Sustainability and the Global Biogeochemical Cycles: Integrated modelling of coupled economic and environmental systems

A thesis presented in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

In

Ecological Economics

at

Massey University, Manawatu, New Zealand

Nicola Jane Smith

2014

Abstract

The global biogeochemical cycles (GBCs), which include cycles of C, N, P, S, Cl, I, and H_2O, are extremely important biosphere functions, critical to the maintenance of conditions necessary for all life. Importantly, perturbation of these GBCs has the potential to affect the structure and functioning of the Earth system as a whole. While biogeochemistry research to date has largely focused on 'natural' processes, human economic activities are increasingly recognised as integral components of the GBCs. This thesis draws on both static and dynamic-system modelling approaches to describe the coupled economic and GBC systems, and to develop tools to assist in learning about these systems, with the aim of progressing towards sustainability. First, by drawing on the theoretical frameworks of Input-Output Analysis and Material Flow Analysis, an extensive and coherent static system model of the global C, N, P and S cycles is presented. Data within that static model are then used to calculate a set of sustainability indicators, based on a new and novel concept of 'ecotime'. Essentially, these indicators describe the level at which the global economy, through its transformation of useful resources (i.e. raw materials) into residuals (i.e. wastes, pollutants, emission), appropriates biogeochemical processes. Changes in these and other indicators, under possible future scenarios, are also able to be investigated by a new dynamic model known as 'Ecocycle'. Ecocycle constitutes one of very few attempts to develop an integrated model of the Earth system, explicitly capturing relationships between the GBCs and human activities. A notable feature of Ecocycle is that it represents the general equilibrium-seeking behaviour of an economy within a System Dynamics modelling approach, rather than through an optimisation approach as typically employed. A further significant methodological contribution of the thesis is the development of a technique for translating IO-based accounts between alternative process-by-commodity, commodity-by-commodity, and process-by-process frameworks. This method is required for both the static and dynamic components of the thesis.

Acknowledgements

I am very grateful for the receipt of a Bright Futures Scholarship (Contract MAUX06024). Without this privilege, it is unlikely that I would have ever embarked on doctoral studies. I am also grateful to my supervisors Murray Patterson and David Kettle for providing valuable critique. I am very thankful to my sister, Kim Smith, and mother, Pam Rainford, for providing assistance in minding my daughters, Ava and Elise, over the Christmas period prior to the completion of this thesis. I am furthermore appreciative of their understanding and acceptance of my limited availability over such a long time.

The topic of Appendix B, Estimation of Symmetric Input-Output Tables, emerged out of work undertaken in collaboration with Landcare Research, funded via the New Zealand Ministry of Agriculture and Forestry and the Foundation for Research, Science and Technology's Cross Departmental Research Pool (Contract 0908-01). Robbie Andrew (Landcare Research Ltd), in particular, provided valuable input during the conception stages of this work. The Ministry of Business, Innovation and Employment research programme 'The Economics of Resilient Infrastructure' (Contract C05X1205) partly funded the development of the economic model described in Chapter 7, A Dynamic Equilibrium *Seeking* Model of the Global Economy.

More than I am able express in words I am thankful to my partner, Garry McDonald, for his never-failing support and commitment to the completion of this thesis. At the time we met, I had never known any persons who had completed PhD studies and had certainly never contemplated that this would be possible of myself. Even more important than convincing me to start on this thesis, Garry convinced me that it was possible to finish it. Any person who chooses to work towards a PhD must struggle to balance the time involved in study against other demands of life. My situation was certainly no exception. Despite medical advice to the contrary, we have been blessed with not one but two wonderful daughters, Ava and Elise, both of whom arrived during the course of writing this thesis. Sadly, however, my father Denis Smith also passed away during this period, both unexpectedly and at an early age. There were many times when faced with trying to juggle the unexpected role of directing my father's company and managing his other affairs, meeting constant deadlines and commitments with our own personal work and company, and caring for two very young children, that I would have been happy to have given up on my studies. However, Garry consistently persuaded me instead to carry on and that it would be possible to finish. I love you very much.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

Acronyms

Acronym	Name
AR4	IPCC Fourth Assessment Report
BOD	Biological Oxygen Demand
CES	Constant Elasticity of Substitution
CET	Constant Elasticity of Transformation
CGE	Computable General Equilibrium
COD	Chemical Oxygen Demand
CTA	Commodity Technology Assumption
DGBCM	Dynamic Global Biogeochemical Cycling Model
DGES	Dynamic General Equilibrium Seeking
DIC	Dissolved Inorganic Carbon
DOC	Degradable Organic Carbon
EDGAR	Emission Database for Global Atmospheric Research
EF	Ecological Footprint
ESAM	Environmentally-Extended Social Accounting Matrix
FAO	Food and Agricultural Organisation
FCS	Fixed Commodity Sales Structure
FIS	Fixed Industry Sales Structure
GHG	Greenhouse Gases
GTAP	Global Trade Analysis Project
GUMBO	Global Unified Metamodel of the Biosphere
IMAGE	Integrated Modelling of Global Environmental Change
IO	Input-Output
IPCC	Intergovernmental Panel on Climate Change
ISW	Industrial Solid Waste
ITA	Industry Technology Assumption
MA	Millenium Ecosystem Assessment
MFA	Materials Flow Analysis
NPP	Net Primary Production
PIOT	Physical Input-Output Table
SAM	Social Accounting Matrix
SIOT	Symmetric Input-Output Table
SUT	Supply-Use Table
TAR	IPCC Third Assessment Report
VOCs	Volatile Organic Compounds

SI Units

Symbols	Prefixes	Multiples
Z	Zetta	1 000 000 000 000 000 000 000 = 10^{21}
E	Exa	1 000 000 000 000 000 000 = 10^{18}
P	Peta	1 000 000 000 000 000 = 10^{15}
T	Tera	1 000 000 000 000 = 10^{12}
G	Giga	1 000 000 000 = 10^{9}
M	Mega	1 000 000 = 10^{6}
k	kilo	1 000 = 10^{3}

Chemical Formula

Formula	Name
C	Carbon
$CaCO_3$	Calcium carbonate
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CS_2	Carbon disulphide
DMS	Dimethyl sulphide $(CH_3)2_S$
H_2CO_3	Carbonic acid
H_2S	Hydrogen disulphide
HCO_3^-	Bicarbonate
HNO_3	Nitric acid
N	Nitrogen
N_2	Dinitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NH_4^+	Ammonium
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_3^-	Nitrate
OCS	Carbonyl sulphide
P	Phosphorus
PO_4^{3-}	Phosphate
S	Sulphur
SO_2	Sulphur dioxide
SO_4^{2-}	Sulphate