v	1	2	3
No Recycling	-1.730	-0.067	-0.002
Lump Sum	0.094	0.038	0.003
Child benefit	0.409	0.007	-0.000
Unemployment benefit	0.008	0.042	0.002

(f) VAT, SWF_b

bution of CVs by expenditure decile across scenarios.[92] These show that higher spending households assume a greater degree of the absolute burden of indirect taxes, but that in proportionate terms the costs are greater on low spending households.

6.5 Concluding remarks

Energy tax reform is urgently needed to both raise public revenues and deliver stated commitments to reduce GHG emissions; in particular, such policies have the potential to promote both greater conservation of energy and substitution from carbon based fuels to cleaner alternatives (particularly important during a period of low fossil fuel prices, despite recent advancements in renewable technologies such as solar).

The process of charging for GHG emissions has substantively begun with the introduction of the EU ETS in 2005. Coordinating the reinforcement and expansion of this scheme with environmental levies on domestic fuels such as gas and gasoline – which are currently exempt from environmental levies – is an important priority in this context.

While the economic efficiency case is compelling, the distributional consequences of taxing basic commodities such as energy, are potentially concerning, because lower income households are commonly more financially reliant on these goods, and may have more limited substitution possibilities than wealthier households (particularly in the short term).

Despite the emergence of these reform issues, detailed evidence on economic and welfare impacts of policy implementation remains scant. A better understanding of the distributional implications of more rational taxation of energy is key to informing policy design, and limiting the most serious inequities through appropriate expenditure policy adjustments.

[92] In a single equation study, Blow and Crawford (1997), find that a 40 percent increase in excise duty, would require average compensation equivalent to around 1 percent of total expenditure.

Table 11
Distribution of compensating variation by expenditure decile

This table shows the distribution of CVs by expenditure decile. In each scenario, higher spending households assume a greater degree of the absolute burden of indirect taxes. A carbon tax of £25 tCO_2, for instance, is projected to cost a household at the 75th percentile of the expenditure distribution around £4 per week in welfare terms, roughly double that of the family at the 25th percentile. However, expressed in proportion to total expenditure, the costs are greater on low spending households: a carbon tax of £25 tCO_2, implemented in conjunction with VAT rate reform, would require compensation equal to 7 percent of total weekly expenditure to maintain the welfare of the household at the 25th percentile, a figure which falls to around 4 percent for the family at the 75th percentile. Broadly speaking, the degree of regressivity is similar across reform scenarios.

	CT25	CT50	CT25+VAT	CT50+VAT	VAT
1	0.55	1.04	3.85	4.31	3.32
2	1.01	1.93	6.02	6.87	5.04
3	1.44	2.79	7.77	9.02	6.37
4	1.75	3.40	8.45	9.98	6.79
5	1.96	3.83	9.36	11.08	7.51
6	2.32	4.55	11.18	13.23	9.00
7	2.79	5.48	11.87	14.34	9.24
8	3.06	6.03	13.63	16.34	10.77
9	3.56	7.05	14.42	17.58	11.11
10	4.51	8.94	17.67	21.70	13.50

(a) Mean weekly compensating variation by expenditure decile (£2008)

	CT25	CT50	CT25+VAT	CT50+VAT	VAT
1	1.12	2.13	8.09	9.02	6.99
2	1.14	2.19	6.75	7.72	5.65
3	1.16	2.25	6.25	7.26	5.12
4	1.09	2.13	5.28	6.23	4.24
5	1.00	1.97	4.79	5.68	3.84
6	0.98	1.92	4.71	5.57	3.79
7	0.96	1.89	4.08	4.93	3.18
8	0.85	1.68	3.80	4.56	3.00
9	0.77	1.52	3.11	3.79	2.40
10	0.63	1.24	2.45	3.01	1.87

(b) Mean weekly compensating variation by expenditure decile (percentage total expenditure)

This chapter demonstrates the large potential of carbon tax and VAT reform to help curb emissions, but the substantial heterogeneity in the likely behavioural responses across socioeconomic groups. It also highlights the possibility of complex and potentially unforeseen interaction effects if these measures are implemented together, emphasising the desirability of sequencing any reforms.

Carbon tax and VAT reform are also shown to have substantial revenue earning potential, which is particularly valuable in the context of reducing the fiscal deficit given the increasingly apparent rigidities in public expenditures (budgets for health, education, defence equipment, overseas aid and debt repayments are effectively protected from further retrenchment).

Ultimately, however, governments are concerned for public welfare (rather than narrow economic impacts). In this regard, the sensitivity of utility losses identified above – together with the efficacy of possible compensation mechanisms – to both the behavioural structure of this analysis, and the precise form of the SWF, warrants particular regard by policy makers considering changes in this area.

7 CONCLUSIONS, LIMITATIONS AND FUTURE EXTENSIONS

7.1 Limitations

A degree of circumspection is required when considering the merits of the various contributions presented above, and planning for their future reinforcement and extension. In this context, it is worth reminding oneself of the host of simplifying assumptions underpinning the theoretical modeling in Chapters 3 and 5 (many of which are nevertheless common place in the literature).

The theoretical models are intended to facilitate insights into the relationship between different environmental effects on the economy, and the influence of key supporting assumptions, as part of efforts to improve the development of climate and wider environmental policy guidance. However, they are inevitably a simplistic representation of, for example, the structure of the economy, technological development and household decision making.

One particularly stern tenet is that of determinism, a criticism which applies broadly in the climate change literature (Pindyck (2013), Stern (2013)). The dimensions of uncertainty affecting such dynamic control problems abound. They include, but are not limited to: the magnitude of stocks, the nature and extent of externality effects, the productivity of investment returns, and even preference parameters.[93]

In terms of the underlying externality effects, for example, an emerging literature has studied the macroeconomic impacts of, and policy responses to, new patterns of natural

[93] Arguably, economists are still searching for robust intellectual frameworks with which to analyse the implications of climate change given the uncertainty which surrounds its possible effects, including the small, but positive, possibility of economic catastrophe (see, for example, Weitzman (2009, 2001)).

disasters – emphasising the potentially important bearing that heightened climatic variability has on the certainty equivalent of investment returns (see, for example Bretschger and Vinogradova (2014), Ikefuji and Hori (2012), Soretz (2007)).[94]

The role of policy in Chapters 3 and 5 is limited to tax-induced substitution between natural and physical capital. As such, they ignore the potential macroeconomic effects of allocating resources to "defensive" technologies and behavioural changes, likely to be an important component of the overall response to climate change (see, for example, Bosello et al. (2009), Millner and Dietz (2015)).[95]

In terms of the representation of production, by incorporating a single fossil energy good, the theoretical models employed do not capture potentially important inter-fuel substitutions, for example between coal and natural gas, and increasingly, renewable energy sources (see, for example, Green (2009) for an overview of the market potential, cost and systems implications of diffusing these technologies).[96]

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[94] Ikefuji and Hori (2012), for example, analyse a model in which pollution increases the occurrence rate of destructive natural disasters. The authors find that the optimal growth rate initially rises, but ultimately declines (since falling productivity cannot be compensated for by faster human capital accumulation or more rapid convergence of the disaster risk). Soretz (2007) finds that, if the variability of capital returns is inversely related to environmental quality, uncertainty has an ambiguous impact on the optimal pollution level since the riskiness of environmental productivity reduces the certainty equivalent of capital return. However, Bretschger and Vinogradova (2014) emphasise that the insights from these studies are limited to simple expectational effects in the presence of risk aversion given the assumption that environmental shocks are idiosyncratic.

[95] An extensive (and related) literature analyses the impacts of environmental policies on growth and employment. The literature on "green growth" is generally mixed in its conclusions (and oftentimes subject to considerable definitional issues). On balance, however, the productivity and employment potential of environmental policies are likely to be small at the macroeconomic level and, in aggregate, negative - particularly in energy intensive economies (see, for example, Bowen (2012), Elliott and Lindley (2014), Jones (2011)).

[96] In exhaustible resource economics, such technologies are commonly modelled as a backstop. Heal (1976) demonstrates that existence of a backstop – coupled with rising extraction costs, causes resource rent to fall over time as the switch point draws closer. The inclusion of extraction costs (for simplicity, I have assumed these to be zero) has limited implications for extraction pathways where these are a constant proportion of energy prices (Stiglitz (1976)), but would otherwise complicate the analysis (for example, the shadow price of the resource increases more slowly if costs increase with cumulative extraction).

In addition, the assumption of a single consumption good does not take account of the potential for structural changes within an economy – for example, between energy intensive manufacturing to cleaner forms of economic output such as in the tertiary sector – which influence fossil fuel usage (changes which are increasingly in evidence today in countries such as China).

Another key dimension of the climate change problem which is ignored here concerns international aspects of climate policy. There is a large game theoretic literature which analyses strategic interactions between nation states in the presence of free rider incentives (see, for example, Barrett (2003), Bloch (1997), Finus (2001) and Rubio and Ulph (2006, 2008)).

This literature generally finds limited prospects for a stable and effective climate coalition, emphasising the likelihood of either "narrow but deep" or "broad but shallow" international agreements (and within heterogeneous frameworks, suggests the need for rather unpalatable transfers from the most (commonly poor) to the least (mostly rich) affected countries).[97]

Thankfully, however, given the wide variation in abatement costs across countries (OECD (2013a)), a number of research developments may offer more promise of effective future coalescence – following on from the recent international agreement in Paris[98] – based on the possibility of multiple coalitions,as well as broader motivations for cooperation (involving, for example, concerns over concepts of fairness) (see Hovi et al. (2015)

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[97] "Coalition" models, in which countries first decide to participate in an agreement and subsequently choose abatement levels to maximise the welfare of participants, find the (Nash) equilibrium number of signatories is no greater than three. In repeated game models, broad and deep commitments suffer stability issues because enforcement strategies (subsequent non cooperation by other coalition members) are mutually harmful, weakening their credibility (Hovi et al. (2015)).

[98] Note, however, that the commitments enshrined in this agreement are likely to be only partially implemented (see, for example, George Monbiot writing in the Guardian 12 December 2015).

for a recent review of a now voluminous literature).

Nevertheless, one important determinant of incentives to cooperative continues to concern the risk that energy intensive, trade exposed, production could relocate to countries outside a climate coalition. Although widely considered to be a key impediment to cooperation (being often politically highly resonant), the literature generally finds weak empirical evidence for "pollution havens".[99]

7.2 Conclusions

This thesis is principally concerned with the economic implications of climate change, which is one of the most pressing long run challenges of our time: Stern (2007) cogently argue that emissions of GHGs constitute "the greatest market failure the world has ever seen". They conclude that, if unchecked, the overall costs of climate change would be equivalent to a permanent loss of at least 5 percent of global income.

While the low discount rate which the authors apply to the future economic costs remains the subject of much debate, the basic conclusion concerning the underlying seriousness of the issue appears sound: on current assessment, global surface temperatures are likely to rise by 2.6-4.8 degrees C – a magnitude which risks large scale economic disruption.

Determining, in economic terms, how seriously to take the problem is a key issue. This question is embodied in the ongoing debate concerning the SCC – the economic damages associated with a small increase in CO2 emissions – but is a challenging undertaking given the complexity of the externality problem (although one which is difficult for economists

[99] In this context, the merits of imposing border tariffs on the carbon content of imports from non cooperating countries have emerged in policy discourse (see Jones et al. (2013) for a discussion). While these are a potentially credible mechanism for encouraging a broader coalition, they may be complex to administrate and potentially subverted in order to hide tariffs or export subsidies.

to ignore).

In this context, a recent debate in the literature has emerged concerning the quality of the policy advice which is derived from IAMs, the central analytic tools underpinning such assessments. Stern (2013) argues, for example, that the damage functions which determine the external effects of energy usage on the economy need to incorporate a broader set of environment-economy interactions.

The other main component of these models is the welfare function. Here, the overwhelming focus in the recent research literature has been on the appropriate discount rate – clearly an important dimension to managing this (and other) long term resource allocation problems,

However, a number of important issues have thus far received little attention in this context including, for example, analysis of interactions between production externalities and different approaches to welfare aggregation (drawing on important lessons from the social choice literature) and consumption habits (increasingly commonplace in modern macro economics).

Chapters 3 - 5 constitute concerted efforts to respond to these challenges by analysing a range of potential environmental effects on the economy, including on capital formation, demographics and consumption patterns (reflecting the fact that energy use is likely to impose multiple social costs on the economy), thereby exposing new insights into the resulting effects under particular assumptions over savings and preferences.

Chapter 3 focusses specifically on the direct effects of climate change on physical capital (highlighted as a priority area for model development by Stern (2013)): buildings and infrastructure, for example, are expected to suffer additional damages from coastal flooding, more powerful wind storms, and subsidence due to more intense rainfall or melting permafrost (Field et al. (2014)); while water scarcity could make some settlements or infrastructure unsustainable.

A few studies to date have analysed these effects (Fankhauser and Tol (2005), Moore and Diaz (2015)). However, these contributions, by employing production functions with only capital and labour, ignore potentially important interactions with the exhaustible character of fossil fuel inputs, which arise because more rapid depreciation affects the Hotelling portfolio condition (by lowering net returns to investment).

Only Bretschger and Valente (2011) have studied this linkage. The authors find that spillovers affecting capital durability influence the level of output but not its growth rate. However, they do not consider the critical role that assumptions over savings behaviour play in this insight, nor questions relating to fiscal policy design (or interactions herewith). In this context, I show that:

- the finding of Bretschger and Valente (2011) rests crucially on assumptions that inter temporal consumption and savings decision making are forward looking. If savings behaviour follows a "Keynesian" rule of thumb, for example, such capital linkages are shown to have negative effects on the time path of output in steady state;[100]
- such direct capital channels have non trivial macroeconomic effects, potentially resulting in a fall in output growth, for example, on the order of 0.05 percent for the Keynesian model under plausible parameter values;
- spillovers affecting capital durability warrant a less steeply declining corrective tax path; and,
- distortions are substantially exacerbated by the presence of an income tax, but are unaffected by public financing requirements if net investment is exempted from the tax base (assuming here that revenues are recycled in lump sum fashion).

[100] The consumption Euler is subject to wider empirical issues, including excess sensitivity to income (Campbell and Mankiw (1998, 1991). Scholars increasingly emphasise, for example, the role of financial innovation and increased liquidity of housing wealth as a determinant of consumption growth patterns in the UK and US (Muellbauer and Murphy (1990), Duca et al. (2012)).

Chapter 4 focuses on the external effects of resource exploitation on demographics. Energy combustion is a major source of air pollutants, an issue which has come into sharp focus with the recent US corporate scandal involving emissions from diesel cars (and "red alerts" over smog in China which prompted mass closure of schools and the imposition of vehicle restrictions).[101]

Pollutants from fossil fuels are strongly linked to human mortality rates in both the epidemiological and social scientific literature: Lim et al. (2013), for example, attribute around 7 percent of global disease to ambient air pollution, around 80 percent of which is due to energy combustion (GEA (2012)).

Links between the climate externality and mortality rates have also been established with some confidence, for example as a result of more frequent and intense heat waves, or through more profligate spread of tropical diseases, such as dengue of malaria. Despite this, growth models featuring exhaustible resources have thus far tended to assume population growth to be exogenous.

Notable exceptions in this context include studies of interactions between resource scarcity, demographics and technological development (Peretto and Valente (2015), Schäfer (2014a)). In contrast, this chapter focuses on the macroeconomic and policy implications of mortality effects (and wider productive externalities), and on the role of preferences over welfare aggregation. In particular, it demonstrates that:

- spillovers affecting mortality have countervailing macroeconomic effects to those arising from capital durability studied in the previous chapter. The former dominate in an optimal growth setting, but are parameter dependent in the Keynesian model;

[101] This issue is increasingly shaping policy in developing countries: in 2013, for example, the Chinese government published an Action Plan for the Prevention and Control of Air Pollution which aims to reduce PM10 concentrations by 10 per cent from 2012 levels nationwide by 2017.

- if the social planner places positive weight on aggregate (rather than average) felicity levels, mortality spillovers potentially imply a 'u' shaped tax path, a policy prescription which diverges from the basic downward sloping paths identified in the resource tax literature; and,
- an exogenous mortality hazard unambiguously increases steady state interest and depletion rates, but in an endogenous setting, the effect of the demographic spillover on interest rates is dependent on interactions between the resulting incentives on the young to save and the Hotelling condition.

Chapter 5 focusses on potential spillovers from energy use to consumption, and their implications for macroeconomic and policy development. It contributes to an emerging body of research highlighting the potential impact of climate change on residential energy demand (Amato et al. (2005), Rosenthal et al. (1995), Ruth and Lin (2006), Scott et al. (1994)); in particular, it demonstrates that a spillover affecting the division of oil resources from consumption to production (as might be expected in the cold and temperate climates) has:

- positive implications for output growth and depletion levels due to faster accumulation of productive capital, provided inter-temporal substitution is sufficiently inelastic; and,
- previously unexplored implications for differential taxation of resources across usages.

The chapter also analyses the macroeconomic and policy implications of fossil fuel usage in the presence of consumption habits: despite the growing popularity of consumption habits within mainstream macroeconomics (Campbell and Cochrane (1999), Fuhrer (2000), Smets and Wouters (2007)), these innovations have been almost universally overlooked in resource economics (Schäfer and Valente (2014a, 2011), Zhang (2013)). I show that:

- introducing an external habit of the form adopted by Campbell and Cochrane (1999) causes steady state depletion and interest rates to rise provided the climate change externality is not too large; and,
- consumption externalities interact with spillovers to capital durability discussed previously, influencing the appropriate tax policy response.

Chapters 3 - 5 analyse macroeconomic and policy issues associated with resource exploitation within a highly aggregated framework, featuring a single representative agent. Such approaches are helpful in approaching this important global problem.

However, distributional issues abound, both within and across countries. In this context, concerns over potentially adverse consequences on the welfare of low income groups – which are particularly reliant on goods such as energy – are potentially key impediments to critical national level policy reforms which are likely to increase their relative prices.

Detailed household level analysis is thus required to assess the economic and welfare costs of more rational taxation of energy goods (including some of the more practical implications of uncertainties over preference forms), and to inform policy makers on appropriate expenditure policy adjustments to avoid the most series inequities.

However, available evidence on detailed distributional aspects of energy tax reforms in the UK – particularly those which capture the effects of potentially divergent behavioural responses across socioeconomic groups – are surprisingly limited (Crawford et al. (1993, 2011), Johnson et al. (1990), and Symons et al. (1994)).

Chapter 6 contributes to this existing stock of research on the economic and welfare effects of carbon and VAT reforms in a number of key regards:

- first, it is only comprehensive behavioural study of carbon taxes to have been conducted since the liberalisation of electricity and natural gas markets, and to analyse tax scenarios which are consistent with current stated government policy guidelines;
- second, it provides the first money metric estimate of the welfare costs of carbon tax incidence in the UK, and to analyse the implications of different approaches to aggregation within the SWF; and,
- third, as far as the author is aware, it is the first analysis of interactions between VAT and carbon tax reforms.

In terms of empirical findings, demographic variables are shown to influence consumption substantially. Budget shares to electricity and gas, for example, increase with the age of the household head, while that of gasoline observes the opposite demographic trend.

There is also some evidence to suggest declining expenditure shares in natural gas and gasoline from the mid 1990s and early 2000s respectively, reflecting improvements in residential insulation, vehicle efficiency, public transport and communications technologies.

Budget elasticities vary by household for all commodities (emphasising the value of highly disaggregated analysis), and are particularly widely dispersed for electricity (which is an inferior good for more than 25 percent of households in the sample). Among the fuels, natural gas is on average the most price inelastic, with behavioural responses diminishing at higher expenditure levels, particularly for petrol.

In the case of carbon taxes, larger proportionate reductions are predicted among lower spending households for gas and petrol. This heterogeneity increases if VAT and carbon tax reforms are implemented in combination.

Unifying VAT treatment at the standard rate increases sample revenues by around 18 percent, equivalent to additional potential revenue of around £22 billion. The opportunities from carbon taxes are here shown to be quite material, at least in the short term: a levy of £50 tCO2, for example, is projected to increase tax revenues by on the order of £10 billion.

The welfare costs of energy tax reform are also found to be substantial, particularly for scenarios involving both VAT and carbon tax reform, and in the cases of an aggregate utilitarian SWF or lower degrees of inequality aversion (highlighting the practical importance of aggregation issues discussed previously).

The detailed behavioural framework adopted has an important bearing on the magnitude of assessed welfare costs, which are generally on the order of 4-18 percent lower compared with estimates based on analysis in which demand is invariant to prices and incomes.

Expenditure measures are shown have strong potential to mitigate these costs, and differ according the adopted revenue allocation mechanism. Further extending an important theme of the thesis, the form of the social welfare function also has an important influence, with the scope for aggregate welfare gains generally greater in the case of a weighted SWF.

7.3 Extensions

A large number of possible future extensions to the theoretic work undertaken thus far merit consideration. For the sake of brevity, I identify three broad areas:

The first concerns strengthening the empirical foundations for the postulated spillover effects and preference forms. For example, the numerical results presented in Chapter 3 could be bolstered by a more systematic analysis of the sensitivity of capital durability to changing weather conditions across different asset classes.[102] The development of empirical evidence base surrounding the existence, and form, of consumption habits – which remains

[102] Achieving a more robust aggregate parameter estimate for θ would inevitably be data dependent, requiring information on capital and maintenance costs and operating lives (and benefiting from variation across climates for similar asset classes).

limited despite the now broad diffusion of these preference structures – presents another fertile opportunity.[103]

A second area for potential empirical follow up concerns the validity of the Hotelling portfolio result. Despite the prevalence of this assumption in the literature, robust empirical evidence remains lacking. This is in part due to the fundamental unobservability of scarcity rents, and the absence of robust production and cost related data (available over a sufficiently extended period and at reasonable degree of disaggregation) for the extractive industries.[104]

Third, it may be desirable to analyse policy issues relating to mortality spillovers within a model of endogenous fertility. However, one issue that could limit such an enquiry is the observed failure of these models to achieve stable, positive population growth in the absence of first best birth taxes (Spataro and Renström (2011, 2012)). Nevertheless, constrained policy insights remain relevant in this context, in part due to the political constraints on imposing child rearing or birth related poll taxes.

In addition, I am currently considering three possible extensions to the empirical work undertaken in Chapter 6:

First, an analysis on energy tax interaction effects with employment markets through a relaxation of the separability assumption between consumption and labour supply. Only Brännlund and Nordstrom (2004) have sought to address this issue as part of a micro

[103] Evidence for or against the formation of energy consumption habits is a potentially interesting subset of this topic. An enquiry on this topic has not been pursued as part of micro econometric analysis above due to identification issues in repeated cross section.

[104] In light of the underlying commercial sensitivities, two possible research strategies bear particular merit. The first involves the identification of scarce resources outside the sphere of the extractive industries for which data on prices, costs and determinants of demand are more readily available (one idea might be to analyse the prices of historic properties, for example). A second course of action could be to seek closer engagement with one or more industry participants, with a view to utilising detailed production data subject to the necessary anonymization of the assets to which they relate.

econometric study on carbon taxes.[105]

Second, a behavioural analysis of energy tax incidence studies in a developing country setting, which contribute to an increasing share of GHG emissions and where potential welfare issues are most acute given lower levels of prosperity. Research has recently begun to emerge using input-output models (Blackman et al. (2009); Datta (2010)), or CGE models with heterogeneous consumers (Devarajan et al. (2009); Yusuf (2007)). However, these fall short of the fully behavioural gold standard attempted above.[106]

Third, a study into interactions between energy taxation and wider long term structural changes such as ageing (perhaps the largest single fiscal challenge facing many countries according to IMF (2015)). The empirical results presented above suggest important age related determinants of energy demand which could be explored more deeply in a future enquiry.

[105] The simplest approach to endogenizing the labour-leisure choice is to introducing a time endowment into the budget constraint (a key challenge being to estimate its appropriate size and value), and subsequently estimate cross price elasticities with leisure goods. Alternatively, one could seek to identify and estimate a discrete choice model of labour supply. It could therefore be interesting to explore whether the large variations in energy and carbon prices in recent years facilitates such an estimation strategy.

[106] A key problem is the infrequent collection of household survey data, which means that price variation over time can be limited. Pashardes et al. (2014), for example, incorporate heterogeneity in household preferences such that effective price changes differ across households, permitting system estimation from a more limited set of household expenditure surveys.

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A APPENDIX TO CHAPTER 3

Lemma 3.1

Totally differentiating equation (3.2) and (3.3) with respect to time, and combining with (3.4), (3.5), (3.7) and yields the following equations of motion in depletion:

$$
\begin{aligned}
(a_1 + a_2)\, \hat{x}\,(t) = h + a_2 n - (1-s)r(t) + \\
j\,(1 - a_1) + (a_1 + a_2 - m)\, x(t) - z(t)
\end{aligned}
\tag{A.1}
$$

Totally differentiating equation (3.3) and (3.6) with respect to time, and substituting for (3.1), (3.4), (3.5) and (3.7) yields the following equations of motion in interest rates:

$$
\begin{aligned}
(a_1 + a_2)\, \hat{r}\,(t) = h + a_2 n - Or(t) - \\
mx(t) + j\,(1 - a_1) - (1 - a_1 - a_2)\, z(t)
\end{aligned}
\tag{A.2}
$$

where $O = \left(1 - a_1 - a_2\left(1 - \frac{s}{a_1}\right)\right)$.

Cross substituting between (A.1) and (A.2), evaluated at their stationary loci, yields expressions (3.8) and (3.9). By inspection, these exist under the stated condition, $a_1 > s$.

By equation (A.1), the stationary depletion locus is downward sloping when represented in x, r space and generates a vertical force of attraction (being otherwise upward sloping with 'knife-edge' properties).

By equation (A.2), the stationary interest rate locus is downward sloping since the adverse productivity effect squeezes rental payments (and exerts a horizontal force of attraction). This is due to self-stabilizing character of the capital-output ratio in the Solow model, which follows from the concavity of output with respect to capital.

The steady state oil and capital market, given by expressions (3.8) (3.9), are thus saddle-path stable in the case of both "strong" and "moderate" climate externalities.

Lemma 3.5

Totally differentiating equations (3.2) and (3.3) with respect to time, and combining with (3.11), (3.5), and (3.7) yields the following equations of motion in depletion:

$$(a_1 + a_2)\,\hat{x}(t) = h + a_2 n + (a_1 + a_2 + (1 - a_1)\,\theta - m)\,x(t) - \\ (1 - s)\,r(t) + j\,(1 - a_1) - z(t) \tag{A.3}$$

Totally differentiating equation (3.3) and (3.6) with respect to time, and substituting for (3.11), (3.12) and (3.5) yields the following equations of motion in interest rates:

$$(a_1 + a_2)\,\hat{r}\,(t) = h + a_2 n - Or(t) + ((1 - a_1)\,\theta - m)\,x(t) + \\ + j\,(1 - a_1) - (1 - a_1 - a_2)\,z(t) \tag{A.4}$$

Cross substituting between (A.3) and (3.9), evaluated at their stationary loci, yields expressions (3.13) and (3.14).

$\theta > 0$ reduces net of depreciation returns as depletion levels rise, lowering stationary values of x for any given gross interest rate. Represented in x, r space, this effect is characterised by a clockwise pivot in the $\dot{x} = 0$ locus, which is downward sloping under a stricter condition than in the baseline model: $m > a_1 + a_2 + (1 - a_1)\,\theta$. In addition, the capital spillover causes stationary values of r to fall more slowly with higher depletion rates, flattening the extraction time path. Thus the stationary interest rate locus also pivots clockwise in x, r space.

If $m < \theta\,(1 - a_1)$, the stationary interest rate locus is upward sloping and exerts a horizontal forces of repulsion – while the depletion locus is also upward sloping, and subject to vertical forces of repulsion – leading to an unstable steady state.

Empirical evidence on direct capital-environment linkages

This section summarizes the current state of the empirical knowledge base concerning possible linkages between climate change and capital durability. In general terms, economic analysis remains scarce, and no study is comprehensive in terms of its coverage of the possible impacts. However, available evidence suggests that depreciation rates could commonly be raised, and by a substantial amount, for a broad class of assets, including buildings and infrastructures.[107]

Although studies differ widely in terms of scope, three core methodological elements exist in common. First, future trends in local climatic conditions, such as surface temperatures, sea levels, precipitation and/or wind speeds, are forecast under different GHG emissions scenarios using meteorological simulation tools, known as General (or Regional) Circulation Models (GCM/ /RCMs). Variance in weather conditions is most commonly assumed to follow historical patterns (e.g. Chinowsky et al. (2013), Jollands et al. (2007), Larsen et al. 2008) and Nemry and Demirel (2012)), although some studies attempt to simulate changes in the frequency and distribution of weather events (e.g. Emmanuel (2011), Feyen et al. (2012), Kunreuther et al. (2013), Ranger and Niehoerster (2012), and Raible et al. (2012)).

Second, estimates are formed regarding the value and location of future assets, based on simple extrapolations from existing infrastructure data. Third, assumptions are formed regarding the vulnerability of the assets exposed to this adjusted profile, drawing either on available engineering evidence (e.g. Chinowsky et al. (2013), Larsen et al. (2008), and Nemry and Demirel (2012)) or statistical estimates of the relationship between weather variables and capital costs (e.g. Jollands et al. (2007)). Assumptions regarding how these

[107] At the macroeconomy level, capital depreciation rates on the order of 5 percent annually are commonly assumed, based principally on evidence from the US (Barro and Martin (1995)). Although the subject of limited research, depreciation rates may be higher in developing countries: imported technologies may be unsuitable to the physical environment in less developed regions, or more poorly maintained due to capacity limitations. Alternatively, less durable goods might be favored by more financially constrained investors (Bu (2006) and Udry and Anagol (2006)). In addition, the sensitivity of capital accumulation to climate change may be greater in developing countries. These issues are untreated due to the lack of empirical evidence.

risks may be mitigated by defensive behaviour are summarized in each case below (I focus on residual capital losses wherever possible).

Chinowsky et al. (2013), Jollands et al. (2006), Larsen et al. (2008) and Nemry and Demirel (2012)) analyse the influence of climate change on transportation infrastructures. These studies identify rising patterns of heat and precipitation related stresses and declining capital costs from freeze-thaw effects. Studies of the EU and US, for example, find large variance in the magnitude of the overall effects across countries and states (Chinowsky et al. (2013), Nemry and Demirel (2012)). Overall, however, available studies tend to predict increased maintenance costs affecting road networks on the order of 1-9 percent, depending on the nature and extent of the climatic changes expected at the local level and assumptions over defensive expenditures.

Chinowsky et al. (2013), for example, simulate the effects of moderate climate change across regions of the contiguous US on road maintenance costs using a GCM developed for the Environmental Protection Agency. By spatially mapping these effects (at a 2.5 degree squared resolution) to a detailed inventory of state level roads sourced from the Department of Transportation (excluding interstate highways), and exploiting functional relationships between precipitation, heat stress (and freeze-thaw) levels and road resurfacing requirements employed by engineers – and assuming that more temperature resistant asphalt binder is used where cost effective (although unpaved roads are assumed to remain unpaved) – the authors estimate a 2 percent increase in annual maintenance costs by 2075.

Nemry and Demirel (2012) undertake a similar study of climate change impacts on EU road infrastructure. Using a very similar methodology to Chinowsky et al. (2013) – including, for example, assumptions over the adaptation of asphalt – the authors finds that average net road maintenance costs are expected to rise on the order of 1 percent. This figure is somewhat lower than Chinowsky et al. (2013), despite the slightly more pessimistic emissions growth scenarios (Special Report on Emissions Scenarios (SRES) A1B/ Representative Concentration Pathway 8.5) employed, which is likely to to be at least partly due to the exclusion of unpaved roads from the analysis (which are more sensitive to changing conditions).

By contrast, Jollands et al. (2007) estimate the statistical relationship between road repair costs reported by relevant public agencies and precipitation in Hamilton, New Zealand (other weather variables such as wind speed and temperature were found to be insignificant). These structural estimates provide a basis for assessing the effects of climate change under high and low emissions scenarios between 2005-2030 (this implicitly assumes the cost effectiveness of defensive expenditures is constant). By 2030, the study projects a 6-9 percent increase in maintenance costs using a GCM developed by the Commonwealth Scientific and Industrial Research Organisation, and little change under the Hadley scenarios using the model of the UK Meteorological Office.

Larsen et al. (2008) analyse the costs of changes in permafrost, flooding risk and coastal erosion due to climate change on the future costs of maintaining public infrastructure in Alaska, including transportation and energy related structures. The authors simulate changes in mean temperature and precipitation in six different Alaskan localities under the IPCCs A1B scenario using a suite of three GCMs in (considered middle of the road in terms of future emissions growth) and map these effects to a database of infrastructure asset values (from public agency and insurance reports).[108] In the case of road infrastructures, the authors predict a 5-6 percent increase in road construction and maintenance costs for the period up to 2030, and a 10-12 percent increase in the costs of maintaining and replacing infrastructure across all asset classes.

A further branch of the literature has analysed the potential effects of climate change

[108] Their adaptation assumptions are crude and more pessimistic than Chinowsky et al. (2013) and Nemry and Demirel (2012), but perhaps not unreasonably so given the 'lumpier' investment profile of the assets under analysis. Specifically, they determine that cost effective changes in the location or construction of each piece of infrastructure only takes place once climatic change reduces the life of a given asset by 20 percent (and more resilient replacement capital is 5 percent more expensive).

on capital losses due to extreme weather conditions. Such events are already hugely costly: average annual insured losses from non geo-physical weather related events between 1990-2010 is estimated to be on the order of $(2008)35 billion, roughly two-thirds of which relate to non tropical storms and floods (Barthel and Neumeyer (2012)).[109] Moreover, these statistics cover a small fraction of the true picture, due to the limited diffusion of insurance in developing countries, commonly just a few percent of the total value of exposed assets (Mills (2005)).

Trends in insured losses due to climatic factors have not yet been robustly identified,[110] perhaps partly due to data availability and statistical challenges associated with ensuring their comparability across time given changes in wealth, population, and the physical exposure of assets to weather events ((Pielke and Landsea (1998), Neumayer and Barthel (2011)).[111] However potential future patterns of extreme weather events are of more concern in this context.[112]

[109] Insured losses are those against which claims have successfully been levied by insured parties. A broader concept of economic losses is most commonly analysed in the literature (see, for example, Miller et al. (2008), Pielke and Landsea (1998), Barredo (2009)), but is of limited use in this context since these capture a wide range of direct and indirect effects (many of which lie outside the sphere of interest here), and are not subject consistent reporting or verification (being self reported rather than the outcome of industry loss appraisal procedures).

[110] Barthel and Neumayer (2012), the only available analysis of global insured losses, fail to identify a robust trend (albeit for a short however the times series). Studies for the US, for example have tended to identify rising patterns of costs (Barthel and Neumayer (2012); Changnon (2007, 2008, 2009a,b). However, time series studies of weather events in Europe and Australia have generally been more equivocal in their conclusions (Barredo et al. (2012), Barthel and Neumayer (2012), Crompton and McAneney (2008), Kunz et al. (2009)). Importantly, the findings of all such studies are sensitive to a range of factors including the choice of normalization and assumptions over defensive measures.

[111] Data limitations have restricted extensive consideration of spatial asset variance. Ward and Ranger (2010) find that increased geographical exposure of assets may at least partly explain patterns of rising economic losses.

[112] GCM simulations predict a wide range of potential changes, which can – with differing degrees of confidence – be related to GHG emissions. Summarizing these, for example, IPCC (2014) predicts that extremely high seasonal sea levels and and summer heat waves (particularly in Europe) are extremely likely (with strong causal links to human activities). More frequent and intense patterns of heavy rainfall are also forecast, with reasonable causal links to climate change. The

Analyses into the relationship between insured (mostly property related) losses and wind damages, indicate that more powerful storms in Europe due to climate change could lead to increases in the expected loss to value ratio on the order of 10-50 percent by the second half of the 20th Century (Donat et al. (2011), Gerstengarbe et al. (2013), Leckebusch et al. (2007), Pinto et al. (2012, 2010, 2007), Schwiertz et al. (2010)). Assuming actuarially fair annual insurance premiums of around 0.15 percent of asset values, and commonly maintained assumptions over building depreciation rates of around 2 percent per annum, this represents an proportionate increase in capital erosion on the order of 0.75-3.5 percent.[113]

Considerably less consensus exists among studies of potential changes in hurricane related capital damages, largely due to fundamental ambiguities in the underlying meteorology. Kunreuther et al. (2013), Raible et al. (2012), and Ranger and Niehoerster (2012), for example, found conflicting signs in the damages across different model projections in the Atlantic.[114] A more limited evidence base also highlights the potential for increased losses from typhoons in Asia, perhaps on the order of 20-40 percent by mid to late century.[115]

nature of changes to hurricane and cyclone activity and causal links with climate change remain highly uncertain.

[113] The findings are somewhat sensitive to whether the local damage threshold – commonly a cubic function of the difference between maximum recorded gusts and the 98th percentile wind speed in a given locality – is adjusted for the new climate adjusted wind speed (a crude measure of adaptive behaviour). Association of British Insurers (ABI) (2005) and Dailey et al. (2009) also predict substantial increases in storm related losses in the UK and Europe (on the order of 14-35 percent) but do not explicitly report insured asset values or premiums, making the results difficult to interpret in this context.

[114] Nevertheless, capital effects have the potential to be important: Entergy (2010) for example analyses the implications of hurricanes, subsidence and sea level rise in 77 counties across US gulf states using a simplified version of the Swiss Re hazard specific loss functions for energy, transport and residential infrastructure. The study predicts an increase in capital losses of $(2008) 5-10 billion by 2030, of which nearly 90 percent is offshore energy and residential infrastructure. Assuming a 4 percent average depreciation rate on these combined assets – reflecting a shorter operating life in the offshore sector relative to buildings – this represents a roughly 9-15 percent increase in capital replacement requirements.

[115] ABI (2005), for example, find increases in wind-related insured losses from extreme Japanese typhoons by around two

Coastal and fluvial flooding is another potentially important channel for climate related capital losses. Economic analyses are inherently more challenging due to the additional dimensionality of the flooding problem (depth!), the complexities of water flows within individual basins, and the generally limited availability of data relating to flood defence costs and capabilities. As such aggregate studies are inherently based on (often grossly) simplifying assumptions.[116] A number of studies take up the challenge for Europe and the US (see, for example, Feyen et al. (2012), Hall et al. (2005), Ntelekos et al. (2010) and Wobus et al. (2013)).

Wobus et al. (2013), for example, analyse the relationship between observed precipitation trends from weather stations and flood damages within 99 different subregions of the contiguous US. Due to concerns over data quality (being largely self reported), the authors estimate a logistic regression to determine the probability of a weather event falling in the top 25 percent of the distribution of damages, using trend variables (with the conditionally expected loss estimated using a Monte Carlo approach which randomly picks (over a 1000 runs) from the uppermost 25th percentile of the empirical distribution of flood damages for the particular sub region). Assuming no change in the built environment, or in the value of affected buildings and property, expected annual losses are estimated to be $747 million per year by the end of the century (a 31 percent increase from current levels).

Feyen et al. (2012) present a more sophisticated study into the costs of river flooding in

thirds to total $(2004)25 – 34 billion. Dailey et al. (2009) project increases in insured typhoon losses of 20 percent for a 2 degree temperature rise (likely by around the 2040s), rising to 32 per cent for a $+4°$C scenario. However, these results should be interpreted with particular caution due to the narrow insured asset base in China (which may be misrepresentative of aggregate hazards due to selection bias issues), and the absence of defensive expenditures in the modelling approach.

[116] Ntelekos et al. (2010), for example, present a toy model in which future flood costs are an exponential function of growth, linearly transposed by emissions, the rate of urbanization, and an initial condition set to current flood damages. The results are somewhat limited in their worth but suggest that, for a long run growth rate of 1.5 per cent, the difference between high and low emissions scenarios (SRES A2/B1) implies additional flood related costs of around $(2008) 3 billion annually by the end of the 20th century.

the EU. Simulating the effects of high (SRES A2) and low (SRES B2) emissions scenarios using models developed by the Danish Meteorological Institute and the Rossby Centre, the authors extract data on flood inundation in each locality. Critically, and in contrast to previous studies, these data capture changes in the variance of rainfall patterns. They are transformed into direct monetary damage using country specific flood depth-damage functions and land use information, with population exposure determined by overlaying the flood inundation information with data on population density.[117] For the EU27 as a whole, they predict a 2.5-3.5 fold increase in current expected annual damages of €6.4 billion to €14–21.5 billion (in constant prices of 2006) by the end of this century, depending on the scenario.

Interpreting these finding for environmentally related depreciation rates naturally must be broached with some trepidation. Feyen (2012), for example – technically the most rigorous study available – projects increases in annual insured losses due to floods of between 0.6 and 4.2 billion (2006) pounds for the UK. Assuming, for simplicity, the residential housing market and diffusion of buildings insurance remains constant at today's levels (£4500 billion and around 2/3rd of all households respectively), and a 2 percent depreciation rate, this represents an increase in that rate of between 1 and 7 percent.

No assessment of aggregate affects across asset classes or climatic effects is available, and studies of particular markets and climatic effects are inevitably subject to considerable uncertainty relating to predictions over future climatic and economic conditions. Yet it

[117] Due to the absence of reliable and comparable flood defence data, the authors develop a simple rule to determine the degree flood protection (which truncates the damage function up to a occurrence probability threshold determined by a functional relationship between per capita GDP relative to the EU average. Hall et al. (2005) employ a more sophisticated treatment of flood protection expenditures (in which the probability of failure by each defensive section for a given load is directly estimated and interpolated for revised climate conditions). They predict notable increases in annual economic flood damages over the next century in the UK under a range of future development scenarios (however, the influence of emissions is not isolated specifically). The UK Government's Foresight Programme estimated that global warming of 3°C to 4°C could increase flood damage costs from 0.1 per cent up to 0.4 percent of GDP. Somewhat counter intuitively, much of the investment in flood defences and coastal protection was predicted in rural coastal areas (Foresight (2004)).

follows from the analysis of the available studies above that there nonetheless appears to be a reasonable degree of confidence that changing climatic conditions substantively influences capital durability: overall depreciation might be expected to increase, proportionately, on the order of perhaps 1-10 percent in the long run (within say 20-50 years).

Lemma 3.6

Utility maximizing behaviour requires that the discounted marginal utility of consumption should equal the shadow value of income in each time period: $e^{-it}c^{-v}(t) = \lambda(t)N(t)$. Taking the time derivative of this first order condition yields:

$$-\hat{\lambda}(t) = i + n + v\hat{c}(t) \tag{A.5}$$

Thus the marginal utility of consumption should decline over time at the same rate as the shadow value of income.

Critically, optimum programmes for capital and oil extraction satisfy the following conditions:

$$0 = \frac{\delta V}{\delta K(t)} - \frac{\delta}{\delta(t)}\left(\frac{\delta V}{\delta \dot{K}(t)}\right) \Longrightarrow -\hat{\lambda}(t) = r(t) - j - \theta x(t) \tag{A.6}$$

$$0 = \frac{\delta V}{\delta S(t)} - \frac{\delta}{\delta(t)}\left(\frac{\delta V}{\delta \dot{S}(t)}\right) \Longrightarrow -\hat{\lambda}(t) = \hat{P}(t) \tag{A.7}$$

Equations (A.6) and (A.7) state that the shadow value of stocks of capital and oil at each date must equal the time derivatives of the shadow values of investment in oil and capital respectively. Combining equations (A.6) and Equations (A.5) yields the stated Euler equation in consumption.

Proposition 3.2

This model requires an additional equation determining the evolution in the ratio of consumption to capital. This is derived by combining (A.6), (A.5) and (A.7) with the budget constraint of the representative household and the marginal product given at (3.5), and given by:

$$\hat{c}(t) - \hat{k}(t) = c(t)/k(t) + \left(\left(n + j + \theta x(t)\right)(v-1) + r(t) - i\right)/v - r(t)/a_1 \tag{A.8}$$

The remaining equations of motion of depletion, interest rates, consumption-capital and output growth are given by:

$$\begin{aligned}\left(\hat{x}(t) - x(t)\right)(a_1 + a_2) = h + a_2 n + \\ \left(\left(1 - a_1\right)\theta - m\right)x(t) - a_1 c(t)/k(t) + \left(1 - a_1\right)j - z(t)\end{aligned} \tag{A.9}$$

$$\begin{aligned}\hat{r}(t)\left(a_1 + a_2\right) = h + \left(\left(1 - a_1\right)\theta - m\right)x(t) + \\ \left(\left(1 - a_1\right)\theta - m\right)x(t) - a_1 c(t)/k(t) + \left(1 - a_1\right)j - z(t)\end{aligned} \tag{A.10}$$

$$\begin{aligned}\hat{Q}(t) = h - \left(m + a_1\theta\right)x(t) + r(t) - a_1\left(c(t)/k(t) + j\right) + a_2 n + \\ \left(1 - a_1 - a_2\right)\hat{E}(t)\end{aligned} \tag{A.11}$$

where: $R = \frac{(1-a_1)(a_1+a_2)}{a_1}$.

As before, θ causes the stationary depletion locus to pivot clockwise (in $x, c/k$ space), since gross returns fall with higher x: the Hotelling condition implies that lower net returns raise growth for any stationary value of r. However, the capital spillover also weakens incentives to save through the Ramsey effect, pushing up gross interest rates for any stationary growth rate (an anti-clockwise pivot in r, g space).

The solution to this system of 4 equations and 4 unknowns is given at (3.19)-(3.22) (further guidance on these derivations is given below).

Equation (3.19) is derived by solving (A.10) and (A.8) for r and c/k respectively at their stationary loci, and then substituting the later into the former expression before rearranging.

To derive equation (3.20), solve (A.9) and (A.8) for x and c/k respectively at the stationary loci. Substitute for x into the later to obtain an expression for c/k. Now further substitute the first and third expressions into (A.10) evaluated at the stationary locus, and rearrange.

Equation (3.21) is derived by solving (A.8) and (A.9) for r and x respectively at their stationary loci; and then substituting for r and subsequently x into the transition equation for rental rates before rearranging the terms.

To derive equation (3.22), substitute for r and $\hat{x} - x$ into (A.11), and then further substitute for x (from (A.8)). Next, solve (A.8) and (A.9) for r and x respectively, then substitute for r and subsequently x into the transition equation for rental rates and rearrange to yield an expression for output growth in terms of c/k.

Finally, solve (A.10) and (A.8) for r and c/k respectively, and then cross substitute to yield an expression for c/k in terms of x. Further substitute for x from (A.9) evaluated at the stationary locus, and for c/k into the previous expression for output growth.

Empirics of inter-temporal substitution

This section summarises available evidence on the empirical magnitude of this parameter. In particular, a substantial body of macroeconomic time series analysis into the predictions of the consumption Euler have commonly found low (and quite precise) point estimates of EIS, in the region of 0-0.5 (for example, Campbell (2003), Campbell and Mankiw (1989, 1991), Hall (1988), Patterson and Pesaran (1992), Yogo (2004)).[118]

[118] This is not to suggest complete consensus: Summers (1982) and Mankiw et al. (1985), for example, derive parameter estimates which significantly exceed 1. However, these point estimates are highly imprecise and may be biased upwards due to inappropriate use of first lags of interest rates as instruments, given serial correlation in discrete time consumption data

By contrast, a large finance literature characterising the responsiveness of investment returns to expected consumption growth have tended to yield higher (but less precise) values of the EIS, in the broad range 1-5 (see, for example, Campbell and Mankiw (1989), Campbell (1999), Grossman and Schiller (1981), Hansen and Singleton (1983), and Mankiw (1981)). However, these "inverse estimates" suffer from more severe identification problems, since consumption is generally less variable than interest rates (Campbell and Mankiw (1989), Yogo (2004)). Such weak instrument problems generally favour placing greater weight on macro time series evidence.[119]

Perhaps more fundamentally, however, economists have disputed the robustness of the inverse equality between inter temporal substitution and risk appetite due to failure of key founding assumptions (see, for example, Hall (1988)). Consumption is unlikely to be log normally distributed, for example, having greater probability mass at extreme values due to prevalence of wars, financial crises, and potentially catastrophic environmental issues (Barro (2009), Stern (2007), Weitzman (2007, 2001)).[120] Moreover, the requirements that consumption today be independent of past consumption, or that inter-temporal responsiveness is constant over time, appears contestable.[121]

Two areas of theoretical advancement generally imply small upward revisions to EIS

(Hall (1988)).

[119] The timing of information acquisition is key to a robust empirical test. A desirable instrument must proxy for all information available at the time a consumption plan or investment decision is formed.

[120] By contrast, cross sectional evidence suggests consumption is well approximated by a log-normal distribution (Battistin et al. (2009)).

[121] The EIS has been shown to rise with deregulation in financial markets in Canada (see, for example, Wirjanto (1995)). By contrast, Patterson and Pesaran (1992) find no evidence of instability in the EIS during the early 1980's in the UK. Blundell et al. (1994) and Attanasio and Browning (1995), for example, show that the EIS increases with income among households in the UK (this is substantiated by cross country studies using aggregate data (Ogaki et al. (1996)).

estimates. First, the emergence of new preference structure which separate risk aversion and inter-temporal preference parameters (while retaining time separability), most notably Epstein and Zin (EZ) (1989). A second branch of research retains expected utility theory, but instead assumes habit formation (e.g. Constantinides (1990), Campbell and Cochrane (1999)).[122]

An extensive micro economics literature also casts light on inter-temporal consumption behaviour, and highlights key heterogeneities.[123] Prevailing point estimates are generally higher than their macroeconomic counterparts, however it is difficult to identify systematic differences due to sampling variation (Groom and Maddison (2013)). They also indicate potentially serious aggregation issues associated with macro economic studies (Attanasio and Weber (1995, 1993)).

Lemma 3.7

The Jacobian matrix, *Jacobian*, of the (log) linear system of differential equations is

[122] Mean estimates drawn from a sample of 8 published studies which tests Euler equations derived from E-Z preference forms are just 0.018 higher (a difference which is readily explained by heightened sample variation). While empirical evidence on habits have generally lagged the theory, evidence suggests that their inclusion generally spurs a modest increase in estimated EIS parameter values (since utility is formed over differences in consumption levels), perhaps on the order of 0.05 on average (Havránek et al. (2015)).

[123] Consumption growth by richer households and those with asset holdings are more responsive to returns (Attanasio and Weber (1995, 1993), Attanasio and Browning (1995), Mankiw and Zeldes (1991), Vissing-Jorgensen (2002) and Zeldes (1989)). In terms of demographic and labour market characteristics, Attanasio and Weber (1995, 1993), for example, find that household size and employment status influence consumption levels. By contrast, Blundell, Browning and Meghir (1994) show that both female labour market participation and household demographics increase consumption growth. Berloffa (1997) finds consumption growth effects relating to the former but not the later. Data issues should not underestimated, however: only short panels are available for broad based measures of consumption, obliging researchers to construct synthetic panels ((e.g. Attanasio and Weber (1993, 1995), Blundell, Browning and Meghir (1994), Vissing-Jorgensen (2002)), or use narrow proxies for consumption, in particular food expenditure (e.g. Dynan (2000), Lawrance (1991), Maurer and Meier (2008), Runkle (1991), Shea (1995), Zeldes (1991)), to avoid potential “small T” bias.

given by:

$$Jacobian = \begin{matrix} \frac{d\dot{r}}{dr} & \frac{d\dot{r}}{d(C/K)} & \frac{\dot{r}}{dx} \\ \frac{d(\dot{C/K})}{dr} & \frac{d(\dot{C/K})}{d(C/K)} & \frac{d(\dot{C/K})}{dx} \\ \frac{d\dot{Z}}{dx} & \frac{d\dot{Z}}{d(C/K)} & \frac{d\dot{Z}}{dx} \end{matrix} =$$

$$\begin{pmatrix} (a_1 - 1)\frac{r}{a_1} & \frac{-a_2}{(a_1+a_2)}\frac{r}{a_1} & \frac{-(m-(1-a_1)\theta)}{(a_1+a_2)}\frac{r}{a_1} \\ \left(\frac{a_1}{v} - 1\right)c/k & c/k & \frac{\theta(v-1)}{v}c/k \\ 0 & \frac{-a_1}{(a_1+a_2)}x & \frac{a_1+a_2-(m-(1-a_1)\theta)}{(a_1+a_2)}x \end{pmatrix} \tag{A.12}$$

The stated condition is sufficient $\mid Jacobian \mid < 0$ and one eigenvalue to be positive (where $\mid Jacobian \mid$ signifies the determinant of $Jacobian$). It follows that the remaining eigenvalues are oppositely signed and the system is manifold stable.

Corollary 3.3

The optimal tax in the presence of spillovers affecting capital durability given at equation (3.11) is derived here.

In the case of the individual household, the first order conditions for the optimal stock and the time path of the flow of oil are given, respectively, by:

$$\frac{dV(t)}{dS(t)} = 0 \tag{A.13}$$

$$\frac{d\left(\frac{dV(t)}{d\dot{S}(t)}\right)}{dt} = - \lambda(t)\left(\frac{(1-a_1-a_2)\,Q(t)}{\dot{S}(t)}\left(\hat{Q}(t) - \hat{E}(t) + \hat{\lambda}(t)\right)\right) \tag{A.14}$$

Setting these expressions equal, and substituting from the time derivative of the marginal productivity condition for oil (3.6) together with the revised Hotelling condition (3.12), yields the standard result that private interests alone are best served without policy intervention.

Unlike the representative agent, the social planner is assumed to factor in the external benefits of leaving an additional unit of oil in the ground, both in terms of higher aggregate productivity and lower capital depreciation. The first order conditions for the optimal stock and the time path of the flow of oil are in this case given, respectively, by:

$$\frac{dV(t)}{dS(t)} = \lambda(t)\left(\frac{mQ(t) - \theta x(t)K(t)}{S(t)}\right) \tag{A.15}$$

$$\frac{d\left(\frac{dV(t)}{d\dot{S}(t)}\right)}{dt} = -\lambda(t)(\frac{(1-a_1-a_2)\,Q(t)}{\dot{S}(t)}\left(\hat{Q}(t) - \hat{E}(t) + \hat{\lambda}(t)\right) -$$

$$\frac{\theta K(t)}{S(t)}\left(\hat{K}(t) + x(t) + \hat{\lambda}(t)\right)) \tag{A.16}$$

Setting these expressions equal, and substituting from the time derivative of the marginal productivity condition for oil (3.6), together with the revised Hotelling condition (3.12), yields equation (3.25).

Lemma 3.8

Exploiting the condition for the optimal investment programme (A.6) gives:

$$(1 - Z_Q)\,r(t) - j - \theta x(t) = -\hat{\lambda}(t) \tag{A.17}$$

Combining (A.17) with the condition for the optimal oil extraction programme ($\hat{P} = -\hat{\lambda}$) yields the following revised Hotelling condition:

$$\hat{P}(t) = -\hat{\lambda}(t) = (1 - Z_Q)\,r(t) - j - \theta x(t) \tag{A.18}$$

Further substituting into the time path of the shadow value of consumption yields the following Euler equation for consumption:

$$(1 - Z_Q)\,r(t) - i - n - j - \theta x(t) = v\hat{c}(t) \tag{A.19}$$

This demonstrates Lemma 3.8.

Proposition 3.3

The equations of motion in output, oil depletion, interest rates and the ratio of consumption to capital in the presence of an income tax are given by:

$$\hat{Q}(t) = h + a_2 n - (m + a_1\theta)\, x(t) + (1 - Z_Q)\, r(t) - a_1 \left(c(t)/k(t) + j\right) + (1 - a_1 - a_2)\left(\hat{x}(t) - x(t)\right) \tag{A.20}$$

$$\left(\hat{x}(t) - x(t)\right)(a_1 + a_2) = h + a_2 n + \left((1 - a_1)\,\theta - m\right) x(t) - a_1 c(t)/k(t) + (1 - a_1)\, j - z(t) \tag{A.21}$$

$$\hat{r}(t)\,(a_1 + a_2) = h + \left((1 - a_1)\,\theta - m\right) x(t) + a_2\left(c(t)/k(t) + n\right) + (1 - a_1)\, j - (1 - Z_Q)\, Rr(t) - (1 - a_1 - a_2)\, z(t) \tag{A.22}$$

$$\hat{c}(t) - \hat{k}(t) = c(t)/k(t) = h + \left((1 - a_1)\,\theta - m\right) x(t) + \left((n + j + \theta x(t))\,(v - 1) + r(t)\,(1 - Z_Q) - i\right)/v - r(t)\,(1 - Z_Q)\,/a_1 \tag{A.23}$$

The solution to this system of equations is given at (3.27)-(3.29).

Lemma 3.9

This is evident from condition (A.6), which implies:

$$r(t) - j - \theta x(t) = -\hat{\lambda}(t) \tag{A.24}$$

Substituting for the Hotelling condition thus yields a tax invariant rate of oil price growth:

$$\hat{P}(t) = r(t) - j - \theta x(t) \tag{A.25}$$

Further substituting for shadow value of consumption yields a consumption growth rate which is undistorted by the expenditure tax:

$$r(t) - i - n - j - \theta x(t) = v\hat{c}(t) \tag{A.26}$$

This demonstrates Lemma 3.9.

Proposition 3.4

The equations of motion in output, oil depletion, interest rates and the ratio of consumption to capital for the optimal model with endogenous depreciation in the presence of an expenditure tax are given by:

$$\hat{Q}(t) = h + a_2 n - \left(m + a_1\left(1 - Z^B_{EXP}\right)\theta\right)x(t) + \left(1 - Z^B_{EXP}\right)r(t) - \\ a_1\left(c(t)/k(t) + j\left(1 - Z^B_{EXP}\right)\right) + \left(1 - a_1 - a_2\right)\left(\hat{x}(t) - x(t)\right) \tag{A.27}$$

$$\left(a_1 + a_2\right)\left(\hat{x}(t) - x(t)\right) = h + a_2 n + \left(\left(1 - a_1\left(1 - Z^B_{EXP}\right)\right)\theta - m\right)x(t) - \\ Z^B_{EXP} r(t) - a_1 c(t)/k(t) + \left(1 - a_1\left(1 - Z^B_{EXP}\right)\right)j - z(t) \tag{A.28}$$

$$\hat{r}\left(a_1 + a_2\right) = h + a_2 n - m x(t) + \left(1 - a_1 - y a_2\right)\left(\theta x(t) + j\right) - \\ \left(1 - a_1 - a_2\right)z(t) + a_2 c(t)/k(t) - \left(R - \frac{a_2 Z^B_{EXP}}{a_1}\right)r(t) \tag{A.29}$$

$$\hat{c}(t) - \hat{k}(t) = c(t)/k(t) - r(t)\left(1 - Z^B_{EXP}\right)/a_1 + \\ \left(n\left(v - 1\right) + \left(j + \theta x(t)\right)\left(v\left(1 - Z^B_{EXP}\right) - 1\right) + r(t) - i\right)/v \tag{A.30}$$

The solution to this system of equations is given at (3.19)-(3.22).

Corollary 3.4

The equations of motion of depletion, interest rates, consumption-capital and output growth for the optimal model with endogenous depreciation, but assuming non separability between capital stocks and productivity growth rates, are given by:

$$(\hat{x} - x(t))\,(a_1 + a_2) = h + a_2 n + ((1 - a_1 - \psi)\,\theta - m)\,x - \\ a_1 c(t)/k(t) + (1 - a_1)\,j - z(t) \tag{A.31}$$

$$\hat{r}(t)\,(a_1 + a_2) = h + ((1 - a_1 - \psi)\,\theta - m)\,x(t) + a_2\,(c(t)/k(t) + n) + \\ (1 - a_1)\,j - Rr(t) - (1 - a_1 - a_2)\,z(t)) \tag{A.32}$$

$$\hat{c}(t) - \hat{k}(t) = c(t)/k(t) + ((n + j + \theta x(t))\,(v - 1) + r(t) - i)\,/v - r(t)/a_1 \tag{A.33}$$

$$\hat{Q}(t) = h + a_2 n - (m + \psi\theta + a_1\theta)\,x(t) + r(t) - a_1\,(c(t)/k(t) + j) + \\ (1 - a_1 - a_2)\,(\hat{x}(t) - x(t)) \tag{A.34}$$

The effects of ψ are qualitatively similar to m: causing the stationary depletion locus to pivot anti-clockwise (in $x, c/k$ space) while leaving the consumption-capital ratio unaffected. The solution to this system of equations is given by (3.33)-(3.36).

Corollary 3.5

The optimal tax in the presence of spillovers affecting capital durability, assuming non separability between capital stocks and productivity growth rates of the form given at equation (3.37), is derived here.

As before, the social planner considers the external benefits of leaving an additional unit of oil in the ground, $\tilde{S}$, as well as the influence of oil extraction, on aggregate productivity and the capital spillover (the oil market is assumed to be comprised of a single agent). As such, her constrained optimization problem can be represented as follows:

$$\underset{\{c(t),E(t)\}_{t=0}^{\infty}}{Max} V = \int_0^{\infty} (e^{-it}\frac{c(t)^{1-v}-1}{1-v}+$$
$$\lambda(t)\left(Q(\widetilde{s}(t),\psi) - c(t)N(t) - (j+\theta\widetilde{x}(t))\,K(t) - \dot{K}(t)\right))dt \tag{A.35}$$

In the centralised case, the optimal oil extraction plan requires that:

$$\lambda(t)\left(\frac{(m+\psi\theta)\,Q(\widetilde{s}(t),\psi)+\theta x(t)K(t)}{S(t)}\right) =$$
$$-\lambda(t)(\frac{(1-a_1-a_2)\,Q(\widetilde{s}(t),\psi)}{\dot{S}(t)}\left(\hat{Q}(\widetilde{s}(t),\psi)\hat{E}(t)+\hat{\lambda}(t)\right) -$$
$$\frac{\theta K(t)}{S(t)}\left(\hat{K}(t)+x(t)+\hat{\lambda}(t)\right)) \tag{A.36}$$

Substituting from the time derivative of the marginal productivity condition for oil (3.6) together with the revised Hotelling condition (3.12), yields equation (3.37).

Corollary 3.6

Assuming physical capital accumulation follows a fixed savings rule given by (3.11), transition equations in depletion and interest rates are given by:

$$(a_1+a_2)\,(\hat{x}(t)-x(t)) = (a_2+\gamma)\,(1-u(t))\,\Omega + a_2 n + j\,(1-a_1) +$$
$$x(t)\,(\theta\,(1-a_1) - \iota\,(a_2+\gamma)) - (1-s)\,r(t) - z(t) \tag{A.37}$$

$$\hat{r}\,(a_1+a_2) = (a_2+\gamma)\,(1-u(t))\,\Omega + a_2 n + ((1-a_1)-(a_2+\gamma)\,\iota)\,x(t)+$$
$$(1-a_1)\,j - Or(t) - (1-a_1-a_2)\,z(t) \tag{A.38}$$

Cross substituting between these expressions (together with 3.39), evaluated at their stationary loci, yields the following equations for steady state interest, depletion and human capital growth rates:

$$\underline{T}x^{*} = \left(\left(a_2+\gamma\right)\left(1-u\right)\Omega+\left(1-a_1\right)j\right)\left(a_1-s\right)+a_2n+zs\left(1-a_1\right) \tag{A.39}$$

$$\begin{aligned}\underline{T}x^{*} = {} & \left(\left(a_2+\gamma\right)\left(1-u\right)\Omega+\left(1-a_1\right)j\right)\left(a_1-s\right)+ \\ & +a_2n+zs\left(1-a_1\right)\end{aligned} \tag{A.40}$$

$$\begin{aligned}\frac{r^{*}}{a_1}\underline{T} = {} & \left(a_2+\gamma\right)\left(1-u\right)\Omega+\left(1-a_1\right)j+ \\ & -zs\left(1-a_1-a_2+\iota\left(a_2+\gamma\right)-\left(1-a_1\right)\theta\right)\end{aligned} \tag{A.41}$$

$$\hat{l} = \left(a_2+\gamma\right)\left(1-u^{*}\right)\Omega-\iota\left(a_2+\gamma\right)x^{*} \tag{A.42}$$

where $\underline{T} = a_1\left(1-a_1-a_2\right)+a_2s+\left(a_1-s\right)\left(\iota\left(a_2+\gamma\right)-\theta\left(1-a_1\right)\right)$.

Steady state output growth is given by:

$$\begin{aligned}\underline{T}Q^{*} = {} & \left(s-\theta\left(a_1-s\right)\right)\left(\left(a_2+\gamma\right)\left(1-u^{*}\right)\Omega+\left(1-a_1\right)j+a_2n\right)- \\ & zs\left(1-a_1-a_2+\iota\left(a_2+\gamma\right)\right)-\underline{T}j\end{aligned} \tag{A.43}$$

Turning to the optimal growth framework, the representative household solves the following dynamic optimization problem:

$$\begin{aligned}\underset{\{c(t),E(t),u(t)\}_{t=0}^{\infty}}{Max} V = \int_0^{\infty} & (e^{-it}\frac{c(t)^{1-v}-1}{1-v}+ \\ & \lambda(t)\left(Q(.)-c(t)N(t)-\left(j+\theta x(t)\right)K(t)-\dot{K}(t)\right)+ \\ & \lambda_2(t)\left(\Omega\left(1-u(t)\right)-\iota x(t)\right))dt\end{aligned} \tag{A.44}$$

The first order conditions with respect to $c(.)$ and $u(.)$ are given by:

$$e^{-it}c^{-v} = \lambda_1(t)N(t) \tag{A.45}$$

$$\lambda_1(t)a_2\frac{Q(t)}{u(t)} = \lambda_2\Omega l(t) \tag{A.46}$$

The optimal investment path once again requires that:

$$\hat{\lambda}_1(t) = i - a_1\frac{Q(t)}{K(t)} \tag{A.47}$$

Human capital accumulation is defined by the following transition equation:

$$\hat{\lambda}_2(t) = i - \frac{\lambda_1(t)}{\lambda_2(t)}\left(AK(t)^{a_1}\left(u(t)N(t)\right)^{a_2}E(t)^{1-a_1-a_2}l(t)_a^{\gamma}l(t)^{a_2-1}\right) -$$
$$\left(\Omega\left(1-u\right) - \iota x(t)\right) \tag{A.48}$$

Substituting for the market clearing condition: $l(t) = l_a(t)$ for all t, yields the following transition equation for human capital in the decentralized economy:

$$\hat{\lambda}_2(t) = i - \frac{\lambda_1(t)}{\lambda_2(t)}a_2\frac{Q(t)}{l(t)} - \left(\Omega\left(1-u\right) - \iota x(t)\right) \tag{A.49}$$

Differentiating (A.46) with respect to time, and substituting for (A.46), (A.48) and (A.49), as well as output and capital growth, yields the following expression for training growth in the competitive setting:

$$\hat{u}(t)\left(1-a_2\right) = \left(a_2+\gamma\right)\Omega - \Omega u(t)\left(a_2+\gamma-1\right) + a_2n + j\left(1-a_1\right) -$$
$$a_1\left(c(t)/k(t)\right) + x(t)\left(\left(1-a_1\right)\theta - \iota\left(a_2+\gamma\right)\right) +$$
$$\left(1-a_1-a_2\right)\hat{E}(t) - j - \theta x(t) \tag{A.50}$$

The remaining dynamic equations in oil demand, interest rates, and the consumption-capital ratio are given by:

$$\left(a_1+a_2\right)\left(\hat{x}(t) - x(t)\right) = \left(a_2+\gamma\right)\Omega\left(1-u(t)\right) + a_2n - a_1c(t)/k(t) +$$
$$x(t)\left(\left(1-a_1\right)\theta - \iota\left(a_2+\gamma\right)\right) + \left(1-a_1\right)j + a_2\hat{u}(t) - z(t) \tag{A.51}$$

$$\hat{r}(t)(a_1 + a_2) = (a_2 + \gamma)\,\Omega\,(1 - u(t)) + x(t)\,((1 - a_1)\,\theta - \iota\,(a_2 + \gamma)) - \\ a_2\,(c(t)/k(t) + n) + (1 - a_1)\,j - Rr(t) - \\ (1 - a_1 - a_2)\,z(t) + a_2\hat{u}(t) \tag{A.52}$$

$$\hat{c}(t) - \hat{k}(t) = c(t)/k(t) + ((n + j - \theta x(t))\,(v - 1) + r(t) - i)\,/v - r(t)/a_1 \tag{A.53}$$

In the case of the social planner, optimal consideration of the externality affecting human capital accumulation, yields the following expressions for steady states in training, depletion and net interest rates under given by:

$$x^*U = (((a_2 + \gamma)\,\Omega - (1 - a_1 - a_2)\,n)\,((v - 1))) + \\ z\,((1 - a_1) + (v - 1)\,(a_2 + \gamma)) + i\,(1 - a_1) \tag{A.54}$$

$$(r^* - j - \theta x^*)\,U = (a_2 + \gamma)\,\Omega v + n\,(a_2 + (v - 1)\,\iota\,(a_2 + \gamma)) - \\ zv\,(1 - a_1 - a_2 + \iota a_2) + ia_2\,(1 - \iota) \tag{A.55}$$

$$Uu^* = \frac{1}{\Omega}(n\,(a_2 + (v - 1)\,\iota\,(a_2 + \gamma)) - \\ zv\,(1 - a_1 - a_2 + \iota a_2) + ia_2\,(1 - \iota)) \tag{A.56}$$

where $U = v\,(1 - a_1) + (v - 1)\,(\gamma + \iota\,(a_2 + \gamma))$.

An interior solution – in the sense of positive efforts made in human as well as physical capital accumulation – implies that:

$v\,(1 - a_1) + (v - 1)\,(\iota\,(a_2 + \gamma)) - i\,(1 - a_1) >$

$$(((a_2 + \gamma)\,\Omega - (1 - a_1 - a_2)\,n - z\,(1 - a_1 - a_2 + \iota\,(a_2 + \gamma)))\,(v - 1)) > 0 \tag{A.57}$$

The long run comparative statics are similar to the model adapted from Sinclair (1992, 1994) above featuring exogenous technological progress: resource depletion, the time allocation to training, and net investment returns increase with the productivity of the education sector and the impatience parameter and falls with the productive externality: $\frac{dx^*}{d\Omega}, \frac{du^*}{d\Omega}, \frac{d(r^*-j-\theta x^*)}{d\Omega} > 0, \frac{dx^*}{di}, \frac{du^*}{di}, \frac{d(r^*-j-\theta x^*)}{di} > 0, \frac{dx^*}{d\iota}, \frac{du^*}{d\iota}, \frac{d(r^*-j-\theta x^*)}{d\iota} < 0$. A rising tax rate reduces depletion, net returns and the allocation of training (through the productivity of the education sector): $\frac{dx^*}{dz}, \frac{du^*}{dz}, \frac{d(r^*-j-\theta x^*)}{dz} < 0$

Comparison of equations (A.40) and (A.54) demonstrates part i) of Corollary 3.11.

Part ii) asserts that the model is manifold stable if $(a_2+\gamma)\,\iota > (1-a_1)\,\theta$. To see, consider the following Jacobian matrix of the (log) linear system of differential equations– which includes the differential equation in the allocation of training – given by:

$$Jacobian = \begin{pmatrix} \frac{d\dot{Y/K}}{dY/K} & \frac{d\dot{Y/K}}{dV} & \frac{d\dot{Y/K}}{dZ} & \frac{d\dot{Y/K}}{du} \\ \frac{d\dot{C/K}}{dY/K} & \frac{d\dot{C/K}}{dC/K} & \frac{d\dot{C/K}}{dx} & \frac{d\dot{C/K}}{du} \\ \frac{d\dot{x}}{dY/K} & \frac{d\dot{x}}{dC/K} & \frac{d\dot{x}}{dx} & \frac{d\dot{x}}{du} \\ \frac{d\dot{u}}{dY/K} & \frac{d\dot{u}}{dC/K} & \frac{d\dot{u}}{dx} & \frac{d\dot{u}}{du} \end{pmatrix} =$$

$$\begin{pmatrix} (a_1-1)\,\frac{r}{a_1} & \left(\frac{(a_2\theta-(a_2+\gamma)\iota)\,\frac{r}{a_1}}{a_1-((a_2+\gamma)\iota+(a_1-a_2)\theta)}\right) & 0 & 0 \\ \left(\frac{a_1}{v}-1\right)c/k & c/k & \frac{\theta(v-1)}{v}c/k & 0 \\ 0 & -x & \left(\frac{a_1-((a_2+\gamma)\iota-(1-a_1)\theta)}{a_1}\right)x & 0 \\ 0 & -u & -\frac{((a_2+\gamma)\iota-(1-a_1)\theta)}{a_1}\bar{u} & \frac{(a_2+\gamma)\Omega\bar{u}}{a_2} \end{pmatrix} \tag{A.58}$$

This condition is thus sufficient condition for $\mid Jacobian \mid < 0$ – and thus the dynamic system to be locally stable (given the existence of a positive eigenvalue).

Corollary 3.7

In the case of the Keynesian model, the capital externality tempers the downward pressure of the productive externality on growth, depletion rates and capital returns.

Once again, assuming that oil taxes are constant in the absence of climate change (i.e. $z=0$ if $m=\theta=0$), it follows from equations (A.40) and (A.54) that the slope of the corrective tax is given by:

$$z = \frac{\left(\iota\left(a_2+\gamma\right)-\theta\left(1-a_1\right)\right)\left(a_1-s\right)\left(\left(a_2+\gamma\right)\left(1-u\right)\Omega+j\left(1-a_1\right)\right)}{s\left(1-a_1\right)\left(a_1\left(1-a_1-a_2\right)+sa_2\right)} \tag{A.59}$$

which is shallower corrective than would be the case under solely the production externality.

Solving for the socially desirable tax rate within the optimal growth model with endogenous technological development – derived in an analogous fashion to Corollary 3.3 – yields:

$$z^* = -\frac{a_2\iota-\theta\left(1-a_1\left(1-\frac{c^*/k^*}{r^*}\right)\right)}{\left(1-a_1-a_2\right)}x^* \tag{A.60}$$

However, in this context, there is an addition externality in the market for knowledge, since the social planner considers the wider influence of individual training decisions on productivity (through average skill levels).

To see this, consider the socially optimal investment in human capital (where the outcome of the social planners decision is denoted by the superscript SP) yields the following rate of change in shadow prices:

$$-\hat{\lambda}_2^{SP}(t) = i - \frac{\lambda_1^{SP}(t)}{\lambda_2^{SP}(t)}\frac{\left(a_2+\gamma\right)Q(t)}{l(t)} - \left[\Omega\left(1-u\right)-\iota x(t)\right] \tag{A.61}$$

Thus, by comparison with (A.49), human capital has a lower scarcity value under the social planner since the full productive benefits are accounted for when allocating training.

Differentiating (A.46) with respect to time, and substituting for (A.61), (A.48), (A.46), as well as output and capital growth, yields the following expression for the training growth in the competitive setting:

$$\hat{u}^{SP}(t)\left(1-a_2\right) = \left(a_2+\gamma\right)\Omega-\Omega u(t)\left(a_2+\gamma\right)\left(1-\frac{1}{a_2}\right)+a_2n+j\left(1-a_1\right)-$$

$$a_1\left(c(t)/k(t)\right)+x(t)\left(\left(1-a_1\right)\theta(t)-\iota\left(a_2+\gamma\right)\right)+\left(1-a_1-a_2\right)\hat{E}(t)-j-\theta x(t) \tag{A.62}$$

Comparison of (A.62) and (A.50) reveals the additional distortion to human capital accumulation arising from the failure of the representative agent to internalize the effect of her own training decisions of average human capital levels (and thus aggregate productivity).

To formalize the policy implications, consider the following decentralized utility maximisation problem:

$$\underset{\{c(t),E(t),u(t)\}_{t=0}^{\infty}}{Max} V = \int_0^{\infty}(e^{-it}\frac{c(t)^{1-v}-1}{1-v}+$$
$$\lambda_1(t)((r(t)K(t) + (1-Z_w)\,W(t)l(t)u(t) + (1-a_1-a_1)\,P(t) - C(t)-$$
$$(j+\theta x(t))\,K(t) - (1-u(t))\,l(t)Z_h(t) - \dot{K}(t))+$$
$$\lambda_2(t)\,(\Omega\,(1-u(t)) - \iota x(t)))dt \tag{A.63}$$

where Z_W, Z_h represent taxes on wage income and training (the cost of training is assumed to be foregone wages). This set up is constrained by the requirement on the government to balance its budget:

$$Z_W(t)W(t)l(t)u(t) = (1-u(t))\,Z_h(t)W(t) \tag{A.64}$$

Differentiating (A.49) and substituting as before, yields the following expression for the growth rate of training:

$$\hat{u}\,(1-a_2) = (a_1+\gamma)\,(\Omega-\iota x(t)) + \Omega u\,(a_2+\gamma-1) -$$
$$c(t)/(t)k + \frac{\Omega Z_h(t)}{a_2\left(1-\breve{Z_W}\right)} - \frac{\dot{\breve{Z_W}}}{a_2\left(1-\breve{Z_W}\right)} - j - \theta x(t) \tag{A.65}$$

where $\breve{Z_W}(t) = Z_W(t) - Z_h(t)$ serves to simplify the notation.

Setting (A.65) equal with (A.62) in the undistorted case (i.e. for $x^*(z^*) = \iota = 0$) – and assuming the labour income levy is stationary (required for the size of the governmental sector to be non explosive), and substituting for the balanced budget constraint – yields the following expressions for optimal policy:

$$Z_W^* = -\frac{Z_h^*}{u} = \frac{\gamma}{(a_2 + \gamma)} + \frac{\iota}{a_2 \Omega u} \tag{A.66}$$

This comprises of a wage tax and subsidy to human capital accumulation. The magnitude of the interventions depends rises with the ratio of the productivity spillover to the undistorted productivity of training and the time allocated to human capital accumulation. This modifies the finding of Gómez (2003) in a model without finite resources or environmental externalities.

B APPENDIX TO CHAPTER 4

Lemma 4.1

Totally differentiating equation (3.2) and (3.3) with respect to time, and combining with (3.4), (3.5), (3.7) and the population growth rate given by equation (4.1) yields the following equations of motion in depletion:

$$(a_1 + a_2)\,\hat{x}(t) = h + a_2 n + (a_1 + a_2 - m - a_2\varphi)\,x(t) - (1 - s)\,r(t) \tag{B.1}$$

Totally differentiating equation (3.3) and (3.6) with respect to time, and substituting for (3.1), (3.4), (3.5) and (3.7) yields the following equations of motion in interest rates:

$$(a_1 + a_2)\,\hat{r}(t) = h + a_2 n - (m + a_2\varphi)\,x(t) - Or(t) - (1 - a_1 - a_2)\,z(t) \tag{B.2}$$

Thus φ causes the stationary depletion locus to pivot anti-clockwise (in x, r space): higher depletion reduces output through the labour supply effect. The stationary depletion locus is thus upward sloping if: $m + a_2\varphi < a_1 + a_2$, and generating a vertical force of attraction (being otherwise upward sloping with 'knife-edge' properties). By imposing further downward pressure on the growth rate as x increases, ψ also causes the stationary rental growth locus to also pivot anti-clockwise (and exerts a horizontal force of attraction). The steady state is thus manifold stable.

Cross substituting between (B.1) and (B.2), evaluated at their stationary loci, yields expressions (4.2) and (4.3). By inspection, these exist under the stated condition, $a_1 > s$. Substituting for interest rates and capital transition into (4.3), yields (4.4).

Lemma 4.3 & Proposition 4.1

The dynamic equations for depletion, interest rates, consumption-capital and output growth are given by:

$$(\hat{x}(t) - x(t))\,(a_1 + a_2) = h + a_2 n - (m + a_2\varphi)\,x(t) - \\ a_1 c(t)/k(t) - z(t) \tag{B.3}$$

$$(a_1 + a_2)\,\hat{r}(t) = h - (m + a_2\varphi)\,x(t) + a_2\,(c(t)/k(t) + n) - Rr(t) - \\ (1 - a_1 - a_2)\,z(t)) \tag{B.4}$$

$$\hat{c}(t) - \hat{k}(t) = c(t)/k(t) + ((n - \varphi x(t))\,(v - \xi) + r(t) - i)\,/v - r(t)/a_1 \tag{B.5}$$

$$\hat{Q}(t) = h - (m + a_2\varphi)\,x(t) + r(t) - a_1 c(t)/k(t) + a_2 n + \\ (1 - a_1 - a_2)\,(\hat{x}(t) - x(t)) \tag{B.6}$$

The solution to this system of equations is given at (4.10)-(4.13).

Corollary 4.3

As before, the private household ignores the influence on declining productivity and population growth from her oil market activity.

The first order conditions with respect to the stock and flow of oil respectively are given by:

$$\frac{dV}{dS(t)} = 0 \tag{B.7}$$

$$\frac{d}{dt}\left(\frac{dV(.)}{d\dot{S}(t)}\right) = \lambda\left(\frac{(1 - a_1 - a_2)\,Q(t)}{\dot{S}(t)}\left(\hat{Q}(t) - \hat{E}(t) + \hat{\lambda}(t)\right)\right) \tag{B.8}$$

By contrast, the optimization problem of the social planner is given by:

$$\underset{\{c(t),E(t)\}_{t=0}^{\infty}}{Max} V = \int_0^{\infty} (\left(\frac{c(t)^{1-v}-1}{1-v}\right)^{\xi} (N(t,\tilde{x}))^{1-\xi} +$$

$$\lambda(t)\left(Q(\tilde{s}(t)) - c(t)N(t) - \dot{K}(t)\right) + \mu(t)\left(\left(n - \psi\tilde{x}(t)\right)N(t)\right))dt \qquad \text{(B.9)}$$

where, as before, the term $\tilde{s}$ reflects the productive benefits from unburned oil in the ground, but also the influence of her oil market behaviour on population growth. The first order conditions with respect to the stock and flow of oil respectively are given by:

$$\frac{dV(.)}{dS} = \frac{\lambda(t)}{S(t)}\left((1-\xi)\,t\psi x(t)\frac{c(t)N(t)}{1-v} + mQ(t)\right) + \mu(t)\left(\frac{N(t)\psi x(t)}{\widetilde{s}(t)}\right) \qquad \text{(B.10)}$$

$$\frac{d\left[\frac{dV(.)}{d\dot{S}}\right]}{dt} = \frac{t\lambda(t)\,(1-\xi)\,c(t)N(t)\psi}{S(t)\,(1-v)}\left(\hat{\lambda}(t) + \hat{c}(t) + \hat{N}(t) + x(t) + \frac{1}{t}\right) -$$

$$\lambda(t)\left(\frac{(1-a_1-a_2)\,Q(t)}{\dot{S}(t)}\left(\hat{Q}(t) - \hat{E}(t) + \hat{\lambda}(t)\right)\right) +$$

$$\mu(t)\left(\frac{N(t)\psi}{\widetilde{s}(t)}\right)\left(\hat{\mu}(t) + \hat{N}(t) + x(t)\right) \qquad \text{(B.11)}$$

Setting conditions (B.10) and (B.11) equal, and substituting for $\mu(t)$, $\hat{\mu}(t)$ $\hat{c}(t)$, yields the following optimal tax condition given at equation (4.15).

Lemma 4.4 & Proposition 4.2

Taking the ratio of outputs in period t and $t+1$, and substituting from the transition equation in oil stocks: $S_t = S_{t-1}(1-x_t)$, together with the Hotelling and marginal factor returns conditions, yields the following expression for output growth:

$$(1+g_{+1})^{1-a_1} = \left(\frac{q_{t+1}(1+n)}{q_t}\right)^{1-a_1} = \frac{(1+h)}{(1-x)^m}(1+n)^{1-a_1-a_2}\left(\frac{r_+}{r}\right)^{a_1}(1+r_+)^{-a_2} \qquad \text{(B.12)}$$

which implicitly defines a law of motion for r. Evaluating equation (B.12) at the steady state, and substituting for $(1-x)(1+r)=1+g$, yields the stationary "Hotelling Curve".

Turning to the capital market, by substituting for the marginal factor returns conditions into the transition equation for oil stocks, one can write steady state growth in terms of rental returns, preferences, the mortality hazard, and the oil extraction rate as follows:

$$1+g=\frac{r}{a_1}\left(b(1-\rho)(1-a_1-a_2)-a_2\frac{(1-x)}{x}\right) \tag{B.13}$$

Further substituting for $(1-x)(1+r)=1+g$, (B.12) and (4.20), evaluated at the steady state, yields the stationary "savings curve".

C APPENDIX TO CHAPTER 5

Lemma 5.1 & Lemma 5.2

Differentiating output with respect to time, and substituting for capital transition and the Hotelling condition, generates the remaining transition equations in output, depletion, interest rates, and consumption-capital:

$$\hat{Q}(t) = h + a_2 n - mx(t) - a_1 c(t)/k(t) + (1 - a_1 - a_2)\,\hat{E}(t) + (1 - a_1 - a_2)\,\hat{\chi}\,(t, x\,(t)) \quad \text{(C.1)}$$

$$\begin{aligned}(\hat{x}(t) - x(t))\,(a_1 + a_2) = h + a_2 n - mx(t) - a_1 c(t)/k(t) - z(t) + \\ (1 - a_1 - a_2)\,\hat{\chi}\,(t, x\,(t))\end{aligned} \quad \text{(C.2)}$$

$$\begin{aligned}(a_1 + a_2)\,\hat{r}\,(t) = h + a_2 n - Or(t) + ((1 - a_1)\,\theta - m)\,x(t) + j\,(1 - a_1) - \\ (1 - a_1 - a_2)\,z(t) + (1 - a_1 - a_2)\,\hat{\chi}\,(t, x\,(t))\end{aligned} \quad \text{(C.3)}$$

$$\hat{c}(t) - \hat{k}(t) = c/k(t) + (n\,(v - 1) + r(t) - i)\,/v - r(t)/a_1 \quad \text{(C.4)}$$

As one would expect, increased oil allocated to production raises output growth in output and oil demand since capital is more abundant. Stationary oil demand and interest rates are now influenced by the preference parameters w and i through the mechanism described above. The ratio of consumption to capital is unchanged.[124]

The solution to this system of equations is given at (5.5)-(5.8).

[124] The assumption of Cobb-Douglas preferences is critical here.

Lemma 5.3

This insight follows by comparing the oil allocation decision of the representative household with decision of the social planner in the undistorted case (made in the absence of a production tax on oil). The former is given by:

$$E(t)e^{-it}\left(\left(1-\chi^{*}\left(\bar{x}\left(z^{*}\right)\right)\right)E(t)\right)^{-w}=\lambda(t)\left(\left(1-a_{1}-a_{2}\right)\frac{Q(t)}{\chi\left(\bar{x}\right)\left(1-Z_{\chi}(t)\right)}\right) \tag{C.5}$$

By contrast the latter is given by:

$$E(t)e^{-it}\left(\left(1-\bar{\chi}\left(.\right)\right)E(t)\right)^{-w}=\lambda(t)\left(\left(1-a_{1}-a_{2}\right)\frac{Q(t)}{\bar{\chi}\left(.\right)\left(1-Z_{\chi}(t)\right)}\right) \tag{C.6}$$

where $\bar{\chi}$ represents the undistorted oil allocation. Equating these conditions and substituting for the marginal product of oil yields the stated condition.

Empirical evidence on linkages between climate change and residential energy demand

This section summarizes currently available evidence concerning the responsiveness of energy demand to climatic conditions.

Some 20 studies have sought to estimate the effects of climate change on residential energy demand, focussing on heating and cooling demands in the US and, to a lesser extent, Europe. These consistently predict countervailing effects from fewer cold winter days (reducing heating related energy demand), and more frequent and intense hot summer spells (resulting in expected increases in energy demand for air conditioning). For large countries, it is therefore desirable to consider the latitude and geographical dispersion of economic activities when calibrating parameters.[125]

[125] This issue is further complicated by potential non linearities in demand responses which could result in the dominance of heat related savings for low levels of warming being reversed with greater degrees of climate change (Hadley et al. (2006)).

A common approach when assessing these magnitudes has been to first infer predictions on the likely changes in the number of Heating and Cooling Degree Days (CDDs/ HDDs) in a given locality (defined as the sum of positive/negative deviations in the average ambient temperature from a given base comfort level over a given period of time) from meteorological models;[126] and then subsequently draw inference for household energy demand, either by extrapolating from observed statistical relationships with existing weather conditions (exploiting locational and/or temporal variance), or from energy systems models (with assumptions drawn from engineering assessments).

The later class of studies have tended to predict high degrees of demand sensitivity. Scott et al. (1994) and Rosenthal et al. (1995), for example, estimate changes in energy demand associated with maintaining existing internal building temperatures across different US cities under altered climatic conditions. They find that, on average, a one degree C temperature rise reduces residential heating demand by around 5-15 percent and increases cooling by 10-25 percent. These early studies are based on simplistic functional relationships between demand and HDD/ CDD, and assume that population size and building characteristics remain static.[127]

A further branch of the literature employs statistical and econometric techniques to analyse the influence of temperature changes on sectoral energy demand.[128] In general,

[126] HDD and SDD measures avoid the need for separate analyses of summer and winter seasons, but are sensitive to assumptions on the comfort threshold, which may vary from region to region (Rosenthal et al. (1995), Sailor and Munoz (1997)). Although mean temperatures have been the principle research focus, a limited number of studies have identified wider climatic effects including wind speed, precipitation and humidity on heating and cooling demand (Howden and Crimp (2001), Sailor and Munoz (1997), Sailor (2001), Sailor and Pavlova (2003) and Mansur et al. (2008)). However, these aspects of climate change are subject to higher forecast uncertainty.

[127] Huang et al. (2006) and Scott et al. (2008) undertake more complex simulations of energy usage aggregated across different buildings types, vintages of heating, cooling and lighting technologies (together with associated costs), and incorporating the effects of expected demographic shifts. However, their findings are quantitatively similar.

[128] See, for example, Amato et al. (2005), Belzer et al. (1996), De Cian et al. (2007), Eskeland and Mideksa (2010), Franco and Sanstad (2008), Howden and Crimp (2001), Mansur et al. (2008), Mendelsohn (2001), Olonscheck et al.

these studies affirm the qualitative trends identified in resource based studies above, but the effects are (on balance) quantitatively smaller. Mendelsohn (2001), for example, exploits cross sectional variance in energy demand identified by Morrison and Mendelsohn (1999) to estimate the potential effects of future climate change. He finds that a 1.5 degree C average temperature increase is likely to have negligible effects on residential energy expenditures in 2060, although energy demand is predicted to fall modestly. Some time series studies are weakened by the failure to include socioeconomic variables such as incomes and prices. [129]

Amato et al. (2005) and Ruth and Lin (2006) undertake more sophisticated econometric analyses for the states of Massachusetts and Maryland respectively using very similar fixed effects regression models (and data sources: monthly state level electricity and fuels sales and price data from 1977- 2001 taken from the Energy Information Administration) to estimate fuel specific commodity demands in the residential and commercial sectors as a function of HDD and CDDs, energy prices, daylight hours (affecting lighting), and trend variables (such as technology and incomes). The findings suggest a high degree of weather sensitivity: demand for residential heating fuels, by contrast, is predicted to fall by 15-33 percent in Massachusetts and around 2.5 percent in Maryland by the same period.[130]

(2011), Ruth and Lin (2006), Sailor (2001), Sailor and Munoz (1997), Sailor and Pavlova (2003), and Summerfield et al. (2010). These studies obviate the need for detailed assumptions regarding technological performance and cost, and have the potential to capture the effects of behavioural change such as market penetration of air conditioners (which have uncertain but potentially powerful effects (Olonscheck et al. (2011), Sailor and Pavlova (2003)). However, they have a number of important disadvantages including their potential sensitivity to model misspecifications, and their reliance on estimating the partial effects of observed weather changes (whereas climate change may imply conditions which lie outside current experiences).

[129] For example, Franco and Sanstad (2008), Howden and Crimp (2001), Sailor and Munoz (1997), Sailor (2001), Sailor and Pavlova (2003), Summerfield et al. (2010), model 1). Although such determinants are not universally found to be significant in more robust structural analyses (Ruth and Lin (2006)) – the potential for false inference is clear (climate is strongly correlated with average income through geography (Horowitz (2009)).

[130] Such effects may nevertheless be small relative to the influence of price, technology, and income changes (see, also

D APPENDIX TO CHAPTER 6

Data and descriptive trends

The underlying data source, collection methodologies, and descriptive trends found therein are discussed below (drawing on Jones (2012)).

Data source and collection issues

Data are drawn from the UK FES between 1986 and 2009. The principal purpose of the survey is to inform the calculation of general price indices, such as the Retail Price Index. However, it is also a useful resource for micro econometric studies of this type. The nature of this data resource is outlined further below.

Cooperating households provide a detailed record of expenditures of more than 50 different categories of goods, including various food products, fuels, and other regular domestic outlays. The survey also records information on, for example: household composition, ages, income, region, and patterns of ownership for certain consumer durables.

For most items, expenditure details are recorded in a two week diary by adult household members. Household spending on energy products made through direct debit is recorded on the basis of average expenditure in the past year. Other energy expenditures, including on coal and coin operated meters, are recorded through the diary.

This approach is likely to provide a reasonably accurate record of total spending: Banks

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Eskeland and Mideksa (2010) in a rigourous panel analysis of electricity demand in 30 European countries). Mansur et al. (2008) is a further study of note. The authors estimate a Dubin-McFadden type discrete choice model in which conditional energy demands are a function of incomes, prices and building related variables, with fuel choice following a multi logit probability distribution determined by climatic, demographic as well as building and firm specific characteristics. This model identifies variation in the sensitivity of heating demand to climate conditions across fuels (low for natural gas, but broadly comparable with Amato et al. (2005) and Ruth and Lin (2006) for fuel oil).

and Johnson (1998), for example, compare aggregated FES expenditure data with the national accounts and find a reasonably stable relationship across time, thus concluding that the data for these individual commodities are likely to be reasonably robust. Nevertheless, there are a number of issues worth highlighting.

First, is the known under-reporting of socially undesirable goods such as such as alcohol and tobacco (Kemsley et al. (1980)).[131] Second, certain groups including students in university accommodation, residents of elderly care homes, members of the armed forces and homeless are underrepresented (Banks and Johnson (1998)).[132] Third, expenditure on infrequently purchased goods, such as consumer durables are only captured if the survey coincides with the timing of these payments (econometric issues arising are discussed below).

Descriptive trends in income and expenditure

Total expenditure on goods for which demand is analysed averaged £271 per week in 2007. Average net household income equalled £531 in the same year. The distribution of expenditures by commodity type are discussed in Table 12.

Turning to distributional aspects of energy related expenditures, Table 13 ranks households according to total non-housing related expenditures and income (i.e. adjusting for rent, rates mortgage and other housing related costs). It shows that average energy outlays rise rapidly across both expenditure and, particularly income, distributions.

[131] A recent literature highlights under reporting of social security and other sources of transfer income in US household survey data, emphasising the potential for bias given disproportionate increases in non response rates among low income groups. See, for example, Meyer et al. (2015, 2009).

[132] This may be relevant when attempting to draw market wide inferences from sample data, particularly where there are systematic difference in behaviour across social groups.

These patterns are not uniform across individual fuels; in particular, higher spending households – although observing larger outlays in absolute terms for all fuels – have a significantly greater propensity to purchase gasoline for private transportation, compared to domestic fuels (shown in Table 14). This raises the potential for more serious welfare issues associated with changing prices of, and demand for, electricity and natural gas.

Systematic differences across socio-demographic groups are also apparent. Table 15, for example, summarises the differences in average budgets shares. It suggests that a range of characteristics, including the size and composition of the family, employment status and patterns of vehicle ownership potentially influence energy demand.[133]

Estimation issues using household survey data

The key issues affecting the empirical analysis are here discussed in more detail (drawing on Jones (2012)); in particular relating to the aggregation of goods; measurement error or simultaneity bias, the incorporation of demographic controls; and the treatment of censored data are here discussed (see also Bopape (2006)).

Commodity grouping and separability

Aggregation of goods is necessary due both to limitations in computational capacity and available degrees of freedom. From a theoretical perspective, the literature proposes two broad approaches to this.

The first suggests grouping commodities based on the behaviour of their relative prices. In particular, the composite commodity theorem of Hicks (1946) and Leontief (1936) asserts that, if prices of individual goods move in parallel, then the expenditure function

[133] Other factors affecting energy demand which are likely to be less transparent in the data include access to supply infrastructure and the diffusion of energy efficiency technologies; see, for example, Brechling and Smith (1991), Crawford et al. (1993), Johnson et al. (1990).

defined over bundles of commodities grouped in this way will satisfy the usual properties (increasing in prices and utility, concave in prices and linearly homogeneous). However, Deaton and Muellbauer (1980b) argue that this approach is limited in its usefulness at least in part because relative prices change over time in practice (for example, due to exchange rate fluctuations affecting traded goods such as oil products).[134]

The second (and more common) approach employed here assumes that preferences are "weakly separable", such that the utility from one commodity is independent of consumption over others. This implies the existence of sub utility functions over subsets of commodities, which allows consumers to break down consumption decisions into multiple stages (Deaton and Muellbauer (1980b)). This assumption, while analytically convenient (since it permits behaviour to be explained through estimation of a smaller number of variables), raises a number of issues.

First, it imposes strong restrictions on the relationship between goods within different commodity groups: direct cross price effects between individual commodities comprising different commodity bundles are precluded, with interactions limited solely to the second order effects of price changes on real incomes. The structure and composition of commodity groups thus becomes key.[135] Conceptually, this would generally favour grouping of close substitutes goods.

Second, it raises questions about the empirical relationship between consumption and leisure. The assumption that leisure is independent of demand may be broadly plausible for total expenditure, but is unlikely to hold for individual goods which may, for example,

[134] Lewbel (1996) develops a version of the theorem which permits a weakening of assumptions over the co-movement of prices. Specifically, he assumes that the distribution of an individual commodity's price is independent of the commodity bundle, and then conducts cointegration tests between each of the individual prices and those of the bundle to which they belong. Reed et al. (2005) extend this generalized theorem in a nonlinear modelling context for food demand.

[135] Moschini (1992) and Moschini et al. (1994), for example, attempt to derive functional relationships that must hold between goods belonging to the same group and those belonging to other groups, and then test whether these hold empirically.

have close functional relationships with labour (for example, commuting) or leisure (such as sporting goods).[136]

For the purposes of this study, the traditional assumption of weak separability is simply maintained (its relaxation is a potential area for extension in future work).

Endogeneity

Expenditure endogeneity (correlated with the error terms in the commodity equations) is a common issue in empirical demand side analysis. Data limitations and computational constraints require estimation on a subset of household expenditures. This may generate simultaneity bias in the event that total expenditure is jointly determined with outlays for the individual commodities under analysis, making it endogenous to the budget share equations.

Such a risk is clearly present in the context of this study. Even a comprehensive survey such as the FES is inevitably incomplete (approximately 90 percent of the consumption data covered by the national accounts (Banks and Johnson (1998)). Moreover, the demand system estimated in this study excludes housing related expenditures (such as rent, mortgage payments, and furniture and furnishing outlays).[137]

Endogeneity issues may also arise if the share equation is misspecified, or the data are subject to measurement error. These problems are ubiquitous in empirical studies. The range of explanatory variables considered is large (including detailed treatment of demographic controls) and has been subjected to a proper robustness testing. Moreover,

[136] Browning and Meghir (1991) analyze the effects of labour supply on commodity demands in the UK and found the independence assumption to be rejected empirically.

[137] This is for two reasons. First, non housing expenditures may be a better measure of disposable income over which consumption choices are formed. Second, these data are "dirty" in the sense that they include a number of (sometimes large) negative expenditures, for example as a result of government or housing agency related rebate programmes.

the diary system underpinning the FES methodology is considered best practice among statisticians (OECD (2013b), page 150).

Nevertheless it is vulnerable to various form of measurement error. Beyond the fact of simple human error, two examples are worthy of particular mention. First, differences in the quality of products are not recorded. Second, and relatedly, prices are assumed to be homogeneous across households within any given quarter (in the case of electricity, for example, we know that low income households have a greater propensity to use pre pay meters, or lack access to direct debit facilities, and therefore pay higher unit charges).[138]

This study adopts the standard practice in the literature of instrumenting expenditure for income following Keen (1986) (see, for example, Banks et al. (1997), Blundell and Robin (1999), Blundell et al. (1993)), paying careful attention to potential efficiency losses from weakness in the informativeness of non linear instrumental variables. The validity of this approach is verified using a Sargan test of over-identifying restrictions.

Zero expenditures

Recording of zero expenditures is a common issue in demand analysis. Keen (1986), for example, reports three possible causes of such patterns including: preference variation (some households are unlikely to buy goods such as tobacco, regardless of the price), misreporting of expenditures (reflecting, for example, social stigmas over certain goods such as alcohol), and infrequent purchases (including, by definition, most consumer durables but also certain storable energy goods such as coal and fuel oil). In cross sectional studies

[138] In practice even the prices of homogeneous goods such as, say, regulated grades of gasoline, may vary across filling stations and regions. A number of possible means of redress have been considered. Cox and Wohlgenant (1986), for example, suggest that unit costs should be adjusted for quality variation before substituting unit costs for prices in estimated share equations. Demographic, regional, and seasonal variables have often been used to proxy for quality and quality-adjusted prices (Gao et al. (1995)).

such as this, it is almost inevitable that surveyed households will consume zero quantities of certain goods, particularly if the demand system is quite disaggregated.

The econometric treatment of zero consumption has received considerable attention from econometricians. If a large proportion of expenditure values for a given commodity is zero, then the dependent variable is censored. Basic regression techniques which fail to account for this factor will therefore tend to be biased. However, dealing with such issues is likely to be somewhat challenging. Simply removing zero observations would introduce selection bias into the estimation of the parameters of the demand system (although analysing conditional distributional may be interesting of itself), and could reduce estimation freedom.

This problem is tractable in a single equation context through the use of a Tobit model, but becomes considerably harder to deal with in the context of a system of equations given the resulting computational complexity arising from the need to compute multiple integrals on non consumption realizations (see, for example, Lee and Pitt (1986), Wales and Woodland (1983)). Such one step approaches are thus inappropriate in this context.[139] A number of two-step procedures have subsequently been developed, drawing on Heckman-type sample selection correction factor (see, for example, Heien and Wessells (1990), Yen et al. (2003)). For the purposes of this study, I have sought to balance these risks through my choice of commodity aggregation.

Demographic controls

Demographic variables have a potentially important bearing on demand. There are two broad ways of incorporating such controls into this type of analysis (see Pollak and Wales

[139] Moreover, they are unsuitable for censoring due to infrequent purchases since observed demand and the consumption decision are assumed to be governed by the same process.

(1992) for a helpful review). The unpooled approach involves estimating individual demand systems on sub-samples of households with the same demographic profiles. It precludes the need to specify the functional relationship between demographic variables and demand system parameters. However, the failure to pool data results in a loss of efficiency. In addition, it is not possible to draw inferences about households from the behaviour of those with different demographic profiles.

Pooled approaches involve specifying a class of demand parameters common to all households (such as prices and incomes), and a further set which depend on demographic variables (together with the functional relationship). Pollak and Wales (1992) review 5 approaches which have been applied to various demand systems, including (i) demographic scaling (Barten (1964)); (ii) Gorman's (1976) specification; (iii) the reverse-Gorman specification; (iv) the Prais-Houthakker (1955) procedure; and (iv) demographic translation (Pollak and Wales (1981)).

Demographic translators are the most common approach in the literature and typically allow subsistence budget shares to depend on demographic controls (through the intercept term). By contrast, scaling functions, reflecting the number of 'equivalent adults" in the household, can be applied to prices and quantities such that preferences are defined over the quantity of goods per equivalent adult. Although intuitive, Deaton and Muellbauer (1980b) point out that theoretically consistent scaling imposes undesirable behavioral assumptions including the absence of substitution possibilities. [140]

No single method is universally preferable (and our capacity to comprehensively rank

[140] The Gorman (and closely related reverse Gorman) form incorporate both demographic translating and scaling, but suffer the identified weakness affecting scaling functions. The Prais-Houthakker approach combines a single income scale with specific modifications for each commodity grouping. However, while permitting additional flexibility by capturing both common and commodity specific scale factors, it yields theoretically consistent demand systems only in the presence of additive utility functions (Pollak and Wales (1981)). This restriction implies that new commodity groups can always be creating through combinations of others, preventing any good occupying a particular position in the utility function (Deaton and Muellbauer (1980b)).

them is restricted by the fact that a number of these approaches are not nested). Any assessment also naturally depends on the particular functional form adopted in demand estimation. Chapter 6 adopts the most common approach in the literature of demographic translation.

Estimation results

Table 12
Average expenditure by commodity groups

This table shows the distribution of average expenditures on each commodity group analysed above in 2007: UK households spent, for example, an average each week around £70 on food and £34 on energy products.

Commodity	Food (non VAT)	Food (VAT)	Electricity	Gas	Petrol	Consumer	Leisure
Mean Weekly Outlay (£2007)	40.88	30.20	8.51	7.09	18.78	87.90	78.51

Table 13
Distribution of energy expenditures

This table shows average weekly total spending, income and outlays on energy products, by (non housing) expenditure and income decile (panel a) and b) respectively). Average energy outlays rise rapidly across the expenditure distribution: from around £9 per week for the lowest decile, for example, to roughly £63 per week for the highest (a seven fold difference). However, energy expenditures comprise a much larger share of the budget among poorer households: 19 percent for the lowest decile compared to an average of 9 percent for the uppermost. When households are ranked according to income, this pattern is still more marked: energy expenditures account for, on average, almost one third of outlays among the lowest decile (although this statistic is susceptible to outliers), but just 4 percent of the top ten percent of households by income.*

Decile	Average weekly energy exp.	% Non housing exp.	Total Non housing exp.	Net income
1	9.27	19.15	48.54	179.52
2	15.45	17.22	89.82	257.26
3	21.11	16.92	124.95	306.23
4	26.36	16.51	159.81	374.40
5	30.10	15.40	195.99	457.48
6	35.44	14.89	238.19	537.69
7	42.69	14.82	288.33	621.77
8	46.47	13.08	355.49	685.22
9	53.46	11.81	454.95	782.83
10	63.37	8.95	763.19	1108.34
All households	34.37	14.88	271.87	531.00

(a) Average weekly total spending, income and outlays on energy products, by (non housing) expenditure decile, 2007 (£2007)

Decile	Average weekly energy exp.	% Net income	Total Non housing exp.	Net income
1	15.82	32.77	102.39	101.19
2	18.01	9.93	131.22	181.70
3	21.67	8.85	153.73	245.79
4	27.44	8.70	197.02	315.37
5	31.27	8.01	229.19	390.66
6	36.16	7.62	256.82	475.02
7	40.91	7.19	309.45	569.80
8	45.83	6.63	370.00	692.59
9	49.09	5.66	395.97	871.21
10	57.52	4.31	573.37	1468.02
All households	34.37	9.94	271.87	531.00

(b) Average weekly total spending, income and outlays on energy products, by net income decile, 2007 (£2007)

*Arguably, the expenditure distribution is a better measure of overall welfare (income being more sensitive to transient employment shocks, for example).

Table 14
Percentage of total energy expenditure by fuel

This table shows the distribution of average expenditure on individual fuels by expenditure decile in 2007: outlays on natural gas and electricity rise less rapidly through the distribution than gasoline: outlays on domestic fuels, for example, are around 2.5 times higher for the top 10 percent of households compared to the lowest decile, but rise more than thirty fold for transportation. Expressed as a proportion of total energy expenditures, poorer households are much more dependent on electricity, which accounts for nearly 60 percent of total energy outlays among those in the lowest spending decile (compared to one-quarter among the top 10 percent). By contrast, more than one half of energy outlays go to transport among the richest 25 percent of households.

Decile	Electricity	Gas	Gasoline
1	59.5	33.9	6.7
2	46.0	34.9	19.1
3	38.5	30.5	31.0
4	34.4	28.6	37.0
5	31.8	24.9	43.3
6	29.3	24.6	46.1
7	26.8	22.1	51.2
8	26.7	20.2	53.1
9	25.7	19.5	54.8
10	24.9	19.9	55.1
All households	33.8	25.7	40.6

Table 15
Average energy expenditure share by demographic variable

This table summarises the differences in average budgets shares as compared to the sample mean in 2007 according to certain demographic and labour market variables. It highlights significant variation across different household types: families with children, for example, allocate roughly 1.5 percent less resource to electricity and gas relative to the sample as a whole, but slightly more to gasoline (perhaps due to the need for school runs and additional entertainment). By contrast households whose head is retired typically allocate a smaller share (around 0.7 percent) of their budget to gasoline, relative to the sample average, but around 1.5 percent additionally to electricity (reflecting the absence of commuting and potentially more time spent at home).

	electricity	gas	gasoline
average budget share	0.114	0.035	0.039
children	-0.014	-0.013	0.009
number of adults (minus one)	0.011	-0.007	-0.003
multiple adult earners	0.000	-0.001	-0.002
number of children in the household	0.000	0.002	0.002
dummy for single adult household	-0.010	0.006	0.011
dummy for retired head of household	-0.015	0.003	0.007
dummy for unemployed head of household	0.005	-0.004	-0.005
dummy for head of household aged 34-49	0.016	-0.004	-0.003
dummy for head of household aged 49-65	0.009	-0.002	-0.004
dummy for head of household aged 65-80	-0.006	0.000	-0.001
number of adult females	-0.001	0.000	0.000
dummy if rented housing	-0.001	0.004	0.005
dummy for car ownership	-0.002	0.000	-0.001
number of cars in household	0.010	0.004	0.002

Table 16
Comparing key parameter estimates: GMM vs ILLE

This table compares a sample of parameter results using both the GMM and ILLE estimators, on a simple model variant.* It shows that the parameter estimates and confidence intervals are very similar. This supports the findings of Blundell and Robin (1999) and Lewbel and Pendakur (2009) that the ILLE achieves consistent, precise and computationally tractable parameter estimates for large disaggregated demand systems observing the conditional linearity property.

	Food (non VAT)				Food (VAT)			
	ILLE (mean)	ILLE (se)	GMM (mean)	GMM (se)	ILLE (mean)	ILLE (se)	GMM (mean)	GMM (se)
Constant	0.215	0.007	0.213	0.007	0.097	0.005	0.098	0.005
Expenditure	-0.067	0.018	-0.074	0.014	-0.007	0.011	-0.004	0.008
Expenditure squared	0.012	0.011	0.006	0.009	-0.012	0.007	-0.009	0.005
Log price food (non VAT)	0.077	0.074	0.104	0.070	-0.052	0.049	-0.074	0.050
Log price food (VAT)	-0.052	0.049	-0.074	0.050	0.086	0.079	0.125	0.076
Log price electricity	0.053	0.047	0.055	0.050	-0.059	0.046	-0.067	0.044
Log price gas	-0.039	0.031	-0.045	0.032	-0.009	0.029	-0.014	0.027
Log price gasoline	0.037	0.025	0.047	0.025	-0.029	0.025	-0.036	0.024
Log price clothing	-0.017	0.023	-0.030	0.022	0.022	0.021	0.031	0.021
Log price consumer goods	0.040	0.019	0.036	0.019	-0.007	0.014	-0.009	0.014
Log price leisure services	-0.061	0.063	-0.036	0.060	0.039	0.061	0.030	0.061
Log price leisure services	0.004	0.032	-0.011	0.029	0.014	0.022	0.022	0.022

*In this case a 10 commodity demand system, excluding demographic and deterministic time controls), with assumptions of symmetry, homogeneity and adding up maintained. For ease of reference, point estimates and standard errors for the first two commodity groups, food (non VAT) and food (VAT) only are reported.

Table 17
OLS regression results

	Food (non VAT)	Food (VAT)	Electricity	Natural gas	Gasoline	Consumer goods
Log expenditure	-0.1104***	-0.0209***	-0.0316***	-0.0248***	-0.0268***	0.0416***
	(-90.31)	(-21.68)	(-56.80)	(-44.91)	(-37.44)	(24.89)
Log expenditure squared	-0.0075***	-0.0047***	0.0013***	-0.0002	-0.0054***	-0.0038***
	(-18.43)	(-14.67)	(6.97)	(-1.13)	(-22.66)	(-6.86)
Child dummy aged 0-2	0.0060**	-0.0147***	0.0004	0.0020*	0.0002	0.0417***
	(2.90)	(-9.00)	(0.44)	(2.10)	(0.15)	(14.64)
Child dummy aged 2-5	-0.0069**	-0.0119***	0.0010	0.0033***	-0.0004	0.0085**
	(-3.23)	(-7.15)	(1.04)	(3.42)	(-0.34)	(2.94)
Number of children in household	0.0268***	0.0090***	0.0039***	0.0022***	-0.0025**	-0.0273***
	(19.74)	(8.36)	(6.26)	(3.63)	(-3.11)	(-14.70)
Number of children squared in household	-0.0010**	-0.0009***	-0.0003*	-0.0004**	0.0005*	0.0026***
	(-2.91)	(-3.36)	(-2.08)	(-2.58)	(2.47)	(5.62)
Number of adults in household(-1)	0.0414***	0.0228***	-0.0016	-0.0052***	0.0068***	-0.0456***
	(18.50)	(12.92)	(-1.55)	(-5.14)	(5.15)	(-14.90)
Number of adult earners in household(-1)	-0.0085***	0.0101***	-0.0021***	-0.0008*	0.0000	0.0007
	(-10.03)	(15.08)	(-5.34)	(-2.02)	(0.08)	(0.56)
Number of adult females in household	-0.0063***	-0.0146***	0.0011*	0.0021***	-0.0084***	0.0500***
	(-5.48)	(-16.12)	(2.05)	(4.12)	(-12.49)	(31.74)
Number of adults in household(-1), squared	-0.0043***	-0.0009*	0.0009***	0.0012***	0.0001	0.0034***
	(-7.86)	(-2.17)	(3.67)	(4.69)	(0.17)	(4.47)
Dummy for single adult household	-0.0453***	0.0042*	-0.0013	-0.0042***	0.0021	0.0201***
	(-21.69)	(2.53)	(-1.31)	(-4.40)	(1.72)	(7.04)
Dummy for retired head of household	0.0019	0.0002	-0.0048***	0.0004	-0.0047***	-0.0039
	(1.15)	(0.18)	(-6.25)	(0.50)	(-4.70)	(-1.68)
Dummy for unemployed head of household	-0.0063***	0.0011	-0.0033***	0.0005	0.0043***	-0.0023
	(-5.13)	(1.13)	(-5.85)	(0.96)	(5.99)	(-1.40)
Dummy for white collar head of household	-0.0081***	0.0098***	-0.0027***	-0.0018**	-0.0060***	0.0035
	(-5.30)	(8.13)	(-3.80)	(-2.65)	(-6.64)	(1.69)
Dummy for professional head of household	-0.0051**	0.0127***	-0.0020*	-0.0007	-0.0095***	-0.0064**
	(-2.84)	(8.98)	(-2.44)	(-0.82)	(-9.02)	(-2.60)
Dummy for head of household aged 34-49	0.0328***	-0.0167***	0.0026***	0.0024***	-0.0041***	-0.0188***
	(24.36)	(-15.80)	(4.31)	(3.93)	(-5.17)	(-10.21)
Dummy for head of household aged 49-65	0.0614***	-0.0319***	0.0054***	0.0042***	-0.0041***	-0.0271***
	(40.30)	(-26.60)	(7.79)	(6.06)	(-4.58)	(-13.02)
Dummy for head of household aged 65-80	0.0609***	-0.0363***	0.0069***	0.0054***	-0.0110***	-0.0196***
	(28.89)	(-21.92)	(7.23)	(5.68)	(-8.88)	(-6.79)
Dummy for head of household aged 80-99	0.0522***	-0.0357***	0.0125***	0.0048***	-0.0147***	-0.0126**
	(16.73)	(-14.55)	(8.83)	(3.39)	(-8.05)	(-2.95)
Dummy for central heating	-0.0073***	-0.0004	-0.0090***	0.0145***	-0.0035***	0.0060***
	(-5.46)	(-0.39)	(-14.85)	(24.01)	(-4.43)	(3.31)
Number of rooms in household	0.0004	-0.0014***	0.0011***	0.0030***	-0.0009***	-0.0031***
	(1.24)	(-5.14)	(7.01)	(19.33)	(-4.25)	(-6.49)
Dummy for rented accomodation	-0.0004	0.0045***	-0.0012*	-0.0050***	0.0034***	0.0003
	(-0.38)	(5.04)	(-2.31)	(-9.79)	(5.16)	(0.21)
Dummy for car ownerships	-0.0457***	-0.0125***	-0.0144***	-0.0088***	0.0675***	0.0401***
	(-29.27)	(-10.13)	(-20.25)	(-12.50)	(73.61)	(18.76)
Number of cars in household	-0.0028**	-0.0036***	0.0040***	0.0000	0.0137***	0.0066***
	(-3.12)	(-5.12)	(9.79)	(0.03)	(26.23)	(5.43)
Minimum temperature in sample month	0.0003	-0.0013**	0.0001	-0.0003	-0.0002	0.0016*
	(0.54)	(-3.09)	(0.42)	(-1.35)	(-0.62)	(2.26)
Max temperature in sample month	-0.0005	0.0017***	0.0002	0.0003	0.0002	-0.0018**
	(-1.08)	(5.14)	(0.92)	(1.60)	(0.81)	(-3.05)
Year dummy 1987	-0.0026	0.0035	0.0006	-0.0003	-0.0021	-0.0112**
	(-0.85)	(1.39)	(0.45)	(-0.24)	(-1.22)	(-2.70)
Year dummy 1988	-0.0111***	0.0090**	0.0011	-0.0016	-0.0011	-0.0041
	(-3.37)	(2.90)	(0.69)	(-1.01)	(-0.56)	(-0.90)
Year dummy 1989	-0.0075*	0.0104***	0.0009	-0.0056***	-0.0021	-0.0044
	(-2.25)	(3.31)	(0.54)	(-3.48)	(-1.07)	(-0.95)
Year dummy 1990	-0.0106**	0.0117***	-0.0017	-0.0086***	-0.0033	-0.0025
	(-3.12)	(3.53)	(-0.97)	(-5.18)	(-1.70)	(-0.53)
Year dummy 1991	-0.0209***	0.0112**	0.0054*	-0.0026	-0.0056**	-0.0077
	(-5.27)	(2.67)	(2.57)	(-1.33)	(-2.62)	(-1.38)
Year dummy 1992	-0.0303***	0.0141**	0.0068*	-0.0022	-0.0032	-0.0149*
	(-6.22)	(2.70)	(2.57)	(-0.94)	(-1.31)	(-2.30)
Year dummy 1993	-0.0256***	0.0198***	0.0091**	-0.0046	-0.0026	-0.0137
	(-4.68)	(3.36)	(3.13)	(-1.77)	(-0.99)	(-1.91)
Year dummy 1994	-0.0299***	0.0223***	0.0037	-0.0043	-0.0026	-0.0096
	(-5.12)	(3.42)	(1.22)	(-1.60)	(-0.97)	(-1.28)
Year dummy 1995	-0.0349***	0.0273***	0.0017	-0.0081**	-0.0020	-0.0064
	(-6.14)	(4.00)	(0.54)	(-3.01)	(-0.74)	(-0.84)
Year dummy 1996	-0.0340***	0.0322***	0.0028	-0.0070*	-0.0014	-0.0029
	(-5.50)	(4.09)	(0.82)	(-2.37)	(-0.47)	(-0.34)
Year dummy 1997	-0.0395***	0.0358***	0.0002	-0.0064	-0.0048	0.0000
	(-5.60)	(3.97)	(0.04)	(-1.94)	(-1.51)	(0.00)
Year dummy 1998	-0.0371***	0.0385***	-0.0048	-0.0106**	-0.0021	-0.0004
	(-4.89)	(3.97)	(-1.15)	(-2.96)	(-0.60)	(-0.04)
Year dummy 1999	-0.0343***	0.0431***	-0.0054	-0.0139***	-0.0011	-0.0011
	(-4.16)	(4.14)	(-1.19)	(-3.62)	(-0.30)	(-0.10)
Year dummy 2000	-0.0388***	0.0468***	-0.0056	-0.0139**	-0.0001	-0.0004
	(-4.19)	(4.14)	(-1.09)	(-3.25)	(-0.03)	(-0.03)
Year dummy 2001	-0.0463***	0.0467***	-0.0065	-0.0145**	-0.0086*	0.0037
	(-4.93)	(3.94)	(-1.21)	(-3.24)	(-2.01)	(0.29)
Year dummy 2002	-0.0449***	0.0453***	-0.0074	-0.0136**	-0.0105*	0.0047

	(-4.40)	(3.48)	(-1.24)	(-2.79)	(-2.31)	(0.35)
Year dummy 2003	-0.0460***	0.0444***	-0.0076	-0.0141**	-0.0101*	0.0081
	(-4.31)	(3.31)	(-1.24)	(-2.79)	(-2.12)	(0.57)
Year dummy 2004	-0.0491***	0.0456***	-0.0061	-0.0140**	-0.0113*	0.0047
	(-4.55)	(3.40)	(-1.00)	(-2.79)	(-2.40)	(0.34)
Year dummy 2005	-0.0535***	0.0495***	-0.0054	-0.0126*	-0.0139**	0.0127
	(-4.75)	(3.62)	(-0.86)	(-2.44)	(-2.89)	(0.89)
Year dummy 2006	-0.0634***	0.0479***	-0.0044	-0.0111*	-0.0144**	0.0088
	(-5.33)	(3.52)	(-0.69)	(-2.09)	(-2.97)	(0.61)
Year dummy 2007	-0.0619***	0.0428**	-0.0012	-0.0094	-0.0167***	0.0091
	(-5.35)	(3.28)	(-0.20)	(-1.83)	(-3.55)	(0.65)
Year dummy 2008	-0.0694***	0.0466***	-0.0034	-0.0117*	-0.0170***	0.0144
	(-6.31)	(3.85)	(-0.59)	(-2.36)	(-3.61)	(1.05)
Year dummy 2009	-0.0671***	0.0422***	0.0007	-0.0078	-0.0191***	0.0088
	(-6.18)	(3.50)	(0.12)	(-1.51)	(-4.19)	(0.64)
Season dummy 1	0.0108***	-0.0054**	0.0059***	0.0097***	0.0027**	-0.0115***
	(6.23)	(-3.17)	(6.73)	(12.01)	(2.69)	(-4.70)
Season dummy 2	0.0061**	-0.0081***	0.0048***	0.0111***	0.0013	-0.0055*
	(3.22)	(-5.10)	(5.47)	(13.02)	(1.17)	(-2.12)
Season dummy 3	0.0021	-0.0051**	-0.0002	0.0041***	-0.0001	-0.0017
	(0.95)	(-2.94)	(-0.24)	(4.24)	(-0.04)	(-0.57)
Child dummy*log expenditure	0.0124***	0.0027	-0.0013	0.0006	0.0013	0.0137***
	(5.49)	(1.49)	(-1.23)	(0.59)	(0.99)	(4.42)
Log price of food (non VAT)	0.0219	0.0314	0.0248*	0.0114	-0.0158	-0.0924**
	(0.82)	(1.19)	(1.97)	(1.09)	(-1.74)	(-3.20)
Log price of food (VAT)	0.0314	-0.0371	-0.0063	0.0030	-0.0184*	0.0675
	(1.19)	(-0.76)	(-0.34)	(0.21)	(-2.03)	(1.77)
Log price of electricity	0.0248*	-0.0063	-0.0084	0.0103	0.0070	0.0028
	(1.97)	(-0.34)	(-0.62)	(1.11)	(1.41)	(0.15)
Log price of natural gas	0.0114	0.0030	0.0103	0.0046	0.0093*	-0.0248
	(1.09)	(0.21)	(1.11)	(0.56)	(2.11)	(-1.67)
Log price of gasoline	-0.0158	-0.0184*	0.0070	0.0093*	0.0343***	-0.0496***
	(-1.74)	(-2.03)	(1.41)	(2.11)	(4.98)	(-3.73)
Log price of consumer goods	-0.0924**	0.0675	0.0028	-0.0248	-0.0496***	0.1853**
	(-3.20)	(1.77)	(0.15)	(-1.67)	(-3.73)	(3.23)
Constant	0.1672***	0.1099***	0.0403***	0.0019	-0.0160***	0.3570***
	(25.42)	(15.89)	(11.97)	(0.61)	(-4.93)	(41.77)
Observations	49109					

t statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 18
ILLE regression results

	Food (non VAT)	Food (VAT)	Electricity	Natural gas	Gasoline	Consumer goods
Log expenditure	-0.0838***	-0.0184***	-0.0107***	-0.0147***	-0.0471***	-0.0357***
	(-14.69)	(-4.20)	(-4.17)	(-6.10)	(-15.02)	(-4.78)
Log expenditure squared	0.0245***	-0.0206***	0.0154***	0.0041*	-0.0119***	-0.0339***
	(6.48)	(-7.09)	(9.03)	(2.58)	(-5.71)	(-6.81)
Child dummy aged 0-2	0.0014	-0.0127***	-0.0041**	0.0002	-0.0011	0.0538***
	(0.49)	(-5.96)	(-3.23)	(0.19)	(-0.69)	(14.67)
Child dummy aged 2-5	-0.0076***	-0.0105***	0.0015	0.0037***	-0.0011	0.0051
	(-3.31)	(-5.99)	(1.45)	(3.82)	(-0.89)	(1.69)
Number of children in household	0.0249***	0.0091***	0.0026***	0.0016*	-0.0012	-0.0227***
	(16.54)	(7.86)	(3.78)	(2.57)	(-1.45)	(-11.51)
Number of children squared in household	-0.0003	-0.0013***	-0.0000	-0.0003*	0.0004	0.0021***
	(-0.87)	(-4.42)	(-0.28)	(-2.03)	(1.86)	(4.28)
Number of adults in household(-1)	0.0460***	0.0175***	-0.0008	-0.0056***	0.0092***	-0.0414***
	(18.57)	(9.25)	(-0.75)	(-5.35)	(6.72)	(-12.72)
Number of adult earners in household(-1)	-0.0063***	0.0071***	-0.0020***	-0.0012**	0.0015**	0.0043***
	(-6.61)	(9.78)	(-4.77)	(-2.92)	(2.77)	(3.46)
Number of adult females in household	-0.0011	-0.0186***	0.0026***	0.0023***	-0.0083***	0.0496***
	(-0.82)	(-18.21)	(4.31)	(4.08)	(-11.24)	(28.32)
Number of adults in household(-1), squared	-0.0059***	0.0003	0.0004	0.0011***	-0.0001	0.0037***
	(-9.66)	(0.57)	(1.38)	(4.19)	(-0.25)	(4.62)
Dummy for single adult household	-0.0635***	0.0167***	-0.0066***	-0.0049***	0.0033*	0.0237***
	(-21.94)	(7.53)	(-5.08)	(-4.01)	(2.05)	(6.24)
Dummy for retired head of household	0.0042*	-0.0019	-0.0043***	0.0003	-0.0039***	-0.0029
	(2.29)	(-1.39)	(-5.19)	(0.41)	(-3.89)	(-1.23)
Dummy for unemployed head of household	-0.0011	-0.0029**	-0.0017**	0.0007	0.0046***	-0.0027
	(-0.79)	(-2.72)	(-2.76)	(1.13)	(6.01)	(-1.46)
Dummy for white collar head of household	-0.0059***	0.0072***	-0.0024**	-0.0021**	-0.0048***	0.0059**
	(-3.55)	(5.67)	(-3.18)	(-2.94)	(-5.23)	(2.69)
Dummy for professional head of household	-0.0065**	0.0101***	-0.0043***	-0.0021*	-0.0059***	0.0053
	(-3.13)	(6.36)	(-4.64)	(-2.42)	(-5.11)	(1.94)
Dummy for head of household aged 34-49	0.0317***	-0.0163***	0.0024***	0.0023***	-0.0035***	-0.0183***
	(21.67)	(-14.57)	(3.64)	(3.76)	(-4.34)	(-9.52)
Dummy for head of household aged 49-65	0.0589***	-0.0302***	0.0048***	0.0041***	-0.0038***	-0.0271***
	(35.47)	(-23.75)	(6.47)	(5.89)	(-4.19)	(-12.43)
Dummy for head of household aged 65-80	0.0560***	-0.0324***	0.0060***	0.0055***	-0.0111***	-0.0211***
	(24.14)	(-18.26)	(5.77)	(5.63)	(-8.69)	(-6.94)
Dummy for head of household aged 80-99	0.0404***	-0.0273***	0.0092***	0.0044**	-0.0144***	-0.0114*
	(11.39)	(-10.05)	(5.80)	(2.95)	(-7.37)	(-2.44)
Dummy for central heating	-0.0032*	-0.0043***	-0.0083***	0.0143***	-0.0025**	0.0083***
	(-2.16)	(-3.78)	(-12.44)	(22.77)	(-3.02)	(4.28)
Number of rooms in household	0.0013***	-0.0029***	0.0010***	0.0028***	-0.0001	-0.0007
	(3.31)	(-9.27)	(5.28)	(16.22)	(-0.31)	(-1.31)
Dummy for rented accomodation	-0.0030*	0.0067***	-0.0018**	-0.0050***	0.0031***	-0.0004
	(-2.38)	(7.02)	(-3.13)	(-9.47)	(4.56)	(-0.26)
Dummy for car ownerships	-0.0201***	-0.0292***	-0.0053***	-0.0069***	0.0661***	0.0288***
	(-6.48)	(-12.28)	(-3.79)	(-5.28)	(38.71)	(7.07)
Number of cars in household	-0.0074***	-0.0033***	0.0009	-0.0014**	0.0166***	0.0173***
	(-5.82)	(-3.35)	(1.50)	(-2.60)	(23.71)	(10.36)
Minimum temperature in sample month	0.0004	-0.0012**	0.0002	-0.0003	-0.0003	0.0013
	(0.79)	(-2.87)	(0.81)	(-1.22)	(-0.83)	(1.71)
Max temperature in sample month	-0.0004	0.0017***	0.0001	0.0003	0.0003	-0.0015*
	(-0.87)	(4.71)	(0.57)	(1.49)	(1.19)	(-2.53)
Year dummy 1987	-0.0037	0.0051	0.0007	-0.0005	-0.0027	-0.0121**
	(-1.13)	(1.90)	(0.47)	(-0.37)	(-1.50)	(-2.82)
Year dummy 1988	-0.0120***	0.0110***	0.0007	-0.0020	-0.0008	-0.0029
	(-3.37)	(3.33)	(0.42)	(-1.27)	(-0.43)	(-0.60)
Year dummy 1989	-0.0074*	0.0117***	0.0006	-0.0059***	-0.0016	-0.0029
	(-2.05)	(3.48)	(0.33)	(-3.64)	(-0.84)	(-0.60)
Year dummy 1990	-0.0099**	0.0127***	-0.0020	-0.0090***	-0.0025	-0.0010
	(-2.71)	(3.60)	(-1.10)	(-5.33)	(-1.28)	(-0.21)
Year dummy 1991	-0.0206***	0.0134**	0.0046*	-0.0033	-0.0044*	-0.0048
	(-4.84)	(2.97)	(2.06)	(-1.68)	(-2.04)	(-0.83)
Year dummy 1992	-0.0288***	0.0159**	0.0060*	-0.0031	-0.0018	-0.0109
	(-5.50)	(2.82)	(2.19)	(-1.33)	(-0.73)	(-1.61)
Year dummy 1993	-0.0239***	0.0213***	0.0086**	-0.0058*	-0.0014	-0.0099
	(-4.01)	(3.33)	(2.81)	(-2.18)	(-0.52)	(-1.31)
Year dummy 1994	-0.0282***	0.0240***	0.0033	-0.0059*	-0.0012	-0.0052
	(-4.41)	(3.39)	(1.02)	(-2.16)	(-0.42)	(-0.65)
Year dummy 1995	-0.0332***	0.0299***	0.0015	-0.0098***	-0.0008	-0.0035
	(-5.35)	(4.01)	(0.45)	(-3.56)	(-0.29)	(-0.44)
Year dummy 1996	-0.0319***	0.0351***	0.0027	-0.0092**	0.0003	0.0001
	(-4.71)	(4.07)	(0.74)	(-3.01)	(0.10)	(0.01)
Year dummy 1997	-0.0371***	0.0377***	0.0006	-0.0096**	-0.0033	0.0037
	(-4.73)	(3.79)	(0.14)	(-2.77)	(-0.98)	(0.36)
Year dummy 1998	-0.0358***	0.0407***	-0.0045	-0.0143***	-0.0006	0.0039
	(-4.20)	(3.79)	(-0.97)	(-3.80)	(-0.17)	(0.36)
Year dummy 1999	-0.0328***	0.0447***	-0.0047	-0.0182***	0.0001	0.0031
	(-3.51)	(3.86)	(-0.93)	(-4.44)	(0.02)	(0.26)
Year dummy 2000	-0.0372***	0.0475***	-0.0046	-0.0188***	0.0010	0.0039
	(-3.53)	(3.78)	(-0.82)	(-4.11)	(0.21)	(0.30)
Year dummy 2001	-0.0436***	0.0470***	-0.0056	-0.0197***	-0.0065	0.0102
	(-4.11)	(3.57)	(-0.95)	(-4.16)	(-1.44)	(0.75)
Year dummy 2002	-0.0419***	0.0457**	-0.0066	-0.0195***	-0.0075	0.0139

	(-3.66)	(3.16)	(-1.01)	(-3.79)	(-1.58)	(0.95)
Year dummy 2003	-0.0427***	0.0446**	-0.0066	-0.0202***	-0.0074	0.0169
	(-3.55)	(2.99)	(-0.97)	(-3.76)	(-1.48)	(1.11)
Year dummy 2004	-0.0456***	0.0453**	-0.0050	-0.0203***	-0.0086	0.0140
	(-3.74)	(3.04)	(-0.74)	(-3.78)	(-1.73)	(0.93)
Year dummy 2005	-0.0514***	0.0490**	-0.0053	-0.0196***	-0.0099	0.0267
	(-4.05)	(3.23)	(-0.78)	(-3.55)	(-1.96)	(1.73)
Year dummy 2006	-0.0574***	0.0452**	-0.0025	-0.0176**	-0.0111*	0.0203
	(-4.30)	(2.98)	(-0.36)	(-3.09)	(-2.19)	(1.31)
Year dummy 2007	-0.0561***	0.0402**	0.0006	-0.0155**	-0.0135**	0.0204
	(-4.33)	(2.77)	(0.09)	(-2.83)	(-2.73)	(1.36)
Year dummy 2008	-0.0643***	0.0449***	-0.0017	-0.0171**	-0.0144**	0.0224
	(-5.28)	(3.35)	(-0.27)	(-3.23)	(-2.95)	(1.53)
Year dummy 2009	-0.0605***	0.0398**	0.0028	-0.0131*	-0.0160***	0.0178
	(-5.06)	(2.98)	(0.45)	(-2.41)	(-3.44)	(1.22)
Season dummy 1	0.0108***	-0.0048**	0.0063***	0.0105***	0.0016	-0.0149***
	(5.76)	(-2.62)	(6.88)	(12.77)	(1.58)	(-5.84)
Season dummy 2	0.0071***	-0.0086***	0.0051***	0.0115***	0.0011	-0.0069**
	(3.51)	(-5.15)	(5.53)	(13.41)	(1.04)	(-2.60)
Season dummy 3	0.0021	-0.0050**	-0.0003	0.0042***	-0.0000	-0.0018
	(0.89)	(-2.80)	(-0.33)	(4.29)	(-0.01)	(-0.60)
Child dummy*log expenditure	0.0047	0.0045	-0.0102***	-0.0032	0.0001	0.0408***
	(1.15)	(1.47)	(-5.61)	(-1.85)	(0.05)	(7.68)
Log price of food (non VAT)	0.0230	0.0321	0.0280*	0.0011	-0.0155	-0.0718*
	(0.76)	(1.10)	(2.08)	(0.10)	(-1.57)	(-2.23)
Log price of food (VAT)	0.0321	-0.0791	-0.0162	0.0148	-0.0123	0.0911*
	(1.10)	(-1.46)	(-0.80)	(0.98)	(-1.24)	(2.17)
Log price of electricity	0.0280*	-0.0162	-0.0006	0.0029	0.0048	0.0025
	(2.08)	(-0.80)	(-0.04)	(0.30)	(0.93)	(0.13)
Log price of natural gas	0.0011	0.0148	0.0029	0.0092	0.0095*	-0.0282
	(0.10)	(0.98)	(0.30)	(1.08)	(2.08)	(-1.80)
Log price of gasoline	-0.0155	-0.0123	0.0048	0.0095*	0.0377***	-0.0380**
	(-1.57)	(-1.24)	(0.93)	(2.08)	(5.37)	(-2.68)
Log price of consumer goods	-0.0718*	0.0911*	0.0025	-0.0282	-0.0380**	0.1711**
	(-2.23)	(2.17)	(0.13)	(-1.80)	(-2.68)	(2.73)
Constant	0.1267***	0.1614***	0.0387***	0.0055	-0.0361***	0.3042***
	(15.07)	(19.38)	(9.41)	(1.49)	(-8.69)	(28.19)
Observations	49109					

t statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

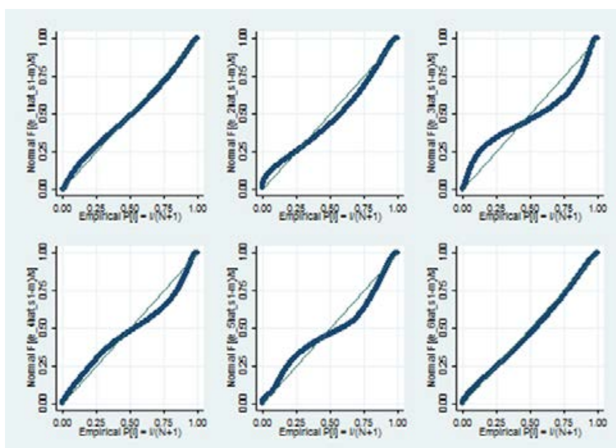
Figure 12
Analysis of predicted errors

This figure analyses the predicted errors under the ILLE: a) summarizes the mean, standard deviation (together with minimum and maximum values) of the predicted errors, which clearly indicate their heterogeneous nature (common in cross sectional data). b) and c) respectively show histograms and standardized normal probability plots for each commodity equation, together with a continuous mapping of the probability densities of the respective distributions. These indicate non-normality in the predicted error distributions, particularly for the energy commodities.

(a) Summary statistics

	Food (non VAT)	Food (VAT)	Electricity	Natural gas	Gasoline	Consumer goods	Leisiure goods
mean	0.00	-0.00	0.00	0.00	-0.00	-0.00	-0.00
standard deviation	0.10	0.08	0.04	0.04	0.06	0.13	0.15
min	-0.77	-0.19	-0.42	-0.18	-0.17	-0.39	-0.85
max	0.75	0.81	0.75	0.72	0.75	0.88	0.82

(b) Estimated residuals: p-normal comparisons



(c) Estimated residuals: histograms

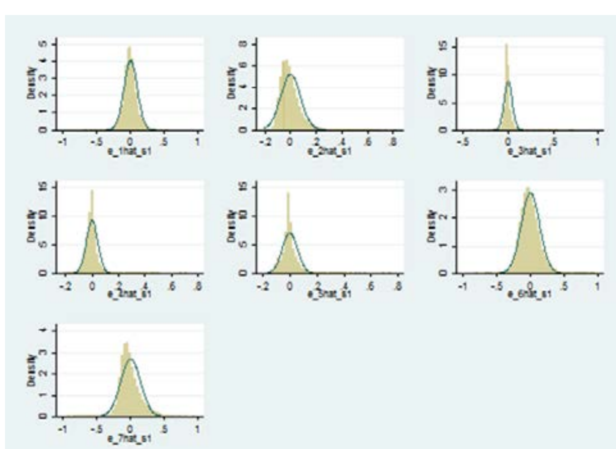


Table 19
Distribution of price elasticities

This table shows the weighted (by expenditure group within decile) own price elasticities by decile. Gas, petrol and leisure goods, for example, appear to become less price elastic among higher spending households. Coefficients on cross price effects are significant for all equations at the 10 per cent level, underlining the value of their inclusion in the analysis.*

	Food (Non VAT)			Food(VAT)			Electricity			Gas			Petrol			Consumer			Leisure		
$e_{ij}^{c(.)}$	75	50	25	75	50	25	75	50	25	75	50	25	75	50	25	75	50	25	75	50	25
Food(non VAT)	-1.07	-1.23	-1.44	1.13	0.81	0.61	0.27	0.19	0.15	-0.09	-0.14	-0.23	-0.09	-0.15	-0.25	0.06	-0.05	-0.26	-0.15	-0.33	-0.78
Food(VAT)	1.02	0.60	0.36	-1.39	-1.77	-2.47	-0.06	-0.12	-0.22	0.37	0.20	0.12	0.00	-0.06	-0.14	1.90	1.26	0.88	-0.34	-0.67	-1.44
Electricity	0.51	0.15	-0.03	0.54	0.34	0.13	-0.98	-0.99	-1.01	-0.05	-0.11	-0.20	0.10	0.02	-0.01	0.50	0.45	0.41	-0.41	-0.77	-1.56
Gas	-0.09	-0.25	-0.43	1.33	0.92	0.62	0.15	0.11	0.09	-0.79	-0.87	-0.90	0.33	0.22	0.14	-0.11	-0.39	-0.84	-0.38	-0.72	-1.47
Gasoline	-0.14	-0.34	-0.73	0.43	0.28	0.17	0.12	0.09	0.07	0.06	0.02	-0.01	-0.37	-0.56	-0.64	0.05	-0.11	-0.36	-0.27	-0.51	-1.02
Consumer	0.17	0.03	-0.10	0.46	0.33	0.23	0.07	0.04	0.03	0.00	-0.04	-0.07	0.00	-0.06	-0.12	-0.04	-0.14	-0.17	-0.35	-0.78	-1.77
Leisure	-0.15	-0.33	-0.78	-0.34	-0.67	-1.44	-0.41	-0.77	-1.56	-0.38	-0.72	-1.47	-0.27	-0.51	-1.02	-0.35	-0.78	-1.77	-0.93	-1.46	-2.29

(a) Compensated

	Food (Non VAT)			Food(VAT)			Electricity			Gas			Petrol			Consum.er			Leisure		
$e_{ij}^{u(.)}$	75	50	25	75	50	25	75	50	25	75	50	25	75	50	25	75	50	25	75	50	25
Food(non VAT)	-1.21	-1.29	-1.45	1.13	0.77	0.55	0.27	0.17	0.12	-0.11	-0.15	-0.23	-0.12	-0.17	-0.25	-0.07	-0.15	-0.30	-0.40	-0.72	-1.41
Food(VAT)	0.69	0.37	0.21	-1.55	-1.88	-2.57	-0.11	-0.17	-0.28	0.31	0.17	0.10	-0.07	-0.11	-0.20	1.43	0.87	0.55	-0.50	-0.93	-1.80
Electricity	0.49	0.12	-0.06	0.55	0.32	0.10	-0.99	-1.00	-1.01	-0.07	-0.12	-0.19	0.08	0.02	-0.01	0.56	0.40	0.27	-0.47	-0.87	-1.69
Gas	-0.22	-0.33	-0.47	1.29	0.86	0.55	0.14	0.09	0.05	-0.80	-0.90	-0.95	0.31	0.18	0.10	-0.29	-0.53	-0.91	-0.43	-0.80	-1.55
Gasoline	-0.27	-0.45	-0.78	0.39	0.19	0.08	0.10	0.06	0.04	0.03	0.01	-0.01	-0.39	-0.61	-0.75	-0.19	-0.29	-0.46	-0.36	-0.65	-1.28
Consumer	-0.10	-0.16	-0.24	0.30	0.20	0.11	0.01	0.00	0.00	-0.04	-0.06	-0.09	-0.09	-0.11	-0.15	-0.32	-0.50	-0.62	-0.81	-1.52	-2.95
Leisure	-0.40	-0.72	-1.41	-0.50	-0.93	-1.80	-0.47	-0.87	-1.69	-0.43	-0.80	-1.55	-0.36	-0.65	-1.28	-0.81	-1.52	-2.95	-1.43	-1.80	-2.55

(b) Uncompensated

* However, one should not set too much store by such estimates, given the complexity of the economic relationships between commodity groups within the demand system. Nevertheless, the moderate degree of substitutability between gas and electricity, for example, which although not statistically significant, seems to accord with reasoned priors.

Policy and tax reform scenario

This section provides background on the carbon tax and VAT indirect reforms analysed above (drawing on Jones (2012)). Table 22 summarizes the overall change in price in each scenario. Key methodological issues and assumptions are set out below.

These tax changes are modelled as proportionate increases in the prices of the aggregate commodity bundles which, given by:[141]

$$p_i^1 = p_i^0 \frac{(1+t_i^1)}{(1+t_i^0)} \tag{D.1}$$

where p_i^0, p_i^1 and t_i^0, t_i^1 are pre and post reform levels of prices and ad valorem taxes on good i respectively.

Specific duties and ad valorem tax rates

Goods such as petrol, and prospective charges on carbon, are subject to specific duties (these components also being subject to VAT).[142] It is therefore desirable to calculate the effective burden of the combined taxes on good i as a proportion of price. One approach is to estimate the specific duty as a proportion of market prices, and subsequently apply it to the available price data. In the baseline scenario, the effective ad valorem rate is given by:

$$1 + Z_i^0 = \frac{p_i^0}{p_i^N} \tag{D.2}$$

[141] This assumes that taxes are fully passed onto consumers (reasonable for a unilateral rate rise in the UK but a more debatable assumption in the context of a broad international coalition).

[142] Differentiated commodity taxes were initially justified on redistributive grounds. However, modern tax theory generally suggests that such objectives should be pursued through adjustments to the income tax schedule or benefits transfer system (see, for example, Atkinson and Stiglitz (1976), Deaton and Stern (1986)). More recently, studies emphasize the significance of administration costs from non-uniform systems (Cnossen (2003)).

Table 20
Distribution of budget elasticities by expenditure decile

This table shows the weighted (by expenditure group within decile) expenditure elasticities by decile. Commodities such as food (VAT), gasoline as well as consumer and leisure goods are more of a luxury at lower levels of household expenditure. Among the fuels, budget elasticities fall with average outlays, particularly for petrol (and to a lesser extent gas).

Decile	Food (non VAT)	Food (VAT)	Electricity	Gas	Petrol	Consumer	Leisure
1	0.40	1.54	0.44	0.76	1.00	1.43	1.78
2	0.41	1.39	0.21	0.69	0.94	1.24	1.94
3	0.42	1.29	0.19	0.65	0.87	1.18	2.08
4	0.36	1.22	0.09	0.56	0.81	1.13	1.93
5	0.35	1.15	0.14	0.52	0.76	1.10	1.86
6	0.41	1.09	0.09	0.50	0.68	1.07	1.94
7	0.33	1.02	0.21	0.46	0.64	1.04	1.82
8	0.38	0.95	0.26	0.37	0.57	1.00	1.76
9	0.31	0.88	0.31	0.31	0.45	0.96	1.66
10	0.33	0.66	0.81	0.33	0.14	0.87	1.58

Table 21
Comparing welfare losses: behavioural vs non behavioural analysis

This table compares the percentage difference in aggregate welfare losses under each policy scenario and SWF computed using non behavioural analysis, with the results shown in Table 9. These findings are materially different – being commonly higher by on the order of 4-18 percent higher (although, as pointed out by Banks et al. (1996), the sign of such a difference need not be universally positive).

v	1	2	3
Carbon Tax £25tCO2	3.9	4.7	5.5
Carbon Tax £50tCO	8.2	10.0	12.1
Carbon Tax £25tCO2+VAT	11.9	12.4	13.3
Carbon Tax £50tCO2+VAT	15.3	16.6	18.5
VAT	10.0	10.1	10.5

(a) Unweighted: SWF_a

v	1	2	3
Carbon Tax £25tCO2	3.7	4.4	5.2
Carbon Tax £50tCO	7.7	9.3	11.5
Carbon Tax £25tCO2+VAT	11.6	12.3	13.3
Carbon Tax £50tCO2+VAT	14.7	16.2	18.2
VAT	9.8	10.1	10.6

(b) Weighted by household size: SWF_b

Table 22
Ad valorem tax rates by policy scenario

This table summarizes the effective (in 2008) ad valorem tax rates implied under by each simulated tax reform scenario: a £25 tCO2 carbon tax (implemented without VAT reform), for example, induces a tax rate of 19.7 percent on natural gas. Since gasoline is already subject to the standard rate of VAT, only carbon taxes have a bearing on its price in the simulations.

Commodity	Baseline Tax	Tax reform scenario				
		Carbon Tax £25tCO2	Carbon Tax £25tCO2+VAT	Carbon Tax £50tCO2	Carbon Tax £50tCO2+VAT	VAT only
Food, non VAT	0	0	0.175	0	0.175	0.175
Food, VAT	0.175	0.175	0.175	0.175	0.175	0.175
Electricity	0.05	0.05	0.05	0.05	0.175	0.175
Gas	0.05	0.197	0.348	0.344	0.52	0.175
Consumer	0.175	0.175	0.175	0.175	0.175	0.175
Gasoline	1.62	1.81	1.81	2.01	2.01	1.62
Leisure goods	0.175	0.175	0.175	0.175	0.175	0.175

where p_i^N represents the price of good i exclusive of taxation. This can be viewed as the underlying (private) resource cost, given by;

$$p_i^N = \frac{p_i^0}{1 + Z_i^{0,VAT}} - Z_i^s \tag{D.3}$$

where Z_i^s represents the specific duty charge and $Z_i^{0,VAT}$ is the pre reform rate of VAT on good i.

Substituting equation (D.3) into (D.2) and simplifying, yields the following expression for the effective ad valorem tax rate in terms or observed tax and price variables:[143]

$$t_i^0 = \frac{p_i^0 Z_i^{0,VAT} - Z_i^s(1 + v_i^0)}{p_i^0 - Z_i^s(1 + v_i^0)} \tag{D.4}$$

It follows trivially that for goods not subject specific duties, this equation reduces to v_i^0 (the baseline VAT rate).

Carbon charges are imposed as a simple extension of this framework where $Z_i^T = Z_i^s + Z_i^c$, where the carbon element of the duty is given by:

$$Z_i^T = C^i * SC^i \tag{D.5}$$

where C^i represents the (or emission factor), and SC^i represents the charge on each unit of emissions.

Calibrating tax rates:

This subsection discusses the assumptions underpinning the simulated ad valorem tax

[143] Specific and ad valorem charges can be equivalent under perfect competition, but diverge under a number of product and market settings. In the case of pure monopoly, for example, an ad valorem (as opposed to specific) charge will cause the profit maximising supplier to expand output, with consequential downward pressures on price (see Keen (1998) for a helpful discussion of these and other issues).

rates, including energy prices, emissions factors, and the choice of levy on carbon.

Values for C^i and P

Data on energy prices in the household sector for 2007, the year for which tax reforms are simulated, are taken from the DECC website. Emissions factors are drawn from government guidelines, which quantify the emissions from a particular fuel type. The methodologies for their calculation are an emerging policy area (see DECC (2011) for a detailed discussion).

A broad definition of the carbon tax base is adopted. Emissions (weighted relative to the global warming potential of CO2) for all GHGs are included in the calculation. Moreover, both direct emissions from the combustion of fossil fuels, as well as those arising indirectly, for example, from upstream processing and transportation, are included in the emissions factor.

In the case of electricity generation, C reflects a weighted average of emissions from the various generation technologies which power the national grid (and includes inefficiencies arising from transmission and distribution). In the case of GHG emissions from road transport fuels, emissions factors adjust for biodiesel and bioethanol in the fuel blend (3.3 and 1.9 percent respectively by unit energy).

Petrol and diesel are not separately recorded in the household expenditure data, and thus a further weighting of the two coefficients is applied (reflecting the roughly 55-45 split in expenditure on diesel and petrol respectively). Table 23 summarizes all relevant coefficients.

A value for SC

Choosing an appropriate carbon tax rate is a complex issue (see Jones et al. (2013) for a detailed discussion), requiring long term predictions on economic development and thus emissions, a postulated relationship between stocks of GHGs and economic damages, and an appropriate choice of discount rate. Not surprisingly then, those studies which have attempted to estimate the social cost of carbon vary widely in terms of results.

In a review of the marginal social damage from carbon emissions, Tol (2007), for example, finds a modal value of around US$6 tCO2, and a median of US$15 tCO2. The US Government (IWG (2013)) arrives at a central value - averaged over a range of IAMs at a discount rate of 3 percent - of around US $35 tCO2. The Stern Review (2007) estimate, towards the upper end of the distribution, is US$85 tCO2; Nordhaus (2007), on the other hand, suggests a starting carbon price of around US$5 tC02.[144]

In practice, however, a more limited notion of optimality (in the sense that it does not maximize welfare) – which involves taking the overall policy objectives on GHGs as given, and then choosing a tax rate which achieves this at minimum discounted cost (as advocated, for example, by Baumol-Oates (1988) – has formed the basis for most policy in this area (in part reflecting the uncertainties involved in full cost-benefit analysis in this context).

The UK government, for example, has formally shifted away from policy appraisal based on estimated social costs of carbon, towards a framework based on evaluating the costs of mitigation (DECC (2009)). Specifically, the government estimates that a carbon tax of £50 tCO2 (within a range of £25-£75 tCO2) in 2008, and rising over time, is likely to be necessary to achieve its objective of reducing emissions in the household sector (DECC (2009)). Reflecting this fact, the government's mean and lower bound switching rates form are adopted for carbon tax scenario in the present work.[145]

[144] For comparison, the EU Emissions Trading Scheme spot price in October 2015 was around £6 tCO2.

[145] Note that these figures are, in general, somewhat higher than those prescribed by the welfare maximizing studies outlined above.

Table 23
Market prices, emissions factors by fuel

This table summarizes the prices, measurement units and assumed CO2 equivalent content of each fuel.

Fuel	P (pence), 2008	Unit	CO2e per unit
Electricity	12	KwH	0.53
Gasoline	107	Litre	2.66
Diesel	117	Litre	3.11
Natural Gas	4	KwH	0.02