Australian Water Security and Asian Food Security: Complexity and Macroeconomics of Sustainability

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To the memory of my grandmother, Zhongmei Zhao (1919 - 2001), from whom I inherited my passion for books and my curiosity about this extraordinary world.

Declaration

I hereby certify that the substance of the material used in this study has not been submitted already for any degree and is not currently being submitted for any other degree and that to the best of my knowledge any help received in preparing this thesis, and all reference material used, have been acknowledged.

Abstract

The thesis focuses on the macroeconomics of sustainable development and the extension to energy, water and food security, using a system dynamics approach, i.e. the methods of differential equations systems with initial values. The work is divided into three related parts that build a narrative concerning the interaction between economics, policy, natural resources and society.

First, after reviewing the concepts of complexity in environmental security, a simple system comprising three coupled differential equations is used to explain the effects of macroeconomic business cycles on the exploitation of ecological resources, and from this is inferred an implied importance of averting business cycles. The concept of entropy production is used to represent the exploitation of ecological resources.

The second part establishes a system methodology inspired by Post Keynesian economics to develop the Murray-Darling Basin Economy Simulation Model that links food production/water users and food consumers at the micro scale, to the macroeconomic system dynamics. The goal of this study is to integrate and analyze the ecological-economic system in the Murray-Darling basin. The concepts of entropy production, useful work and income distribution are used as a bridge between the micro and macro subsystems. The system parameters are estimated using an ecological-economic dataset for the Murray-Darling basin and for Australia (where data of the Basin are unavailable) from 1978-2005, and the model is validated using data from 2006-2012. The results reveal important structural linkages between the two subsystems and are used to predict the consequences of business cycles and government intervention for the coordination of growth and sustainability.

The third, and final, part presents the development of an "Asian Food Security Risk Engine" that predicts the threat of civil unrest from food insecurity in Asian developing countries. A basal characteristics index for each developing country in Asia is defined and evaluated. Based on these measures, and introducing the concept of flow of anger, we use a differential equation system to integrate the threat of food security, the trigger for food riots, and food policy. The system parameters are estimated using a dataset tracking indexes for threat, trigger and policy for Asian developing countries from 2006-2008, and the model is validated using data from 2009-2012. The results show the possible alternative approaches to simulating threat severity from food insecurity and are used to predict the threat of social unrest due to food security for a given country one month ahead.

Preface

As I turn to complete my thesis draft today, the three big news events from around the world are *Climate Panel Cites Near Certainty on Warming* in *The New York Times*, *More water releases may lift River Murray inflows into SA* in *ABC News*, and *Egypt arrests supreme leader of Muslim Brotherhood amid crackdown on protests* in *Fox News*. There is ever increasing evidence that these three events are not independent, but are fundamental to a bigger picture. Each is a different dimension of the challenge of sustainable development - reconciling economic, societal and the environmental imperatives.

The approach to, and attainment of, sustainable development requires a sufficiently strong scientific foundation. The issue of global climate change shows a typical evolution from realization to the development of abatement and adaptation strategies using the natural and physical sciences. Our understanding of global climate change is rapidly increasing along with the development of modern technologies and their applications. For instance, Geographic Information Systems (GIS) and remote sensing makes big data available for climate analysis from both historical and current perspectives. The evolution of modern computers provides an increasing potential for processing the available climate data.

However, while having a scientific foundation is a necessary condition, it is not sufficient. The human dimensions, such as politics and economics, play a major role in the implementation of scientific solutions. Humans may deserve the benefits from our accomplishments; meanwhile, our accomplishments have costs that humans must bear. Unfortunately, human nature is such that we underestimate the costs, and overestimate the benefits. Almost every generation has its own set of issues and political controversies that arise. For instance, the potential solutions to over-exploitation of the Murray-Darling basin have even more economic and political perspectives than scientific ones. Therefore the development of economic analyses is at least as important as scientific analyses, and more important still, is the ability to unite them into a single integrated picture.

Even though the scientific and economic analyses are available, the failure to integrate them and convert them into mutually consistent policies results in conflict, not only in the long run but also the short run. North Africa and the Middle East offer an example. The impact of the Arab spring continues four years after it started so abruptly, and this follows a pattern that has happened in countless conflicts throughout history. Hopefully a greater convergence of economic, societal and environmental perspectives can lead to fewer conflicts in the future.

The thesis covers all topics mentioned above. However the core has been always under a common roof, i.e. complexity of sustainable development. It is ambitious to solve any one question whole, and I recognize my own capacity, but I still wish my works can contribute a little.

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First and foremost my greatest debt is to my supervisors Prof. John Crawford and Prof. Colin Richardson, who have always supported me and my work with their expertise, insights and suggestions. Indeed, from the beginning of my PhD I have felt lucky to have John and Colin as my supervisors, and later also as friends. John played a very important role by encouraging me in pursuing ambition in my research. Colin has encouraged and corrected me in details of modern economics and the study of up-to-date research methods. John and Colin also introduced me to collaborate with the Center for International Security Studies in the project on food security which broadened my research interests.

More people than I can name were instrumental for the development of this work, including Prof. Geoff Harcourt, Prof. Steve Keen, Prof. Michael Harris, Prof. Willem Vervoort, Prof. Budiman Minasny, Prof. Inakwu Odeh, Mr. Senani Karunaratne, Ms. Lucy Liu, Mr. Timur Burykin, Mr. Rob Burdock, Mr. Yufei Sun, and seminar participants at the University of Sydney and many other organizations.

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Chapter 1

Introduction

Although apparently modern constructs, the research areas of ecological macroeconomics or environmental macroeconomics have a long history. For example, the first generation of economists in the pre-Keynesian era proposed the importance of natural capital as an essential limit to the development of an economy. Particularly, in his seminal work, *An Essay on the Principle of Population* [MG93], Robert Malthus highlighted that the limits of nature and the growth of population would hurt economic growth, even leading to human disasters. Just after the start of the industrial revolution, he predicted that prosperity would lead to population growth and rising demand for food, eventually reaching the natural limitations of agricultural productivity with catastrophic consequences. However, with the onset of the industrial revolution and rapid technological progress that loosened the reigns of a purely organic economy, ecological limits and finite environmental inputs were relatively neglected as factors influencing economic growth for over two hundred years. Even today, there is a faction within macroeconomics that would like to confine their thinking to the concepts of growth, economic output, unemployment, politics, fiscal and monetary policies, without consideration of the natural environment. In contrast, there is a growing body of effort addressing solutions to natural crises, such as climate change, but one that ignores both the macroeconomic links to ecological limits, and particularly, the effects of the macro-economy on the environment.

The last half-century has seen a rapid fusion of these two areas, even though the first use of the term environmental macroeconomics appears after 1990. Either growth-centered study or distribution-centered study focuses on the economic system per se even though technical change is introduced and highlighted. In the face of the compromise proposed and acknowledged by most macro-economists that there can be substitution between human-made capital and natural resources, Herman Daly famously pointed out that it is absurd to talk about substitutability between capital equipment and natural capital when the latter is the very basis for producing the former.

At the same time, the study of business cycles has attracted and occupied almost every macro-economist. A large number of explanations and theories on macroeconomic fluctuations have accumulated as a result. On the causes of business cycles, Joseph Schumpeter argued that the absorption of technological change causes cycles; Michał Kalecki proposed that reduction in the intensity of innovations causes a disturbance in the cyclical fluctuation; and Hyman Minsky taught that the causes of business cycles are the expansion and validation of financial commitments. Once cycles happen, John Maynard Keynes's analysis of the business cycle in chapter 22 of *The General Theory of Employment, Interest and Money* [Key36] proposed the remedy to stabilize the cycle, that is,

> …the remedy for the boom is not a higher rate of interest but a lower rate of interest! For that may enable the so-called boom to last. The right remedy for the trade cycle is not to be found in abolishing booms and thus keeping us permanently in a semi-slump; but in abolishing slumps and thus keeping us permanently in a quasi-boom.

However, the effects of business cycles causing over-exploitation of ecological resources have been neglected for a long time. An economic boom brings more demand through stronger investment and consumption; therefore it leads to a greater use of ecological resources. When macroeconomic fluctuations exist, economic bust follows economic boom, and advocacy for government intervention or free market advocacy help economic recovery through, respectively, the recovery of demand or supply. From the perspective of effective demand, economic recovery from a low level of utilization relies on a rising wage share, which boosts output due to the paradox of thrift, which a decrease in the propensity to save leads to an increase in consumption, thus causing profits and investment demand to raise after a time lag. This recovery process, or course, requires increased ecological inputs.

The largest macroeconomic fluctuations bring with them the largest ecological consumption increases, and this may result in failure of the macroeconomic system if the ecological support systems begin to break down. The on-going security of water and food availability is an old and persistent issue. It currently receives even greater attention, and not only in developing countries but also in developed countries. This is due to the confluence of unprecedented stressors including human-made climate change, increasing population burden, unequal international trade and unsustainable intergenerational mobility. Better understanding of the causes (particularly economic causes) of water insecurity in an advanced country would give both policy-makers and public the opportunity and time to avert imminent unsustainable development. More thought on the effects (particularly social effects) of food insecurity in the developing world gives a deeper insight into consequences for social dynamics, and an evaluation of appropriate international action. The multiplicity and interconnectedness of fine scale (bottom-up) and broad scale (top-down) factors necessitate a complex system perspective, and preclude a simple linear cause-effect interpretation.

Water resources are a major public issue in Australia because of their scarcity and extreme variability. Although the coastal fringes are relatively well endowed with water, and are therefore where most of the population resides, the interior is arid and water is very scarce, making Australia the driest inhabited continent on Earth. The Murray-Darling basin, an interior river basin, lies in south-eastern Australia and contains more than 20 major rivers as well as important groundwater systems. Major rivers include the Murray (2,530 km) and its three main tributaries: the Darling (2,750 km), the Lachlan (1,450 km) and the Murrumbidgee (1,700 km). Covering more than 1 million km^2, or approximately 14% of the continent (roughly equal to the size of France and Germany combined) the Murray-Darling basin spans most of New South Wales, Victoria, parts of the states of Queensland and South Australia, as well as the Australian Capital Territory. Approximately 86% of the water currently used in the basin is surface water, with groundwater providing the rest. Water availability varies greatly across the basin and almost 80% of the vast catchment area contributes little or no water to the rivers. The main run-off comes from the southern and eastern boundaries of the basin.

Average annual water consumption in the basin is approximately 11 billion m^3, which equates to almost half of the annual surface water potential of the basin. Currently, 84% of the water is used for agriculture. The remainder is lost during the storage and transfer of irrigation water. The Murray-Darling basin is Australia's "food bowl". Agriculture is practiced across approximately 80% of its area, accounting for about 40% of the country's total agricultural production. The amount of water used to maintain livestock-related agricultural activities corresponds to around half of Australia's total water consumption and around 60% of total agricultural water use. As rainfall in the basin is both extremely variable and on average relatively low, the major rivers of the basin have all been impounded to provide a more reliable water supply. In addition, significant inter-basin transfers occur in the south, bringing water from coastal catchments.

Since the 1990s there has been a progressive shift towards integrated water resources management in the basin. In 1993, the Murray-Darling Basin Commission was established to promote and coordinate the equitable and sustainable use of water across the basin. It was replaced in 2008 by the Murray-Darling Basin Authority, which acts as a government statutory agency. The basin's water resources are managed by the Murray-Darling Basin Authority in conjunction with the states and territories that make up its catchment area. Its main responsibilities are to measure and monitor water resources in the basin; to prepare, implement and enforce the management plan; to set surface and groundwater abstraction limits; and to develop a water rights information service to facilitate water trading. The severe drought that affected most of south-eastern Australia (including the southern part of the Murray-Darling basin) began in 1997 and continued for 12 years, causing significant economic losses across the region. The average annual rainfall deficit of this drought was similar to that of the 1935-1945 drought. However, the recent drought has led to a much stronger decrease in run-off and groundwater recharge. This can be explained by a change in rainfall patterns during the 1997-2009 drought: lower inter-annual variability and less rainfall in autumn and winter. The drought ended with rains that caused some of the highest flood-waters on record in 2010-2011.

In the coming decades, food insecurity and the threat of global water shortages pose the real risk of regional food crises leading to conflicts and mass refugee movements. The developing economies of Asia are experiencing serious environmental and social problems that threaten to undermine future development, food security, and regional stability. Rapid economic transformation, increasing income and rising populations in developing countries have been key drivers behind the fast-growing global demand for food. Asia, home to over 4 billion of the world's 7 billion people, is the world's most populous region. The region is central to meeting the challenge of sustainable food security at the global level. Food security remains a problem of economic access in Asia as hundreds of millions of Asians continue to live in extreme poverty. At the same time, a number of complex and interactive trends such as population growth, rising incomes, changing food consumption patterns, environmental degradation, climate change, growing competition for natural resources, such as land and freshwater, as well as urbanization and industrialization are coming together to exert tremendous pressure on food systems in the region. How governments and other actors in Asia respond to emerging food security challenges at home will have far-reaching consequences for human security and peace and stability of communities and states in Asia and in other parts of the world.

Food insecurity is inherently interlinked with political security, socio-economic development, human rights and environmental protection. When food prices increase sharply and suddenly, they cause hunger and malnourishment in the short term, and also lead to potentially longer-term reversals in poverty reduction and human development by cutting back on health care and education in order to maintain immediate staple food consumption. Poverty is the main cause of hunger, and the two have a mutually reinforcing relationship. The scale of poverty in Asia makes the region's populations particularly vulnerable to sudden and sharp increases in food prices, as the poor spend as much as 70% of their household incomes on purchasing food. Although some countries do have social safety nets in place to protect poor and vulnerable sections of their populations from food price hikes, these often suffer from substantial inefficiencies and wastage due to problems of weak institutional and infrastructural capacity, poor management practices and corruption. Across the region, smallholders - who produce the vast majority of Asia's food - continue to lack stable and secure access to the land they live and work on, and suffer from livelihood insecurity. Without the surety of benefiting from long term sustainable use and management of renewable resources like arable land, rivers, lakes and forestlands, there is often insufficient incentive for small farming households and communities to invest in such practices that would otherwise lead to positive outcomes for the environment and agricultural productivity. When combined with serious levels of poverty and malnourishment, weak governance, widespread socio-economic inequalities, lack of social justice and phenomena such as rising food prices, and illegal or forced land eviction the situation can rapidly escalate to trigger violent protests, demonstrations and riots. Previous work has suggested some approaches to deal with the prediction of regional food riots but has not harnessed all of the benefits of systems theory based on quantifiable catastrophic shifts.

In chapter 3, we develop a simple system comprising three coupled differential equations which are used to explain the effects of macroeconomic business cycles on the exploitation of ecological resources. From the linkage between entropy production, unemployed labor and unutilized capital stock, we show that business cycles increase the exploitation of ecological resources.

In chapter 4, we develop an alternative economy simulation model based on effective demand - a concept that connects both economic and ecological systems. From this new definition we link income distribution and useful work, and therefore connect Keynesian economics with ecological economics. We apply this technique to the Murray-Darling basin through an examination of three perspectives: the micro land/water user, the micro food consumer and the macro economy, in order to reflect the feedbacks in the dynamical system and the heterogeneity of agents within it.

Finally, in chapter 5, we develop an index system by introducing and defining a basal characteristic index, a dynamic factors index, a trigger potency index, a policy effectiveness index and a threat severity index. We fuse the scheme of indexes in a system of differential equations in order to predict the threat in the coming month, given the current situation.

Chapter 2

Complexity in Environmental Security

'Complexity' is used by many people in many different situations, but is ill-defined in most contexts. For example, physical scientists use the term 'complexity' for a class of theories to contrast with simple models that are based on Classical Mechanics, i.e. Newtonian Mechanics, instead of Einstein's theory, and also use the term when comparing linear and ergodic models based on Classical Mechanics and the First Law of Thermodynamics respectively. Perhaps the most widely accepted definition of complexity relevant to natural and economic systems is provided in the context of complex adaptive systems by Simon Levin [Lev02]. The properties that define a complex adaptive system are (1) diversity and individuality of components, (2) localized interactions among those components, and (3) an autonomous process that uses the outcomes of those interactions to select a subset of those components for replication or enhancement.

The dynamical properties of a complex system are one of its most fundamental characteristics. Dynamics is defined in the span of time where evolutionary process can be seen as resembling dynamics. From the aspect of operator theory, dynamics can be distinguished as either linear or nonlinear. For linear dynamics, we focus on how to solve it. For the case of nonlinear dynamics, however, analytical solutions do not generally exist and we must resort to numerical analysis to characterize the behavior of the system.

Environmental security issues implicate a diverse range of issue, such as energy, water, and food, which are relevant to the coupling of natural resources to human behavior. The path towards sustainability and the path of sustainable development chosen by people and policy-makers are not the same thing. The underlying 'natural laws' that determine the ongoing availability of natural resources are immutable and do not respect the external man-made rules that dictate the dynamics of associated socio-economic systems.

An essential feature of any successful coupling of ecological and economic systems is the concept of uncertainty which arises from Keynes's notion of fundamental uncertainty in economic systems. Fundamental uncertainty is consistent with the non-determinant philosophy that admits path dependency of the evolutionary process. Uncertainty can destabilize a complex system. In other words, stability is temporary and unknowable while instability is permanent and inevitable without the intervention of policy.

In this chapter, we will first review the concise definition of complexity. Secondly, we will introduce the differential equation approach to modeling the complexity in a given system, where we will distinguish the nonlinear properties as essential. Thirdly, we discuss the significance of openness in a complex environmental system. Next, we will critique the determinant theory. Finally, we link complexity and sustainability.

2.1 Complexity

Complexity is the idea that "there is a pluralism of levels, systems, and dynamic patterns of phenomena in the natural, biological and social worlds" [Wib00]. The science of complexity allows investigation of open systems in which "the collective behaviour of many basic but interacting units evolves over time, with self-organisation and adaptation" [CH95]. A complex system is a system that "exhibits nontrivial emergent and self-organizing behaviors" [Mit09]. Although the definition of complexity is vague and context-dependent [Wib00], a complex system, particularly in social science, has four key features, i.e. (1) emergence, (2) low level of predictability at a point in time, (3) limited cognition of individual agents, and (4) multiple possible histories [Orm09]. Emergence stems from underlying nonlinearities in the system; low level of predictability at a point in time implies a system out of equilibrium; limited knowledge of individual agents results in fundamental uncertainty; and multiple possible histories means the system is uncertain.

2.2 Dynamics

The theoretical analysis of nonlinear phenomena and their simulation is performed on the corresponding set of nonlinear dynamical system equations. These equations describe the dynamic evolutionary behavior; that is, the evolution in time of the system under consideration. There are two main types of dynamical systems [Str94]: differential equation systems and difference equation systems. Differential equations describe the evolution of systems in continuous time, whereas difference equations are applied to problems where time can be broken down to a progression of discrete events. The differential dynamical systems target to construct the relations between the change of variables in the scale of time and/or space and the variables themselves. The approaches have been developed for mechanics initially, and have spread on many other areas. Linear differential dynamical systems are thoroughly studied and a wide range of analytical tools are available to solve these equations exactly. In contrast, nonlinear differential operators are more difficult and generally cannot be solved exactly. The common method to deal with a nonlinear differential operator is to linearize it based on the Banach fixed-point theorem. In effect, Banach theorem addresses the dependency of the solution on the initial values however the application of the theorem cannot reveal the dynamics of the system that the nonlinear differential operator describes.

2.3 Openness

Sheila C. Dow defines an open system as a system in which "not all the constituent variables and structural relationships are known or knowable, and thus the boundaries of the system are not known or knowable" [Dow96]. Therefore an open system is a system that is open to "flows of matter, energy or information across its boundary" [Hod01]. In closed systems, research can afford to rely, to a degree, upon testable observations of empirical regularities such as the well-known relations between temperature, volume and pressure in equilibrium thermodynamics. Open systems, conversely, typically evade such insight and require abstractions to categorize components contributing to an event [Say92]. An ecological-economic system is open rather than closed. There are flows of matter, energy and information across the boundary of economic system and ecological system. General equilibrium economics considers the flow between two systems. In the sense, there is no distinguishing between general equilibrium economics and non-equilibrium economics. However, we argue that the boundaries of ecological-economic system are not known or even unknowable. The boundary of the system is dynamic rather than static. In our environmental security system, i.e. a system that embeds into ecological-economic system and that integrates economy to energy, water or food, openness is inevitable.

2.4 Uncertainty

Keynes argues for fundamental uncertainty in an economic system [Key36]. Meanwhile, deterministic uncertainty can be a characteristic in an ecological-economic system. Deterministic uncertainty is the irregular but not random motion in nonlinear dynamical systems whose dynamical laws uniquely determine the time evolution of the state of the system from knowledge of its past history. It is not due to external noise, to the fact that the system may have an infinite number of degrees-of-freedom or to any "Heisenberg uncertainty"-like relations operating on the quantum level [EMS04]. The source of the observed irregularity in deterministic uncertainty is non-ergodicity and path dependency, i.e. an intrinsic sensitivity to initial conditions and system parameters.

Biodiversity, and ecosystem stability and resilience are important concerns of ecologists [May73, Hol73], where biodiversity can link to ecosystem stability, and contributes to ecosystem resilience. However, in an ecological-economic system, there is no guarantee attaining stable state even if diversity is enhanced, due to the intrinsic instability of the market economy, i.e. business cycles. In another words, the existence of business cycles may weaken the biodiversity and furthermore the stability. Therefore stability can be temporary while instability is permanent.

2.5 Sustainability

A synthetic system is not only a coupled system that links economic factors and ecological factors as an input-output flow system, but also an integrated system that combines the micro-level characters and macro-level characters, and distinguishes the importance of the characters and factors that appear in the system.

Simple input-output analysis of energy, matter or information is not sufficient to create a synthesis of economic and ecological system dynamics. However, it is not necessary to discard the results from previous system theory developed by ecologists and economists. Therefore, a synthesis that regards the dynamics, openness and uncertainty as a whole system should be developed. The idea is to acknowledge the system dynamic rather than the static, non-equilibrium rather than equilibrium, to see the system open based on the wholeness of the system, and to consider intrinsic uncertainty as a basal characteristic.

The synthetic idea is feasible. First, researches on ecosystems from the systemic viewpoint in the past four decade provide the basis for understanding the new synthesis. Second, the development of Post Keynesian economics since 1930s has become integrated. Third, an increasing consensus on sustainability and sustainable development can enhance the spread of the new synthetic idea.

Chapter 3

Business Cycles

Business cycles[1] has been defined by Arthur Burns and Wesley Mitchell [BM46] from the National Bureau of Economic Research of the United States in 1946 as:

> a type of fluctuation found in the aggregate economic activity of nations that organize their work mainly in business enterprises: a cycle consists of expansions occurring at the same time in many economic activities followed by similar general recessions, contractions and revivals which merge into the expansion phase of the next cycle.

The study of business cycles has attracted and occupied almost every macroeconomist. This chapter reviews the issues on business cycles, but does not concentrate on the economic causes of business cycles or on the explanation of the emergence of macroeconomic fluctuations. Furthermore, it does not discuss the disputed viewpoints on business cycles between different economic schools. The focus here concerns its impacts on natural resource consumption.

The chapter proceeds as follows. Section 3.1 presents the interdependency and interaction between natural and economic systems, where we review the macroeconomic impacts that affect climate change, natural forces that affect the economy and the mechanisms that link the economic system to the natural system. Section 3.2 outlines the macroeconomic behavior framework of business cycles, i.e. recovery, prosperity, recession, and depression. Section 3.3 describes the effect of business cycles on ecological resource exploitation. Section 3.4 reviews the Post Keynesian explanation of the causes of business cycles. Section 3.5 presents a model to link business cycles and entropy production, and section 3.6 describes the predictions of the model. Section 3.7 discusses the findings and concludes.

[1]The evolution of thought in the study of business cycles is outlined by Victor Zarnowitz [Zar85].

3.1 Two Interacting Systems, One Integrated System

This section presents the interdependency and interaction between natural and economic systems where we review the macroeconomic impacts that affect the natural system, the natural influences that affect the economy, and the mechanisms that link the economic system to the natural system. Anthropogenic impacts on natural systems involve climate change, greenhouse gas emission, water/air/soil pollution and biodiversity loss. The second law of thermodynamics is highlighted as a critique of mainstream economic analysis where technological progress is claimed to mitigate these anthropogenic impacts on the welfare of future generations. Natural impacts on the economic system focus on drought and temperature. The contribution of natural resources to economic growth is also discussed. Finally, viewpoints on the integrated system are reviewed.

3.1.1 Anthropogenic Impacts on Nature

Climate change and greenhouse gas emissions (GHG) come from both natural and anthropogenic sources. The *2007 Fourth Assessment Report* (AR4) of the Intergovernmental Panel on Climate Change (IPCC)[2] [CPR07] details the unequivocal warming of the Earth's climate over the last 50 years, most of which is very likely a result of increases in anthropogenic greenhouse gas emissions. There has been a rapid 35% rise in atmospheric GHG concentrations since preindustrial times and in 2005 atmospheric GHG concentrations were higher than any levels recorded or estimated for the previous 650,000 years. Anthropogenic climate change is having a significant impact on physical and biological systems globally and at a continental scale in some places [RKV+08]. For example, twentieth-century anthropogenic greenhouse gas emissions has increased the risk of floods occurring in England and Wales [PAS+11], while food systems are key drivers of environmental change [PT10] contributing 19%-29% of global anthropogenic greenhouse gas emissions [VCI12] where four-fifths of agricultural emissions arise from the livestock sector [FDG+09].

The consequences of anthropogenic pollution of water [Qui01, KPB+12], air [FDG+09, GK94, CEGL13] and soil [JJ00, Har93] are significant and are becoming increasingly serious in the era of global climate change. For example, anthropogenic air pollution increases the destructiveness and intensity of tropical

[2]The Summary for Policymakers of the IPCC Working Group I assessment report *Climate Change 2013: The Physical Science Basis* [SQP+13] which was published in 27 September 2013 and will contribute to the IPCC Fifth Assessment Report concludes that human influence on the climate system is clear.

cyclones in the Arabian Sea [Sri11]. When land is occupied and irrigated, the associated appropriation of freshwater resources reduce the availability of irrigation water in the surrounding and downstream farmland areas, with the potential effect of causing water stress and poor water quality in those areas [RSD13].

Human activity also has played a key role in biodiversity loss. Agricultural activity is a leading cause of biodiversity loss [EE13]. The combination of environmental change and biodiversity loss with long term and persistent human disturbance increases vulnerability to abrupt environmental change and ecosystem collapse [MMGT13]. Land-use change by human activity is significant for agricultural production, emissions and sequestration of greenhouse gases, open-access recreational visits, urban green space, and wild-species diversity [BHM+13].

Economic activities need energy. Economists generally agree on the first law of thermodynamics [NAB+13], i.e. we cannot create energy or matter. However, most economists neglect the second law of thermodynamics, i.e. large energy inputs are required to maintain highly organized systems. This omission leads to an underestimate of the impacts of economic growth on energy flow and underrates the contribution of energy on economic activities. The contributions of useful work (the sum total of all types of physical work by animals, prime movers and heat transfer systems) to economic development are highlighted by Robert Ayres and his colleagues [AAW03, AW05, Ayr08, WAE+10, WA10]. They included changes in energy and useful work consumption, energy efficiency and related gross domestic product (GDP) intensity measures. Finally, the authors tested the replacement of raw energy by useful work as a factor in a Cobb-Douglas production function, and conclude an almost zero Solow residual[3] depending on other economic policies, i.e. the total factor productivity is overestimated.

3.1.2 The Impacts of Nature on the Economy

A direct approach to measuring the impacts of the natural system on economic activities is to value ecosystem services. The valuation of ecosystem services[4], i.e. estimation of the benefit from conversation of ecosystem services and cost from the loss, is seen as increasingly important as simultaneous resilience of the environment and global economy is in doubt. In 1997 Robert Costanza and his colleagues estimated the current economic value of ecosystem services and argued that, for the entire biosphere, the value is in the range of 16-54 trillion (10^{12}) US Dollars per year [CddG+97]. In 2012 Drew Shindell and his colleagues estimated

[3]The Solow residual measures the change in total factor productivity (the ratio of outputs produced to inputs used) where most of the growth was attributable to exogenous technical change in the original Solow/Swan model [Sol56, Swa56].

[4]Several critical reviews on the economics of biodiversity and wider ecosystem services have been conducted [DSA+00, ABM12, HH12].

the benefits of methane emissions reduction are valued at 700 to 5000 US Dollars per metric ton [SKV+12]. A unique framework for the assessment and valuation of water quality-related services is also proposed [KPB+12].

Although there is no clear assessment of the impact of anthropogenic climate change on drought at the local scale [PCH+10], drought hurts the economy and agriculture. Models predict a 10-40% increase in run-off in eastern equatorial Africa, the La Plata Basin and high-latitude North America and Eurasia, with a 10-30% decrease in run-off in southern Africa, southern Europe, the Middle East and mid-latitude western North America by the year 2050 due to the changing climate [MDV05]. Environmental problems have contributed to numerous collapses of civilizations in the past [EE13]. For example, the droughts that occurred during the disintegration of the Maya civilization represented up to a 40% reduction in annual precipitation [MER12, LBBD12, AH11]. Today a severe drought imposes a direct cost of 1,605 million US Dollars in Iranian economy [SST09]. Population growth is in general constrained by food production while food production depends on the access to water resources [SRMD13].

Temperature also is strongly linked to the economy. The number of record-breaking events has increased approximately in proportion to the ratio of the warming trend to the short term standard deviation [RC11]. The negative relationship between temperature and economic growth was first documented in de Montesquieu's seminal work *The Spirit of Laws* [dMCMS89], which stated that an "excess of heat" made men "slothful and dispirited". Recently, William Nordhaus argued that the temperature-income relationship may not be negative, and depends on how income is measured: a negative relationship exists if measured by income per capita, and a positive relationship is found if measured by income per area [Nor06]. These results are rejected by providing evidence for a purely negative relationship between temperature and economic activity [NZ11]. At the micro level, high temperatures lead to large reductions in U.S. labor supply in industries with high exposure to climate and similarly large decreases in time allocated to outdoor leisure [ZN10]. At the macro level, higher temperatures diminish worker productivity, decreasing economic growth and agricultural and industrial outputs in poor countries and suppress agricultural exports of various kinds, as well as light manufacturing products [DJO08, JO10, DJO12]. The output losses occurring in non-agricultural and in agricultural production in Caribbean basin countries due to climate change and the impact on the economy of surface temperatures has also been quantified, i.e. a temporary 1 degree Celsius increase in surface temperature is associated with a contemporaneous 2.5% reduction in economic output [Hsi10].

According to the "biodiversity hypothesis", reduced contact between people and the natural environment may adversely affect the human commensal microbiota and its immunomodulatory capacity [HVHF+12]. Biodiversity degradation is threatening human well-being [DFCT06].

Exploitation of ecological resources is linked to economic growth. Countries rich in natural resources constitute both growth losers and growth winners. The Dutch Disease effect is one symptom, where resource booms induce appreciation of the real exchange rate and makes the non-resource sectors less competitive [MMT06, VDP11].

3.1.3 Towards a Synthetic System

Faced with interacting economic and ecological systems and unsustainable development, the formulation of a unifying synthetic model of the economy and the environment is as essential a feature of any solution as it is in the physical sciences [RCC11]. To develop a synthetic system not only needs an understanding of ecosystem valuation and environmental risk assessment but also depends on a deeper fusion of sustainable ecosystem services and stable macroeconomic dynamics.

At the micro-level, for example, a coupled hydro-economic spreadsheet model [MKQ07] is developed for the Murray-Darling basin that allows analyses of water allocation and use by different sectors including agriculture and environment under alternative policy scenarios, and examines approaches of acquiring water for reallocation to the environment, and their impacts on irrigation water use and regional income from agriculture.

At the macro-level, perhaps the best known integrated economic-environmental model is Nordhaus's Dynamic Integrated Model of Climate and the Economy (DICE) model [BP12, LT12, HK12a]. DICE is a Ramsey-Cass-Koopmans growth model that has an aggregate world economy interacting with a climate module. Gross economic output is determined by an endogenous capital stock, an exogenously growing labor force, and exogenously improving production technology. Gross output produces carbon dioxide emissions. Non-abated carbon dioxide emissions accumulate in the atmosphere and ultimately translate into global warming, which causes damage proportional to world output. Cumulative temperature change affects the total output available for allocation by the policy-maker. The control variables are abatement and consumption, and the residual output not allocated to these two options becomes capital investment. The state variables are capital per effective unit of labor, the stock of carbon dioxide in the atmosphere, the change in global mean surface temperature since 1900 and, to keep track of exogenously evolving variables, time.

Although addressing some of the same research challenges, ecological economics is different from environmental economics in its research methodology. Therefore, integrated ecological-economic models have dissimilar features. For example, agent-based modeling is applied to develop a macroeconomic model to study the impacts of flood risks [SBH13]. An integrated hydro-economic model is established based on a general equilibrium model [BH08]. Colin Richardson and his colleagues developed a policy-oriented integrated ecological and economic model that fuses Post Keynesian economics with ecosystem services as a distinguishing methodology [RCC11].

3.2 The Macroeconomic behavior of Business Cycles

Business cycles describe fluctuations in the macro-economy. According to Michał Kalecki [Kal35], business cycles can be divided into four phases, i.e. recovery, prosperity, recession, and depression where

> recovery is the phase of the cycle . . . , when the volume of investment orders begins to exceed the volume of the demand for restoration of industrial equipment. But the very volume of the existing industrial equipment is not yet increasing, as deliveries of new equipment still remain below the demand for restoration of equipment . . . during prosperity also deliveries of equipment exceed the demand for restoration of the equipment, thus the volume of the existing equipment is increasing. The rise of [the volume of industrial equipment] at first hampers the rise of investment orders and, eventually, causes their drop. The output of capital goods follows suit, and begins to fall off in the second phase of prosperity . . . during recession investment orders are below the level of the demand for restoration of the industrial equipment, but the volume of the existing industrial equipment is still on the increase, since deliveries are still below the demand for restoration . . . during depression deliveries of equipment are below the level of the demand for restoration of the equipment, and the volume of the existing equipment is falling off. The drop in [the volume of industrial equipment] at first smooths the downward tendency in investment orders, and then calls forth their rise. In the third phase of depression the production of capital goods, too, begins to increase.

John Maynard Keynes [Key36] described the succession of economic boom and slump in terms of the fluctuations of the marginal efficiency of capital relative to the rate of interest. The growth cycle model developed by Richard Goodwin [Goo67] divides business cycles into two phases, i.e. over-accumulation of capital in the prosperity phase and mass unemployment in the stagnant phase. Kalecki's observation on business cycles reflects the disequilibrium between demand and supply of industrial equipment, the hysteresis of the output of capital goods, and the failure of application of ergodicity in investment by the holders of capital that depends on the idea expressed in Say's Law, i.e. profits determine investment. When disequilibrium and hysteresis are under the influence of fundamental uncertainty, any economic decisions determined by accurate mathematical calculation produces the instability, and only the existence of unemployed labor and unutilized capital is certain. According to Hyman Minsky's "financial instability hypothesis" [Min86], in an economic depression the economic agents become pessimistic so that they refrain from investment, and the repayment of the existing debt and hedge financing dominate in such an environment. As the amount of debt decreases, investment becomes more vigorous and a bolder speculative financial climate becomes dominant. At the last stage of prosperity, economic agents become excessively optimistic and they become engaged in Ponzi financing. During this stage the finance sector's equivalent of "pyramid selling" in the retail sector dominates, i.e. the financiers pay interest to existing bondholders using funds sourced from new buyers of bonds, rather than from current investment income earned on the financiers' existing investment portfolios. However, defaulting on payments by some of economic agents can trigger off a financial crises and the economy rapidly descends into a serious depression. In a depression, hedge financing becomes dominant again. In this way, the waves of "pessimism" and "optimism" are repeated sequentially.

The influences of 'financialization' on investment, profits, savings and income distribution from both Keynesian and Kaleckian perspectives have been identified in recent Post Keynesian analyses [HVT10]. As Gerald A. Epstein points out, "financialization means the increasing role of financial motives, financial markets, financial actors and financial institutions in the operation of the domestic and international economies" [Eps05]. Neoclassical models of financialization (which include New Classical models established based on endogenous growth theory and New Keynesian models based on information economics) neglect effective demand and income distribution conflict between different social groups. In contrast, the analysis based on Post Keynesian models that incorporate financialization [HVT10] conclude that (1) financialization increases bargaining power of shareholder power in relation to managements and labors, increases the rate of return on equity and bonds held by rentiers, and decreases managements' animal spirits[5]; (2) financialization increases the potential for wealth-based and debt-financed consumption; and (3) financialization decreases wage share, and therefore increases inequality of wages.

3.3 The Effects of Business Cycles on Ecological Resources

Although business cycles attract the attention of economists' from different perspectives including demand, investment, accumulation of capital, marginal efficiency of capital, the rate of interest, unemployment, accumulation of debt, etc., the behavioral effects on over-exploitation of natural resources by business cycles per se have received relatively less attention.

A simple analogy is given here: because there exist seasonal cycles - spring, summer, fall, and winter - the needs of energy to heat in winter and to cool in summer increases the consumption of energy, compared with the situation where there are no seasonal cycles and the temperature throughout the year is fixed at the average value.

In direct analogy with the increase in consumption of energy to maintain comfortable temperatures, business cycles may increase the consumption of energy, therefore increasing the production of entropy. An economic boom brings more demand through stronger investment and consumption, and therefore more usage of ecological resources relative to a situation where economic growth had stayed on trend. When macroeconomic fluctuations exist, after the boom there follows an economic bust, which calls for both government intervention or for free market policies to help the economy through the recovery of demand or supply. From the perspective of effective demand, the economic recovery from a low level of utilization relies on a rising wage share, which boosts output due to the increase in demand for consumer goods, which is followed by a rise in investment demand due to enhanced profitability. This recovery process needs more ecological inputs.

In the face of different understandings of the causes of business cycles and even different viewpoints on the measurement of GDP, and hence business cycles,

[5]The term animal spirits was first introduced in the field of economics by Keynes (Keynes, 1936), who argued "a large proportion of our positive activities depend on spontaneous optimism rather than mathematical expectations, whether moral or hedonistic or economic. Most, probably, of our decisions to do something positive, the full consequences of which will be drawn out over many days to come, can only be taken as the result of animal spirits - a spontaneous urge to action rather than inaction." Animal spirits, therefore, refer to the role of emotional factors and to the fact that both optimism and pessimism exist. The consequence is that it is impossible in practise to calculate the mathematical expectations that are best known as fundamental uncertainty, but typically assumed by mainstream economists to determine almost all economic decisions [Qui10].

a simple model is established to fuse independent entropy production into the traditional concept of economic output in order to illustrate that, however we measure the macro-economy and deal with entropy, fluctuations in the macro-economy will produce an more consumption of natural resources which is reflected in increase in entropy production.

3.4 The Macroeconomic Causes of Business Cycles

Post Keynesian economists have different explanations for the causes of business cycles from neoclassical economists partly due to the opposite viewpoint on the relationship between the microeconomic and macroeconomic systems. As Steve Keen [Kee01] argued,

> Post Keynesians reverse the neoclassical pecking order, to argue that whatever microeconomics is developed must be consistent with the observed behavior of the macro-economy. A microeconomic model which is inconsistent with such things as business cycles, sustained unemployment, commonplace excess capacity, and the importance of credit, is to Post Keynesians an invalid model.

A business cycle is a consequence of the fluctuation of aggregate investment. John Maynard Keynes [Key36] argued that the business cycle originates especially from investment, which is influenced by the fluctuation of the marginal efficiency of capital under uncertainty. Michał Kalecki [Kal43] argued that profit is a significant variable that influences investment, and emphasized his "principle of increasing risk". In other words, increasing investment eventually results in debt accumulation, which may be unsustainable. Richard Goodwin [Goo67] argued that the conflicts between labor and capital produce the cyclical employment and accumulation rate. Hyman Minsky [Min86] argued that financing investment increases the tendency to swing between pessimism and optimism and so dampens and encourages investment finance per se. Following these observations, investment and profit, fundamental uncertainty, effective demand, income distribution, and financial instability are reviewed.

3.4.1 Investment, Profit and Fundamental Uncertainty

Since profits are savings in the Kaleckian framework, Kalecki takes the view that investment determines savings while Say's Law argues that savings determine investment. If Say's Law is correct, i.e. profits/savings determine investment at the micro level, an insufficiency of investment cannot occur because gaps from the profits/savings will be filled by the business community through financing. However, according to Kalecki's "principle of increasing risk", the firm's access to external capital is largely determined by its internal entrepreneurial capital. Investment is limited by finance that is in turn inversely affected by the degree of indebtedness.

Colin Richardson and Peter Romilly [RR08] found that the essence of the determinants of investment expenditure, in the investment theories of all schools of economics, is the gap between the rate of profit and the risk-adjusted market rate of interest. Because the accumulation of capital decreases the rate of profit, even more investment is required to widen this "profitability gap" and keep up the demand for investment. On the other hand, investment can be depressed by the existence of fundamental uncertainty stemming from the fact that there is no possibility of forecasting the future based on the past by using mathematical tools. This is because an economy moving through historical time is not "ergodic" like the timeless physical world, in which experiments can be repeated, Newton's planetary orbits are fixed and Einstein's field equations rule space-time. According to this framework, capitalists cannot predict the rate of profit, the gap in the rate of profit, or the expected demand, and ignore what might modify the environment where they have to take their decisions and invest [Dav91, AGD12]. However, capitalists have to adopt some view about their own future profitability, otherwise there would be stasis. In practice, they tend to look to their most recently realized results as a guide to what they should expect the future will bring.

Keynes's fundamental uncertainty cannot be treated like a risk [Dav91, Dav10, Dav12]. Facing fundamental uncertainty, people rely on convention to make judgments on further investment decisions. Therefore, investors tend to have a short term horizon and are mainly driven by speculative motives; that is, they are mainly occupied with forecasting "the psychology of the market" rather than "the prospective yield of assets over their whole life" [Key36].

Lack of attention to Keynes's fundamental uncertainty yields biased macroeconomic policies. For instance, Amitava Dutt [Dut11] argued the debate between the opponents of government activity and those who think of government policies as a panacea is ill conceived, because

> government policies may not work as precisely expected, and frequent changes in macroeconomic policy may make the future more uncertain and create more instability. However, the expectation that unregulated free markets will solve macroeconomic problems . . . fails to take into account . . . problems due to the existence of fundamental

uncertainty and the fact that individual attempts to tame it, cope with it, and reduce it may not have socially desirable outcomes.

Minimizing fundamental uncertainty needs sustainable effective demand. According to Jerome Levy, in a capitalist economy with external trade in balance, total profits equal investment, where investment is an independent variable while profits are dependent [Min89], i.e.

$$\text{Profits} = \text{Investment} \tag{3.1}$$

To expand this to a sophisticated capitalist economy, the profits equation [Min89] becomes

$$\begin{aligned} \text{Profits} = \text{Investment} & \\ & + \text{Government Deficit} \\ & - \text{The Deficit on International Trade} \\ & - \text{Savings out of Wages} \\ & + \text{Consumption out of Profits} \end{aligned} \tag{3.2}$$

The Levy-Kalecki profits equation [WP03] "...demonstrates that profits are identically equal to investment, plus the government's deficit, less the current account deficit, plus consumption out of profits, and less saving out of wages." On the left hand side of "identically equal" is "profits". Yet the business sector cannot control its own profits, so it must be the right hand side that determines this aggregate. So, to sustain effective demand, those with power to make larger investments and increase consumption out of profits (capitalists) should do so. Likewise, workers should consume more out of their wages and the government should act to increase its budget deficit, by spending more and/or taxing less. Action to raise exports and/or lower imports is also indicated at times when effective demand needs to be sustained.

3.4.2 Effective Demand and Full Employment

Full employment makes effective demand sustainable. John Maynard Keynes [Key36] pointed out that the economists in the pre-Keynesian era assume that full employment is reached automatically. That is, there is only one intersection between the labor demand function and the labor supply function. Effective demand for goods and services is what drives employment [Kal43], therefore involuntary unemployment is caused by deficient effective demand.

Effective demand is made up of investment expenditure and consumption expenditure [Key36, Key37], and is a core concept for understanding macro-dynamics. According to John Maynard Keynes [Key36], the value of the effective demand equals the intersected point between the aggregate demand function and the aggregate supply function, where both functions depend on the level of employment, as will be discussed in the next section. In order to distinguish from the pre-Keynesian economic assumption that the aggregate demand will self-adapt to the changing aggregate supply automatically, John Maynard Keynes [Key36] also argued that effective demand may not have a unique equilibrium value.

John Maynard Keynes [Key36] proposed a theory of the determination of employment and economic output based on the analysis of aggregate demand, rather than on the analysis of the growth of inputs to production and improvements in technology. He also proposed that the determination of aggregate demand depended on consumption demand and investment demand, rather than on aggregate supply, the latter depending on the supply of factors of production, such as capital and labor, and their productivity. In short, his was not a "supply-side theory" as promoted by orthodox economists, whose prescriptions for raising employment include real wage cuts, reduced public sector employment and transfer payments, lower taxation of corporations/dividends/interest, and increased work intensity, all of which tend to reduce effective demand.

As for investment demand determinants, Colin Richardson and Peter Romilly [RR08] examined the equations of investment theories proposed by Adam Smith, Karl Marx, John Maynard Keynes, Michał Kalecki, James Tobin, Dale Jorgenson, and others, and argued that pre-Keynesian economic uniform profitability, Keynesian marginal efficiency, accelerator mechanisms, and neoclassical q-theory and user cost investment functions are specific expressions of a single generic investment function, i.e. the profitability gap between the profit rate and the risk-adjusted interest rate. Julio Lopez and Tracy Mott [LM99] pointed out that Kalecki's investment theory strengthens Keynes's investment theory: (1) that wage cuts in the general case do not increase employment, and (2) that taxation of capital income can increase the economic well-being of all [LM99]. Nicholas Kaldor [Kal57] also points out that Keynes used the declining marginal efficiency of capital function, while Michał Kalecki used the principle of increasing marginal risk.

As for consumption demand determinants, John Maynard Keynes [Key36] introduced a novel analytical tool, i.e. the consumption function. The rationale for the consumption function is:

> the fundamental psychological law, upon which we are entitled

> to depend with great confidence both a priori and from our detailed knowledge of human nature and from the detailed facts of experience, is that men are disposed, as a rule and on the average to increase their consumption as their income increases, but not by as much as the increase in their income.

Therefore, according to Hyman Minsky [Min08],

> the cyclical consumption-income relation embodies an initial stability of absolute consumption standards, which is followed by an adjustment toward a longer-run sustained ratio of consumption to income: the consumption-income ratio adjusts upward as increased income is sustained and adjusts downward as decreased income is prolonged.

On the other hand, John Hicks [Hic37] claimed that liquidity preference is the important difference between Keynes and the Classics and stated that the equation embodying the consumption function and the multiplier "is a mere simplification and ultimately insignificant". After four decades, John Hicks clarified in *Journal of Post Keynesian Economics* his 1937 model lack of macroeconomic basis because the model required the assumption that the macro-economy was always in equilibrium [Hic80].

As for international demand, it is reasonable to translate the net exports aggregate into its wage and profit components to consider its effects on effective demand. Neoclassical economists insist that increasing net exports following a decrease in wages has only a positive effect on domestic effective demand: decaying wages will improve international competitiveness and therefore ultimately net exports, furthermore net exports will have a positive effect on investment due to rising profitability. Lack of any comparison between net export demand and consumption demand contributes to this simple result. Distinguishing between economies that are wage-led and profit-led prevents it. In a profit-led economy, increasing net exports can substitute for decreasing wages more readily than in a wage-led economy. Robert Blecker [Ble89] introduced net exports into the demand components in the Kaleckian model, and showed that an increase in the wage share may lower international price competitiveness and has a negative impact on investment by assuming that the measure of international price competition is exogenously given.

The arguments presented above suggest that to achieve full employment better income distribution is required.

3.4.3 Income Distribution

Understanding the determinants of income distribution is a central concern of economics. Income distribution is clearly an important social and political concern, having ramifications for fairness and the social and political stability of society [Pal06]. The dominant neoclassical approach to income distribution is marginal productivity theory, which emphasizes demand for factors of production and supply. The determination of income distribution is therefore part of the workings of the price system, according to orthodox economists. They claim that distribution is determined by competitive market forces that ensure factors are paid for appropriately to their contribution to production, and the process of determining factor prices in turn links the determination of factor employment.

Income distribution is a key concept in economic growth theory [Pal06, Dut08, Lav09b, CLSV10, HVT10, HLVT11, HVT11, Lav11, KS11, Dut12a, NF12, HLVT12, RS12b, Pal13a, Pal13b, Pal13c]. Income distribution that is appropriate for a given macroeconomic environment and local ecosystem services will favor economic growth and environmental sustainability. A better income distribution causes weaker economic fluctuations and business cycles, which in turn assist environmental sustainability through sustainable investments and consumptions in the long run. In a demand-driven economy, a higher wage share will give workers the incentives to consume more, but leave more environmental problems and use more ecosystems services, hence making it harder to maintain the resilience of ecological systems. However, a higher profit share will give holders of capital more stimuli to invest in the future, but weaken current consumption. This will be reflected in lower wages, and then hurt profits in the coming period, thus also investment for the future at least in the short term. Meanwhile a higher profit share also can affect macroeconomic stability through financial burdens, once the expectation of instability takes hold of investors.

A crucial question raised in growth theories that propose that aggregate demand is a major determinant of growth, is how income distribution between wages and profits affects the economy [Cas12]. Post Keynesian models of economic growth propose a central role for income distribution. They emphasize complex dynamic interactions between growth and income distribution [Dut12a] through concentrating on the effect on economic growth of income distribution between wages and profits, and examine whether growth is wage-led (i.e. increases in the wage share increase the rate of growth) or profit-led (i.e. increases in the profit share increase the rate of growth). The works of Michał Kalecki [Kal35, Kal43, Kal62, Kal68] contribute to the theory of the dynamics of economic growth and income distribution for economists who take the view that the unemployment of resources, such as labor and capital, can persist in the economy over long periods of time [Dut12b]. In his theoretical work, Michał Kalecki argues that the determination of output level and income distribution are merged in a unique theory, so that "the long-run trend is but a slowly changing component of a chain of short-period situations; it has no independent entity, and the two basic relations mentioned above should be formulated in such a way as to yield the trend cum business-cycle phenomenon" [Kal68]. He also holds that income distribution is crucially determined by the price setting behavior of oligopolistic firms, which depends on the degree of competition and on the strength of labor unions, i.e. "the degree of monopoly power" [Kal71, Dut84, SO04].

Meanwhile, the debate has focused more on the effects of income distribution than on its determinants. Income distribution has an important impact on savings. When the paradox of thrift exists in the long, as well as in the short term, an increase in the saving rate, which is usually intended to cause faster growth since saving is thought of as sacrificing current consumption for future consumption[6], actually reduces output. This is because an increase in saving implies a reduction in effective demand, and firms react to this by producing fewer goods. New Keynesian[7] economists would agree with this line of reasoning for the short term. However, the Kaleckian models show that the paradox of thrift also may hold in the long term, i.e. an increase in the propensity to save reduces the long-run rate of growth. Although Post Keynesian models emphasize the consequences of income distribution for growth, they pay much less attention to how growth and other factors affect income distribution [Dut12a]. Technological progress affects income distribution as well as employment [SO04]. If there is a labor-displacing technological change, a shift in income distribution away from wages toward profits can result in a decline in demand if the marginal propensity of capitalists to consume is lower than the marginal propensity of workers to consume [For03, For06].

[6] Current saving flows (made by sacrificing current consumption of consumer goods) are not necessarily used by investors (in making future consumption goods). If it were true that more real saving reduces real interest rates, that would tend to raise real investment. However, interest rates are determined by supply and demand in the money markets. There are no physical markets where foregone consumption goods can be exchanged for extra investment goods, at a price called the real interest rate. Real interest rates are computed by dividing money interest rates by the inflation rate.

[7] New Keynesian macroeconomics has been absorbed by the neoclassical paradigm and is referred to in the economics literature as the new neoclassical synthesis, which dominates mainstream economics.

3.4.4 Financial Instability

According to Hyman Minsky [Min86], the fundamental propositions of the financial instability hypothesis are "capitalist market mechanisms cannot lead to a sustained, stable price, full-employment equilibrium" and "serious business cycles are due to financial attributes that are essential to capitalism". Furthermore, Hyman Minsky [Min86] pointed out that

> ... the financial instability hypothesis stands in sharp contrast to the neoclassical synthesis, which holds that unless disturbed from outside a decentralized market mechanism will yield a self-sustaining, stable-price, full-employment equilibrium. The difference between the two views reflects the way in which finance and financial relations are specified. The financial instability view makes much of the way in which ownership or operating control of capital assets are financed, something standard theory ignores. Further, the financial instability theory points out that happens change as institutions evolve, so that even though business cycles and financial crises are unchanging attributes of capitalism, the actual path an economy traverses depends upon institutions, usages, and policies. In the final analysis, history remains history, although the range of what can happen is limited by basic economic relations.

Steve Keen [Kee95] established a model of the "financial instability hypothesis" based on Goodwin's limit cycle model, i.e. the tendency of capitalists to incur debt on the basis of euphoric expectations; the importance of long term debt; the destabilizing impact of income inequality; and the stabilizing effect of government. This Goodwin-Minsky-Keen model demonstrates the prediction of Minsky's hypothesis, i.e. that expectations of profit during economic booms may lead profit-earners to incur more debt than the system's capacity of financing allows; and that debt-induced depression can induce an economic breakdown. In his model, Keen introduced the concept of complexity to Minsky's "financial instability hypothesis" by modeling the rate of change of real wages, net investment, capitalists debt use to finance investment, the rate of change of output, the rate of change of employment, the rate of change of the employment rate, the rate of change of workers' share of output, the rate of change of the debt ratio, and the rate of change of bankers share in a dynamical system environment. In the part of economic policy, Keen continued his model with Minksian government to stabilize an unstable economy by introducing the variables on government behavior, i.e. the rate of change of government spending, the rate of change of taxation, the rate of change of capitalist debt, and the rate of change of government debt.

3.5 The Model

In ecology, a basic system describing the dynamics of the relationship between a single prey species and a predator species is the Lotka-Volterra equations [Hol73, ML75, Lev92, Dro01, KF11, DB12]

$$\frac{\mathrm{d}x}{\mathrm{d}t} = (A - By)x, \quad A, B > 0, \tag{3.3a}$$
$$\frac{\mathrm{d}y}{\mathrm{d}t} = (Cx - D)y, \quad C, D > 0, \tag{3.3b}$$

where x is the population of the prey, and y is the population of the predators, and A, B, C, D are system-dependent constants. The prey population, x, grows exponentially in the absence of y, but is reduced for non-zero y as a result of predation on x. The predator population, y, depends for sustenance entirely on prey, x, and decreases as the value of x decreases. With reduced pressure from the predator, the x population begins to grow until it again represents a significant food source to y. Thus the y population grows until it has over-depleted x and then decays, and so the cycle continues. Although the Lotka-Volterra equations are highly simplified and somewhat unrealistic (e.g., the exponential growth in prey in the absence of predators), they prove instructive, and with modification are very useful [KF11]. Scaling x, y, and t, the equations can be simplified to

$$\frac{\mathrm{d}x}{\mathrm{d}t} = (1 - y)x, \tag{3.4a}$$
$$\frac{\mathrm{d}y}{\mathrm{d}t} = \alpha(x - 1)y, \quad \alpha > 0, \tag{3.4b}$$

where α is a system-dependent constant to replace the constants A, B, C, and D in Lotka-Volterra equations above. Hence α can be viewed as a characteristic of any given system that follows the Lotka-Volterra equations.

In economics, Richard Goodwin introduced the Lotka-Volterra equations to represent the dynamical links between the employment rate and the income distribution [Goo67]. The Goodwin equations have become important tools for macrodynamic analysis recently [RJ09, VHT11, RJ11b, RJ11a, GCL12]. In his recent work, *Post Keynesian Perspectives and Complex Ecologic-Economic Dynamics*, J. Barkley Rosser, Jr. concluded the Goodwin equations in the form below [RJ11b]

$$\frac{d\lambda}{dt} = \lambda\left(\frac{1-\omega}{\nu} - \alpha - \beta\right) \tag{3.5a}$$

$$\frac{d\omega}{dt} = \omega(P(\lambda) - \alpha) \tag{3.5b}$$

where ω is the wage share, given by the ratio of wage to output, λ is the rate of employment, given by the ratio of employed workers to the size of the labor force, $P(\lambda)$ describes a linear Phillips curve relation [AD11, LK07] between the rate of employment and the rate of change of wages, ν is the capital-output ratio, the accelerator relation α is the rate of technological change, and β is the rate of labor force growth. J. Barkley Rosser, Jr. correctly considers the implications of complex ecological economic dynamics from a Post Keynesian perspective, and argues that non-linear, catastrophic, chaotic, and other complex dynamics reinforce the conceptual foundations of the Keynesian notion of uncertainty, and links predator-prey models to Post Keynesian macro-dynamic models [RJ01, RJ09, RJ11b].

The Goodwin equations can be interpreted as implying that as the employment rate begins to increase, the wage share increases, and that means the profit share diminishes. Hence profit diminishes in the short run, investment decreases, then the employment rate decays. And vice versa, as the employment rate begins to reduce, the wage share decays, and that means the profit share increases. Hence profit rises in the short run, investment grows, and then the employment rate increases.

The motivation for Goodwin's theory is the pre-Keynesian economic assumptions that saving is determined by investment and that profits provide all the saving in the economy. Since first introduced by Richard Goodwin, his version of the equations has been interpreted in terms of other scenarios [Fla09], including the Keynesian view of effective demand as the prime economic driver, substituting for the pre-Keynesian view of saving-driven investment [FM11]. This theory describes the economy in terms of interactions between the degree of capacity utilization and income distribution.

Following the Keynesian tradition of effective demand, and emphasizing the dynamics of entropy, a simple model is developed by assuming that entropy production[8] is determined by only two factors : the waste arising from capital stock

[8] In a steady state economy, the dissipation of capital stocks has to be compensated for, which raises the question to qualify entropy produced for this compensation [KM01]. Unfortunately, no reliable quantitative estimates of the stock size have been available yet, and there is none of the dissipation rate. We here avoid introducing the measurement of the system for capital stock, but focus on the idle capacity which produces the loss of efficiency of the system and

and the waste from labor stock. The capital waste is seen as the gap between full and actual utilization of capacity, while the labor waste is seen as the unemployment rate, i.e. the gap between full and actual employment of available labor, that is

$$\partial\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)\Big/\partial x > 0 \tag{3.6a}$$

$$\partial\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)\Big/\partial y < 0 \tag{3.6b}$$

where E is the stock of entropy, with the unemployed labor x and the employed capacity y being given by Equations (3.4). During economic prosperity, once employment begins to grow (thus increasing incentives), because output is still at a higher level in short run, the utilized capacity rises. During an economic recession, due to extensive unemployment and a decaying wage share, insufficient consumption demand brings with it increasing underutilized capacity. During an economic depression, saving increases but investment and consumption decay, so unutilized capacity continues to increase. During economic recovery, profit begins to grow and hence so does investment, causing unemployed labor to diminish and utilization to eventually fall.

Furthermore, in order to reflect the relationship between the unemployment, the utilization of capacity, and the production of entropy, we specify Equations (3.4) and (3.6) into

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{x}{y} \tag{3.7}$$

and $\alpha \in \{1, 2, \ldots, 10\}$. Given initial value $x_0 = 2$, $y_0 = 1$, and $E_0 = 10$, time span $t \in [0, 20]$. The equations were solved using the Runge-Kutta method[9] with 5th order truncation error to estimate the local error in the 4th order Runge-Kutta method to choose the appropriate step size.

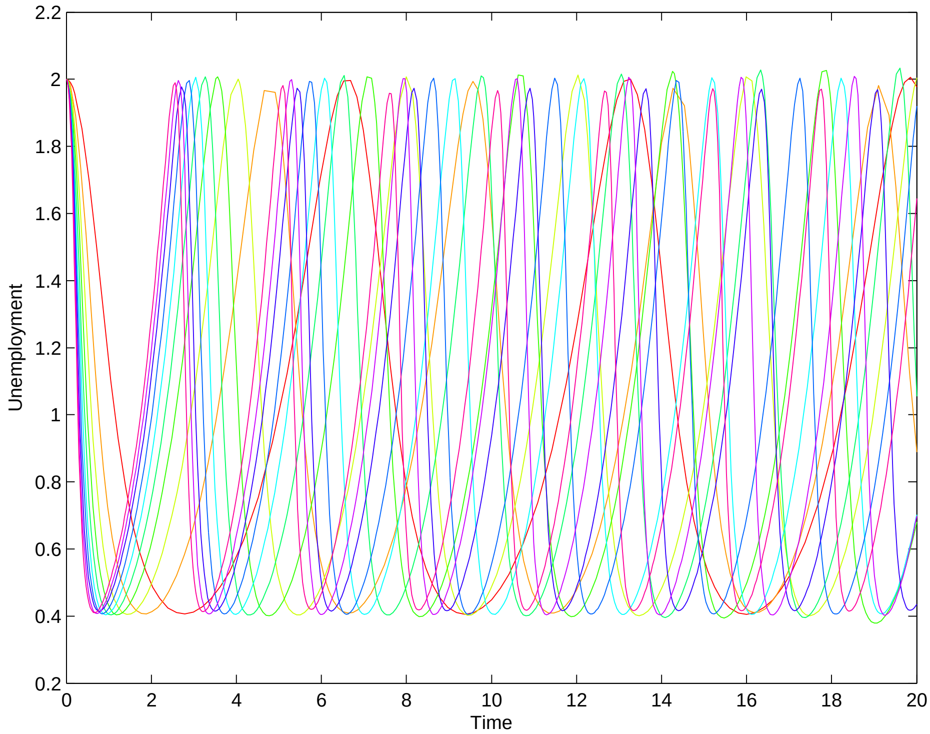
3.6 Results

This section shows the solutions of Equations (3.4) and Equations (3.6) under the combination given by Equation (3.7). Since the introduction of α in order to scale and simplify the Lotka-Volterra system, it is expected that the variable

needs more compensation that produces the extra entropy.

[9] The Runge-Kutta method will evaluate the right-hand function using a greater number of points, essentially seeking to compute the slope at the current and future points in an effort to improve the accuracy of the prediction [BGP09].

Figure 3.1: Unemployment rate over time for different values of the technology growth rate. The variable representing the unemployment exhibits fixed-amplitude periodic motions with different frequency according to different values of α.



representing unemployment has a fixed-amplitude periodic motion with different frequency according to different values of α. Hence, a lower value of α produces a less frequent motion. The variable representing the utilization of capacity is also a vibration with increasing amplitude and rising frequency accompanying a bigger value of α. Hence, a lesser value of α produces a lower amplitude and frequent motion. The variable representing the production of entropy is an increasing function despite the rate of growth depending on the value of α where a smaller α means a slower growth.

Figure 3.1 displays the different examples of the dynamics of unemployment for different values of the rate of technological change, α. A lower value of α produces a less frequent motion.

Figure 3.2 shows the effects of different values of the rate of technological change, α, on the dynamics of capacity utilization. A lower value of α produces a smaller amplitude and less frequent motion.

The relationship between unemployment and capacity utilization is given by Equations (3.4) and shown in Figure 3.3.

Figure 3.2: The effect of rate of technology growth on capacity utilization. The variable representing the utilization of capacity is also a vibration with increasing amplitude and rising frequency accompanying a larger value of α.

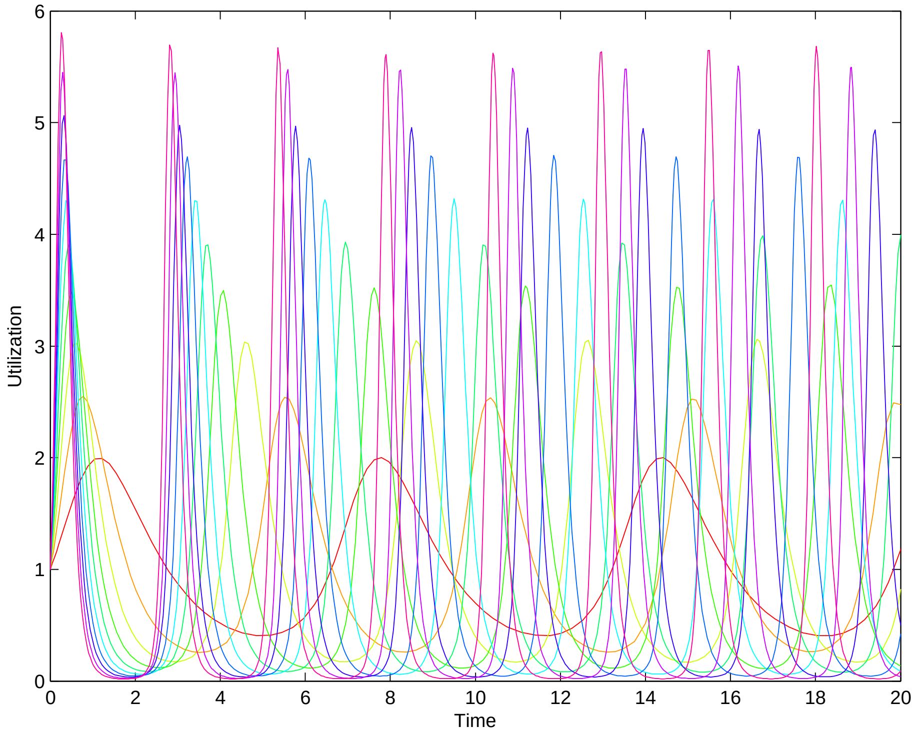


Figure 3.3: Unemployment versus capacity utilization for different rates of technology growth. The variable representing the production of entropy is an increasing function despite the rate of growth depending on the value of α.

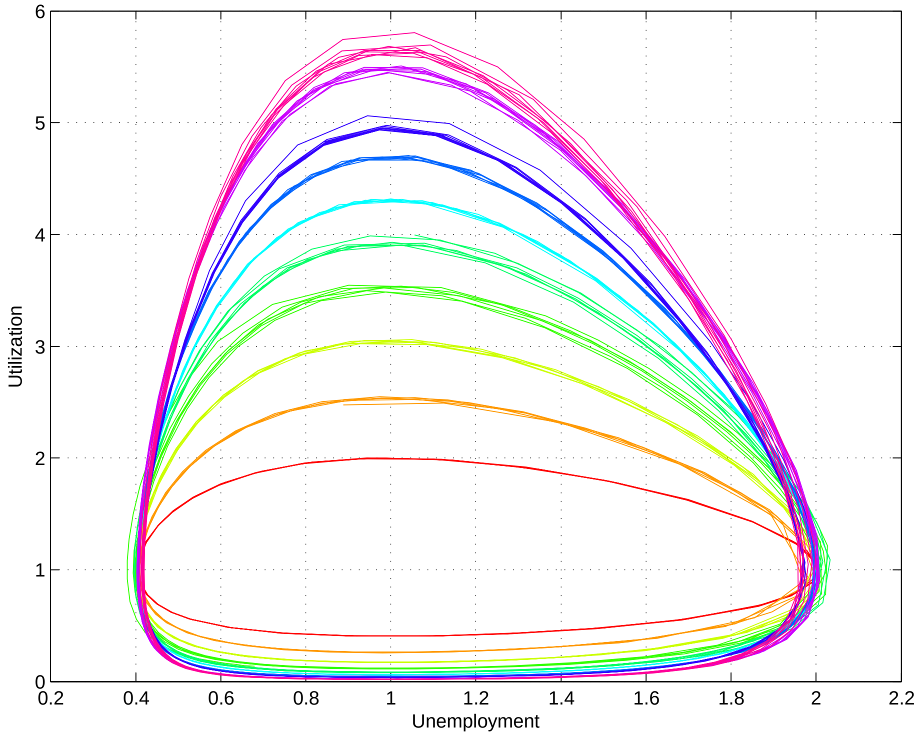


Figure 3.4: The stock of entropy production and its dependence on the technology growth rate. A higher amplitude cycle is generated by a bigger value of α.

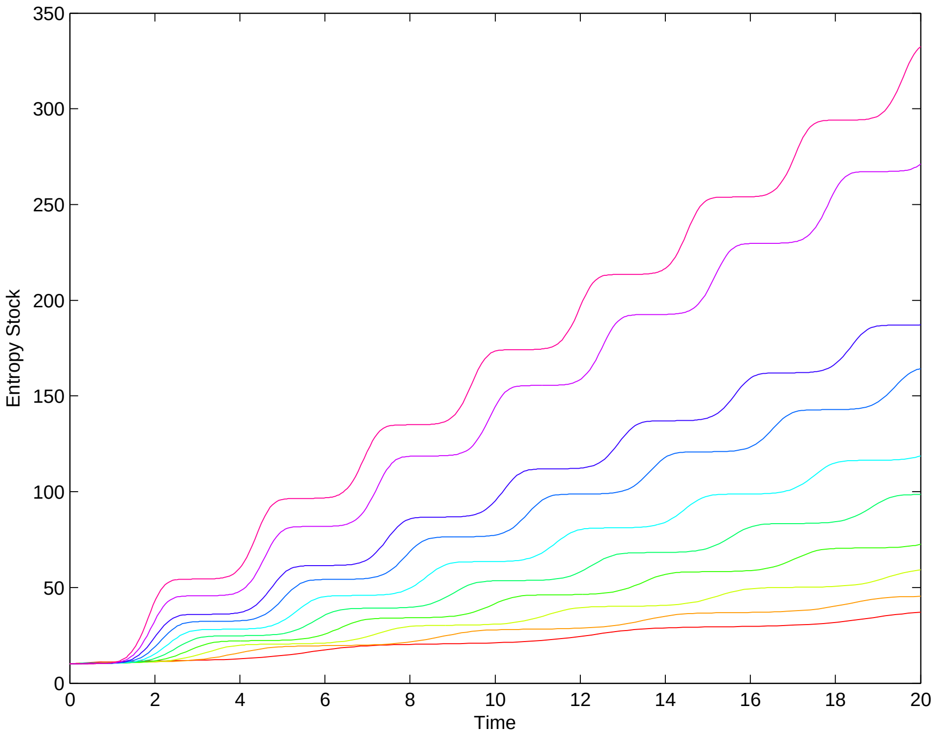


Figure 3.4 shows the dependency of the entropy stock on the rate of technological change, α. A smaller α means a slower growth.

As shown in the figures, larger and more frequent fluctuations in the economy lead to more entropy. That means, given different scenarios of unemployment and utilization of capacity for the macro-economy, different production levels of entropy are induced, where larger value of α defined in Equations (3.4) represents more frequent fluctuation in unemployment, and larger amplitude and more frequent fluctuation in utilization of capacity, and leads to more entropy production. Therefore mitigation of business cycles on either amplitude or frequency can increase the efficiency of the system, hence weakening the production of entropy.

3.7 Conclusion and Discussion

The inclusion of entropy production as a concept relevant to business cycles is a significant contribution that has the potential to promote a broader understanding in many areas at the interface of economics and ecology. However, it has not received attention, despite economists' interest in the effects and causes of business cycles, and the development of explanations according to different economic schools of thought [Zar85], as well as the contributions from ecology to the concept of entropy production and maximum entropy theory in natural systems [MB10]. This is because of the challenge of linking the underlying mechanisms of the impacts of business cycles on entropy production. Entropy production can be thought of as a natural phenomenon associated with economic and human activities which can reflect the requirement of energy or useful work [AW05] for economic growth. However, the interdependency between entropy production and the energy requirement for economic development is unclear. The Goodwin equations relating wage share and unemployment [Goo67] and its recent application to the relationship between capacity utilization and income distribution [RJ11b] provide an opportunity to incorporate the concept of entropy production in a description of economic cycles. The modification of the Goodwin equations using the rate of capacity utilization and the rate of unemployment is based on the understanding of energy wastages, i.e. that insufficient utilization of existing capital and under-full employment are two economic wastages that contribute the unnecessary energy demands. The major task then becomes building the relationship between entropy production and the rate of capacity utilization and the relationship between entropy production and the rate of unemployment, then developing an acceptable paradigm of entropy production via an equation reflecting path dependency. This is a difficult problem to solve, since large amounts of data would be required in order to discover the possible interdependency between these three variables. However, different understandings on entropy production make the process controversial and challenging.

The main achievement of this section is to seek a simple and acceptable method of integrating entropy production into the macroeconomic dynamic system to review the effects of macroeconomic activities on entropy and then to address the problem of forecasting entropy produced by business cycles. In general, predicting the entropy produced by business cycles is an extremely difficult problem, and it is necessary to focus on a relatively well understood explanation of business cycles. A simple scaling ratio between unemployed labor and underutilized capacity is chosen. We have detailed the basic principle of a Lotka-Volterra equations-based prediction of dynamics in ecological-economic applications. We have also demonstrated, using the Runge-Kutta method with 5th order truncation error to estimate local error in the 4th order Runge-Kutta method to choose the appropriate step size, that our business cycles approach can indeed fully construct the path dependency of entropy production and dynamics, based on which the recognition of capacity utilization and employment can be anticipated.

The results of this chapter suggest that extended Lotka-Volterra equations can be useful in understanding the impact of business cycles on the entropy production and the essential path dependency of entropy.

Chapter 4

A River Basin Economy

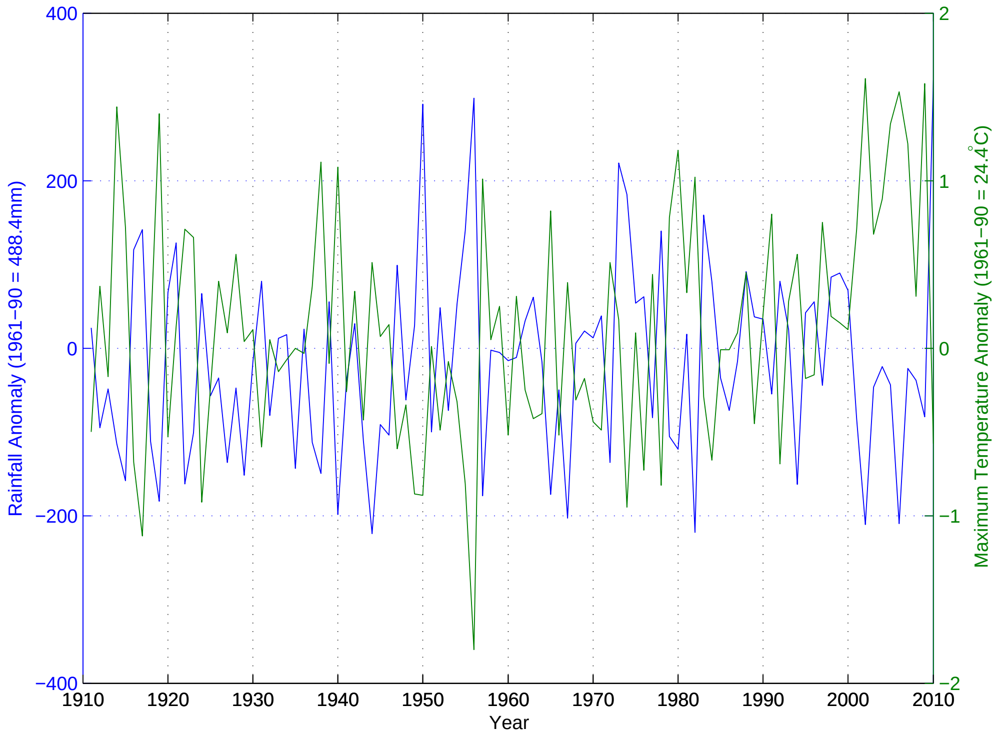
A river basin is generally defined as the area drained by a river and its tributaries where surface run-off collects, often comprising sub-basins of drainage divisions. River basin economics used to be a branch of regional economics[1], having links to geography, urban and regional planning, environmental science, political science, sociology, and other disciplines.

The Murray-Darling basin has a highly volatile climate and drought conditions are common. For example, the "Federation drought" (1895-1902) was associated with dry conditions covering most of the eastern two-thirds of Australia, and the average annual inflow was only 5.4 billion m^3 [CC08, WLW+11]. From 1937 to 1945, south-eastern Australia was subjected to another multi-year drought, known as the "World War II drought" [BD05, VKK09, GLLO10, WLW+11]. Since 1997 a large part of southern Australia was gripped by the most severe drought ever, the so-called "Big Dry", a prolonged dry period in Australia that did not break until 2009 [WLW+11, MW05]. Increases in Australia's average temperature of 0.7 degree Celsius from 1910 to 1999, with the largest increases occurring since about 1950 [QSCK10], are consistent with global trends ascribed to climate change, and the observed warming in the basin fits this projection. An enhanced greenhouse effect is likely to have an influence on increasingly dry conditions in the basin. At the very least, a rise in temperature will exacerbate the dry conditions during ongoing drought [MT08]. Historical data provided by the Bureau of Meteorology, Figure 4.1 shows, respectively, an annual rainfall anomaly[2] [Bur13c] and maximum temperature anomaly [Bur13a] over the period 1911-2010. The natural environment of the Murray-Darling basin has experienced increasing maximum temperatures and decreasing rainfall, particularly in

[1] Recent examples include a regional model, Climate and Regional Economics of Development (CRED) [ASB13], and a dynamic multi-regional computable general equilibrium model, The Enormous Regional Model (TERM) [QSQP09, WG11].

[2] The time series anomaly is a new time series that describes the difference between the original series and its average.

Figure 4.1: Annual rainfall and maximum temperature in the Murray-Darling basin from 1910 to present

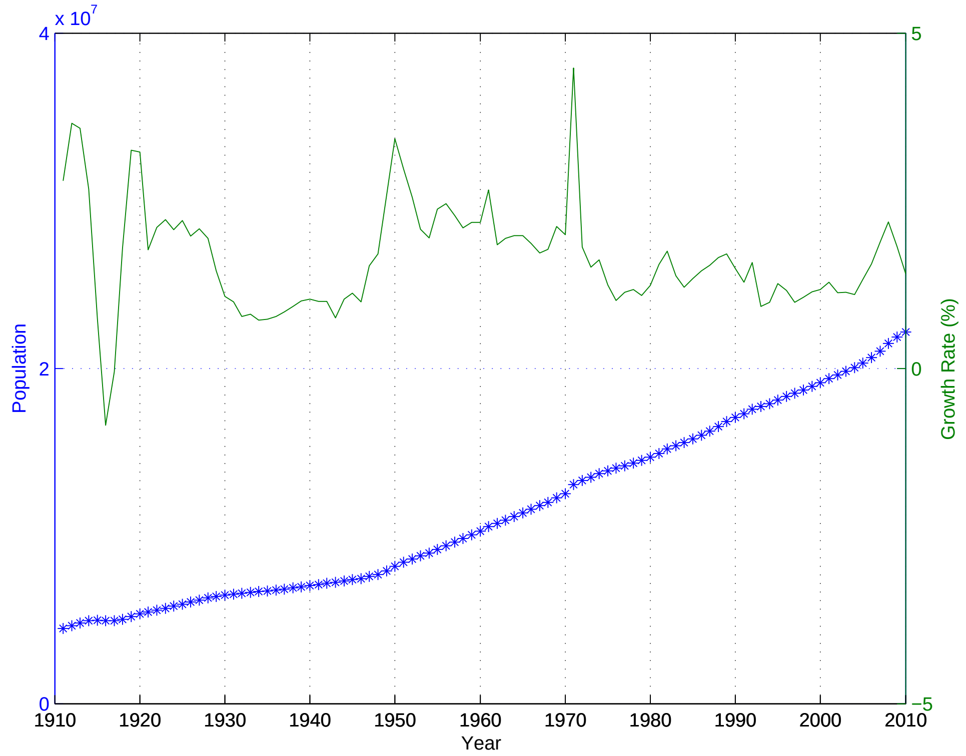


the most recent decade. According to the Year Book Australia 2012 [Aus12], temperatures were relatively stable until 1950, and since then have followed an increasing trend.

Australia's average population growth rate for the period 1911-2010 was 1.61% annually, and total population has grown nearly 5 times from less than 4.5 million to more than 22 million. Figure 4.2 displays this trend using data from the Australian Historical Population Statistics [Aus13b] till 1991 and Australian Demographic Statistics [Aus13a] from 1992 onwards. Starting from mid 1970s the growth rate became relatively stable.

Australia's average GDP growth rate for the period 1911-2010 was 7.79% annually, and total current prices GDP has grown nearly 1,820 times from less than 685 million to more than 1240 billion. Figure 4.3 provides a time series for GDP over the period 1911-2010. As comparable time series are not available for the whole period, four overlapping data sets are shown for each aggregate. The first three data sets covering the period of 1911-1960 are taken from the Year Book Australia 2001 [Aus01]. The fourth data set covering the period 1960-2010 is taken from the 2011-2012 issue of the Australian System of National Accounts [Aus13d]. Although there are conceptual and methodological differences between

Figure 4.2: Historical population and its growth in Australia from 1910 to present

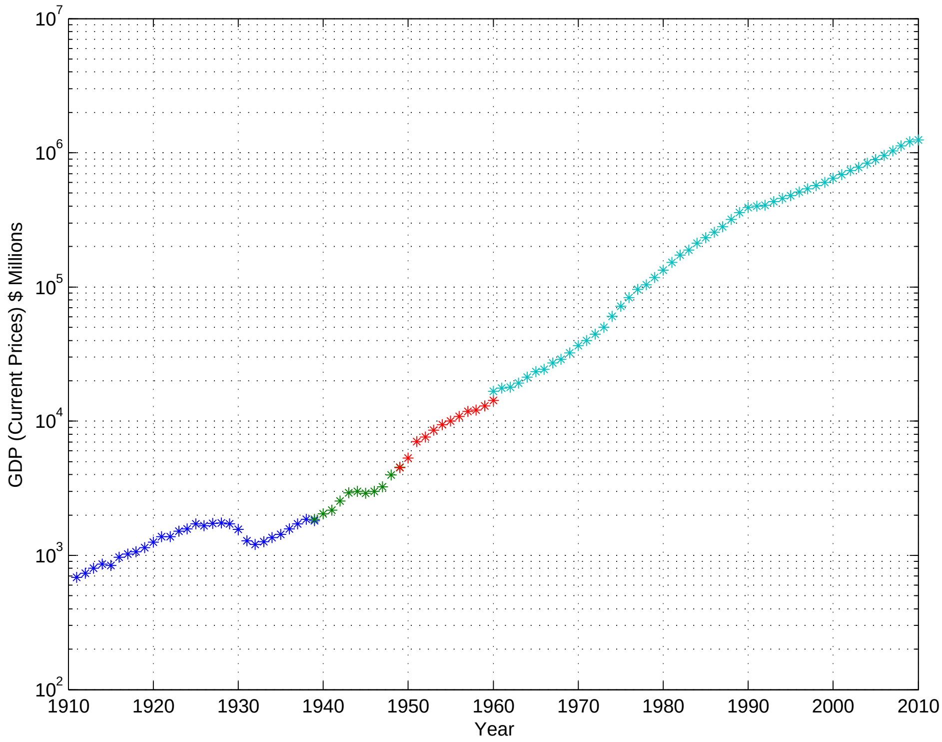


the estimates for the various time periods, it provides the best available time series for the Australian GDP over the last 100 years.

Figure 4.4 provides the time series for wage share, i.e. the share of compensation of employees in GDP over the period 1960-2010, and the time series for unemployment rate over the period 1978-2010. The wage share has fluctuated throughout the last 50 years with several peaks and troughs. In 1960, the wage share stood at 46.6%, and increased to 52.2% in 1972, before rapidly reaching a peak of 57.2% in 1975. This high wage share persisted for four years, before it fell rapidly to below 53.3% by 1979. It then increased again, reaching a peak of 55% in 1983. The wage share has been generally falling since then. In 1988, the wage share stood at 49.7%, and fluctuated at around this rate until 2010. The rate of unemployment also has fluctuated throughout the last 30 years with two peaks. In the early 1980s, the unemployment rate increased rapidly from around 5.2% to a peak of 10%. It then decreased to 6% at the end of the 1980s before it rose rapidly to above 10.6% by 1992. It then decreased again, reaching a lower level of 4.2% in 2007 before it increased again to above 5.7%.

Under a panoramic, yet fragmentary and fuzzy, view of Australian macroeconomy and ecosystem services in the Murray-Darling basin, the chapter pro-

Figure 4.3: Historical GDP in Australia from 1910 to present

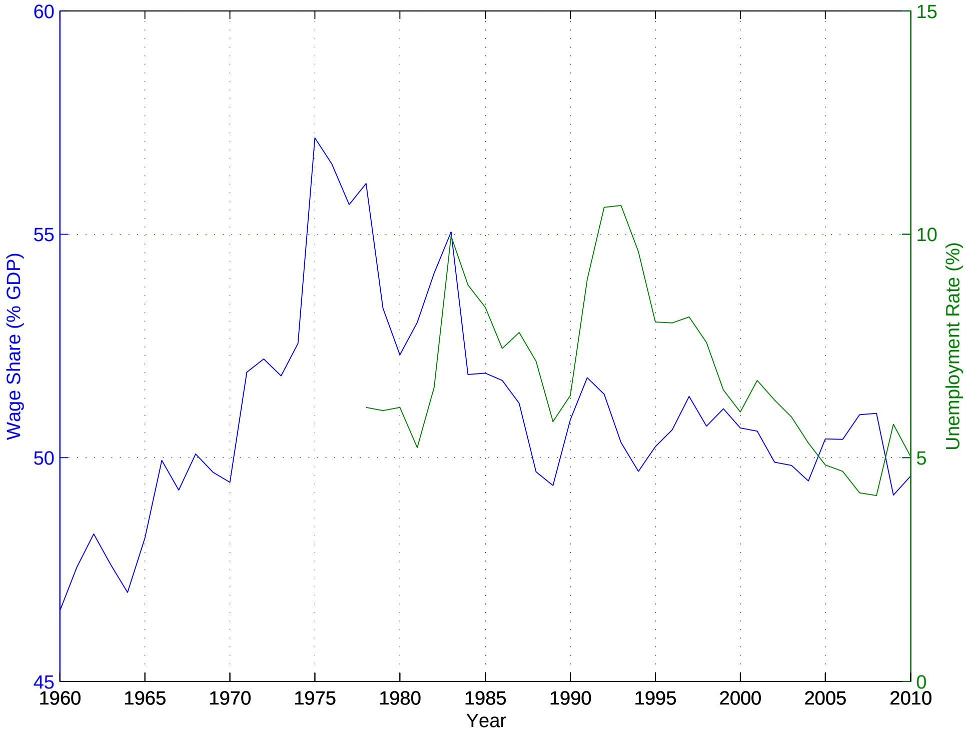


ceeds as follows. Section 4.1 presents a description of previous models of the economy of river basins following two contrasting approaches, i.e. a bottom-up micro-based price-oriented approach, and a top-down macro-based policy-oriented approach. It also includes a review of the comparison for these two kinds of approaches. Section 4.2, section 4.3, and section 4.4 present the agent-based models for micro land/water users, for micro food consumers, and the model for the system-based macro-economy, respectively. Section 4.5 describes the framework for the Murray-Darling Basin Economy Simulation Model as a summary for further modeling in the next sections. Then, section 4.6 and section 4.7 describe the results for estimation of parameters, interpret these estimates and the results for calibration. Section 4.8 describes the forecasting results. Section 4.9 discusses the findings and concludes.

4.1 Methodology and Previous Literature

Neoclassical environmental/ecological economic arguments propose numerous analytic methods to calculate the cost of ecosystem services in order to approach economic optimization and sustainable development. These include

Figure 4.4: Historical wage share and unemployment rate in Australia from 1960 to present



(1) economic and financial valuation, including willingness-to-pay (WTP), determined from the estimated economic value for the use of ecosystem services [VMM+05, PVASPV08, GTEMH+12, Pin12], the polluter pays principle (PPP) that ensures those who use society's scarce natural resources compensate the public for their use [CO92, Ayr08], and individual transferable quotas (ITQs) which are a measure of capacity and reflect the level of investment on the basis of history [Bro00, BSH09, HHFT12];

(2) a free market approach that assumes that competitive equilibrium automatically exists and persists indefinitely [Arr62, MZ74];

(3) the institution of private property, which is said to incentivize humans to make a system more "perfect" in the sense of efficiency of use [Har68, Qui93, Das96, Bro00];

(4) central government-based conservation that controls and allocates natural resources [BO95]; and

(5) economic growth that follows the so-called environmental Kuznets curve (EKC) which asserts that pollution follows an inverted-U path with respect to economic growth, and once the economy grows beyond the peak pollution rate, environmental health will be restored or repaired automatically, now that the population has grown rich enough to care about the environment they daily inhabit and make political demands for its restoration to a more pristine state [GK94, Ste04, Ayr08].

Once concentrating on river basin water management and river basin economy, an integrated hydro-economic model[3] captures the complexity of interactions between water and the economy [BH08, PVASPV08, GJ11, KNBJ11]. For example, such a model should be a fundamental tool for assessing management and infrastructure strategies to improve the economic efficiency of water use in the context of competition over scarce water resources. Such a model can reproduce the physical behavior of the system, with a realistic representation of the different surface and groundwater resources, including their interaction, and the spatial and temporal variability of resource availability. Such a model might also incorporate the value of water for different urban, agricultural and industrial uses and users.

Two main approaches are distinguished: bottom-up approaches which explicitly specify options for water usage, food production and food consumption using

[3] As we focus on an integrated ecological-economic system, we will not attempt to cover hydrological models alone. Famous models include the micro-scale Integrated Quantity and Quality simulation Model (IQQM) for water resource and salinity management [SPC96], macro-scale hydrological models based on future climate change [CDP+10], water trading [DKH+12], and water footprint [HM12]. An excellent historical review on hydrological modeling has been given by [Sil06]. An excellent review on catchment water balance modeling in Australian history is provided by [Bou05].

both ecological and economic parameters; and top-down approaches which rather are oriented to analyzing the causality relationships and possible interdependencies between macroeconomic variables. In the following paragraph, we survey previous studies that have incorporated endogenous technological growth[4].

4.1.1 Sustainability: Weak versus Strong

According to the Food and Agriculture Organization of the United Nations (FAO), sustainability means "ensuring human rights and well-being without depleting or diminishing the capacity of the earth's ecosystems to support life, or at the expense of others' well-being". Similarly, according to the Report of the World Commission on Environment and Development, *Our Common Future* [Wor87], sustainable development is a type of "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Although people have descriptions of sustainability and sustainable development like these [Ste97, SP00, ADM03, BV03, ADG+04, Tai06, PS09, Hea11, DQB11, RCC11, BAB+12], the meaning of the terms "sustainability" and "sustainable development" has remained unclear and diluted. Therefore, the notion of sustainability has become extremely wide.

As a descriptive concept, sustainability comes in two varieties, weak and strong: We are weakly sustainable if what we are doing will let future generations achieve our living standards or better, or if we aren't compromising the ability of future generations to meet their needs, which is the core of the World Commission on Environment and Development definition. We are strongly sustainable if all forms of life on our planet can be sustained regardless of any economic trade-offs.

To be more precise, weak sustainability [SERB03, Sch09] requires that for economic growth to be considered sustainable, the total aggregate stock of capital, both physical and natural, should not decline over time. In other words, even if there is an environmental drag created by pollution and resource exploitation, or more broadly the reduction of natural capital, economic growth may still be sustainable provided that the level of physical (and other) capital increases at least as quickly as natural capital is depleted. By contrast, strong sustainability, according to Herman Daly [Dal96, DF03], would require maintaining both humanly created and natural capital intact separately, on the assumption that they are complements rather than substitutes in most production functions.

[4]We do not attempt in this section to provide an entirely exhaustive survey of all bottom-up and top-down studies accomplished. Instead, the studies reviewed here represent a considerable number of important methodological developments in the hydro-economic field, which together permit emphasizing the most important conclusions to retain from large-scale models incorporating water usage.

4.1.2 Micro-scale Analysis: Inevitably Optimizing

For advocates of complete substitution (zero complements) between capitals, or for advocates of partial substitution (partial complements), or for advocates of zero substitution (complements only), optimization is a direct approach.

Particularly for substitution advocates, Harold Hotelling's pioneering paper *The Economics of Exhaustible Resources*[5] provides their preferred model of optimal depletion [Hot31]. For example, the model of optimal growth theory [Arr09] defines a net price[6] path as a function of time, while maximizing rent as the full extraction of a non-renewable natural resource is approached [RCC11]. It establishes that a necessary condition for the efficient intergenerational allocation of exhaustible resources is that the price of an exhaustible resource should increase at the world interest rate (including a risk premium). Microeconomic bottom-up approaches to environmental economics typically apply agent-based modeling to problems of ecological resource usage.

In a typical resource management scenario, an initial stock of natural resource K_0 is to be exploited over a period $t \in [0, T]$, where t is the running time and T is the end of the period which may or may not be predetermined. At any instant of time the remaining stock $K(t)$ is given and the exploitation rate $q(t)$ generates the instantaneous benefit $u(K(t), q(t), t)$ and changes $K(t)$ according to

$$\frac{\mathrm{d}}{\mathrm{d}t} K = G(K(t), q(t), t) \tag{4.1}$$

where $G(K(t), q(t), t)$ represents the natural resource flow (e.g., growth, replenishment). If we denote Γ as the set of all feasible policies, an exploitation policy $\{T, q(t), t \in [0, T]\}$ generates an economic payoff

$$\int_0^T u(K(t), q(t), t) e^{-\rho t} \mathrm{d}t + e^{-\rho T} v(K(T)) \tag{4.2}$$

where ρ is the rate of discount over time and $v(K(T))$ is the post-planning value (the present value at time T of the benefit stream over the post-planning period $t > T$). The policy is feasible if it satisfies some given constraints on T and on $\{T, q(t), t \in [0, T]\}$, e.g., T is given or restricted to a certain range, and the stock $K(t)$ is positive or bounded in some range and $q(t) \leq 0$ for all $t \in [0, T]$. The optimal policy is the feasible policy that maximizes (4.2) subject to (4.1) given

[5] The formulation of the resource management problem considers exhaustible (non-renewable) resources and characterized optimal extraction policies in different market settings, using the calculus of variations to verify economic reasoning. The development of optimal control and dynamic programming methods opened the way for a wide range of extensions, including the incorporation of uncertainty of various kinds and forms.

[6] Net price is defined as the difference between price and marginal extraction cost [Hot31, Sol74, HK13].

$K(0) = K_0$. The value of (4.2) obtained under the optimal policy is denoted $V(K_0, \Gamma)$ and is called the value function.

4.1.3 Macro-scale Analysis: Three Roads Lead to Two Sustainabilities

In macroeconomic top-down approaches to sustainable development, ecological and environmental economists prefer using neoclassical theory[7] which includes New Classical economic growth theory [Arr62, Luc88, AH90, Rom91, Rom94, MRW92] and New Keynesian economic growth theory [Sol56, GS88, Man89, MRW92, Rom93]. In his paper *The Economics of the Environment*, Partha Dasgupta [Das96] highlights that "macroeconomic models involving long-run production and consumption possibilities typically make no mention of the environmental resource-base; the implicit assumption being that natural resources aren't scarce now, and won't be scarce in the future." For instance, Robert Solow in his frequently-cited paper *A Contribution to the Theory of Economic Growth* [Sol56] assumes that "there is no scarce nonaugmentable resource", and this contributed to the later New Keynesian economic growth theory. Furthermore, in the popular aggregate production function, natural resources are seen as one kind of capital input, making (constant) elasticity of substitution a suitable assumption underlying the smooth curve displaying trade-offs between numerous labor-capital combination technologies. Technological progress is assumed to be exogenous, lifting the production function to higher levels as "logical time" passes [Sol57]. In his paper *On the Mechanics of Economic Development*, Robert Lucas [Luc88] also states that

> there are two kinds of capital ... in the system: physical capital that is accumulated and utilized in production under a familiar neoclassical technology, and human capital that enhances the productivity or both labor and physical capital, and that is accumulated according to a law having the crucial property that a constant level of effort produces a constant growth rate of the stock, independent of the level already attained.

[7] A survey of the literature on development theory covering from 1940s to mid 1960s has been given [HM64], while the literature on development involving both exogenous and endogenous factors from the mid 1950s to 1990 is reviewed [SIM90a, SIM90b]. For modern macroeconomic analysis, three competing approaches exist [Nig06] in contemporary macroeconomics: New Classical Economics, based on the neoclassical notion of an inherently self-regulating economy characterized by steady growth and requiring minimal government intervention; Post Keynesian Economics, in which the economy is characterized by chronic unemployment and instability problems and an uneven growth process requiring systematic government intervention; and New Keynesian Economics, in which occasional episodes of instability require periodic government intervention and government policy can affect the endogenous growth rate.

In this way, Robert Lucas replaces exogenous technical progress developed by Robert Solow with a kind of endogenous progress due to human capital accumulation.

Contrary to mainstream environmental macroeconomic claims, in recent times ecological economists[8] propose a-growth theory and degrowth theory [Kal11, KKMA12, VDBK12], which suggest that preventing environmental degradation and unsustainability needs technological progress or economic degrowth. As for the degrowth scenario, individuals do face a strict condition of "to profit or to die", but not the economy in aggregate. Yet individuals at the micro scale can continue to profit, even if the overall macro-economy shrinks, because profit does not require expansion, and individuals can make profits in multiple ways other than by increasing production [Law11]. Furthermore ecological macro-economists argue that governments need to set social and environmental limits first (a throughput cap and a job guarantee) and then capitalism does what it does best [Law11], i.e. allocate resources to competing needs through the price mechanism. In economies with capped resources, the most innovative firms will adapt, maintaining profits through qualitative changes and shifting to less resource-intensive production. Caps will reduce resource use to a steady state, "greener" sectors and firms will grow and accumulate, and "blacker" or "browner" sectors will disappear. Whether a green capitalism is possible can be judged by comparing three schools in ecological economics [Law11], i.e. the steady-state school, green-growth school and anti-growth school. In the progress of building the growth paths, the core has always been an ecological production function that represents the production of ecosystem services. This is conceptually analogous to the standard production function used in neoclassical economics to describe how inputs are combined to produce intermediate or final outputs [PS09], and that a balanced local ecological production function would necessarily include solar energy, nutrients, air (or oxygen) and water as factors, along with living organisms (biomass) as capital [Ayr04].

The rest of this subsection will focus on three macroeconomic approaches for analysis, and two distinct concepts of sustainability. Table 4.1 shows all relevant references.

[8] In 2012 a special issue on "environment, sustainability and heterodox economics" in *Cambridge Journal of Economics* displays the variety within heterodox approaches to environmental sustainability. For example, in order to test for the existence of differences in terms of methodological and ideological approaches, a classification of work in the field of environmental policy is introduced [SR12].

Table 4.1: Three roads lead to two sustainabilities

	Weak Sustainability	Strong Sustainability
New Classical	[FS11, Heu12, HF13, HK13, HR13, Bar13]	[HI09, Dou12, BD12]
New Keynesian	[HGDH08, Qui09, HHFT12, Qui13]	[Dal91, Hey00, Law03, Sim06, KK12]
Post Keynesian	[For03, For06, RCC11, SD13]	[Kro10, RTM13, SRM13, SBA13]

Environmental Macroeconomics concerns the study and design of environmental policy following the definition of weak sustainability. In comparison, Ecological Macroeconomics concerns the study and design of environmental policy following the principle of strong sustainability.

New Classical Macroeconomics [FS11, Heu12, HF13, HK13, HR13] incorporates pollution into a standard real business cycle framework that develops the model to address questions about the relationship between environmental policies, macroeconomic fluctuations, and endogenous technological growth that stresses the importance of path dependency in environmental technology policy. The standard real business cycle model is a dynamic stochastic general equilibrium (DSGE) model that has an individual representative consumer who optimizes consumption, leisure, and saving over his or her entire lifetime, and a single representative firm that optimizes capital and labor inputs over its entire lifetime. There are exogenous business cycles that provide shocks to the total factor productivity (TFP), and these affect the returns to inputs and therefore prices in general equilibrium. Consumers and firms respond rationally to these cyclical changes. The standard endogenous growth model assumes persistent growth is obtained by transforming labor from a scarce resource to a fully reproducible factor by interpreting it as human capital.

New Keynesian Macroeconomics [Rom93] recognizes some imperfections in the process of economic adjustment, contrary to New Classical Macroeconomics, whose theory of efficient markets essentially recognizes none. However, like the New Classical approach, New Keynesian macroeconomic analysis usually assumes that households and firms have rational expectations, i.e. it applies a dynamic stochastic general equilibrium (DSGE) model that has a representative consumer and a representative firm optimizing as explained above. The New Keynesian approach asserts that price rigidities can prevent market clearing, so that excess supplies and demands are the result of a lack of price and wage flexibility.

Post Keynesian economics[9] has concentrated primarily on the issues of unemployment from an historical macroeconomic perspective. Post Keynesians have highlighted the theory of effective demand and its consequences - spending drives macroeconomic performance, an economy can experience prolonged bouts of high unemployment, and economic policies are necessary to assure full employment, low inflation, and stable financial markets. Unlike most New Classical and New Keynesian macroeconomic models, Post Keynesian economists do not view the existence of unemployment as a temporary problem that will be solved in the long run once wages, prices, and interest rates are sufficiently flexible; they see unemployment as a problem that will not disappear unless effective macroeconomic policies are used to create jobs. While the New Classical economics and New Keynesian economics view interest rates as equilibrating savings and investment, hence leading to more spending and growth even though demand can be inadequate, Post Keynesian economists hold that history is more important than equilibrium, and that investment is driven by historical profitability gaps and hence "animal spirits". Most New Classical and New Keynesian macroeconomic models assume that demand adjusts automatically to increases in supply or productive capacity, and that long-run growth is thus determined by supply constraints - resources are insufficient or the usages of resources are inefficient. Post Keynesian macroeconomic models, in contrast, highlight growth as being demand-led - wage-led or profit-led. First, demand affects the utilization of productive resources, such as the increase of labor force participation which increases output and makes firms more willing to adopt new technologies, and the increase of utilization of capacity which saves natural resources. Second, demand influences the ability to produce goods in the future and thus the living standards of future generations.

4.2 Food Production

This section covers the simulation model for land/water users (agricultural agents), i.e. food producers. For the entire subsystem, capital stock is detailed and distinguished from agent to agent, while the cost of wages (or wage bill) is seen as a whole, therefore, wage-earners are not distinguished. Each agricultural agent, facing exogenous impacts on water availability from climate change, chooses an investment strategy depending on the feedback from the profit of food in order to increase water efficiency to some extent, which then affects the production of

[9] Post Keynesian Macroeconomics, according to Steve Keen [Kee13], is distinguished from New Classical Macroeconomics and New Keynesian Macroeconomics in six key areas: the role of equilibrium, the nature of expectations, the need for micro-foundations, the model of production, the role of money, and the role of government.

food. Meanwhile, the interaction between agents takes place through the rank for each agent, which determines their capital stocks, and the production costs which affect food profit.

Capital stock is determined by the rank of the agents that is variable in time, and the number of agents which also is a dynamical variable along with the exogenous environment's changes. Capital stock also depends on investment, which is an input flow that adds to capital stock. Water efficiency is a linear function of capital stock, and furthermore determines food production along with water availability, which is a combined consequence of exogenous climate change and endogenous water efficiency. The potential influence of climate change on capital stock is included as a fusion of the concept of strong sustainability where climate change is assumed to reduce the capacity of flow of capital that is independent of human activities. This assumption highlights complementarity rather than substitution between natural capital and human-made capital.

Investment, on the one hand, is determining the capital stock over a given period; and on the other hand, depends on the rate of profit that is defined as the ratio between the profit and the current capital stock. Profit from food is simplified as turnover less cost of food sold, where food turnover depends on the exogenous mark-up rate, i.e. higher food cost means higher food turnover for a given agent. The wage bill is simply determined by the difference between the value of total agricultural output and total profit.

4.2.1 Expenditure and Revenue

The process from food production to food consumption is simplified. Producers buy means of production (physical, non-human inputs) and human inputs at given input prices and wages, then sell the food products with a mark-up on cost of production (output price). The rate of mark-up is endogenously determined by the distribution of income in the macroeconomic system.

Given M agents, for the jth agent ($j = 1, 2, \dots, M$), the expenditure of food production E for a unit in a period $\mathrm{d}t$ follows decreasing capital expenditure to scale of capital stock K, e.g. buying equipment, and increasing operational expenditure to scale [Kal71], e.g. salaries and benefits for employees, i.e.

$$\frac{\partial E_j}{\partial K_j} = \alpha_1 - \alpha_2 \tag{4.3}$$

where K_j is capital stock for jth agent, and all αs are positive parameters, here α_1 is the rate at which the more capital stock adds the larger operational expenditure, while α_2 is the rate at which more capital stock saves the larger capital expenditure. The revenue of food production R_j marks up the food expenditure by a rate of mark-up m that is determined by an amount based on income distribution [Kal68, Har74, Ble89, BM90, Ste99], then for food produced by ith agent, the food price per unit (also known as food revenue per unit sold) is determined by

$$R_j = (1 + m)E_j \tag{4.4}$$

where the food revenue is always marked up to food expenditure at a given rate in production. This is also our micro pricing equation where price equilibrium may exist, but also may never be stable.

4.2.2 Capital, Profit and Investment

Capital consists of six categories, i.e. productive, infrastructure, human, financial, social, and natural. According to Colin Richardson and Peter Romilly [RR08], capital is accumulated by firms in the production and finance sectors, by households and governments, and hence by the economy as a whole. In order to highlight the effect of capital accumulation on the whole economy, it is assumed here that there are only two kinds of capital, the first is the capital which can be accumulated, e.g. infrastructure and productive capital, the second is the capital which cannot be accumulated straightaway, but contributes to technical progress or efficiency that may enhance the capacity of capital accumulation, e.g. human capital, social capital and/or natural capital. Given time t, the stock of the capital of the first kind K_j is assumed to follow Zipf's law[10] [Axt01, New05, YRJ09]

$$K_j = K_1 \left(1 - \frac{\log j}{\log M}\right) \tag{4.5}$$

where K_1 is the capital stock for the biggest food producer at time t. In the subsystem, for a given agent j may not identify her. In essence, j is an index to identify the distance with the biggest producer to jth producer by measuring capital stock, i.e. the index can change from time to time. Similarly, the biggest food producer can change as well in the subsystem, and so can the number of food producers. The output for the jth agent can be

$$Y_j = D_j \times (R_j - E_j) = mE_jD_j \tag{4.6}$$

where D_j is the amount of food production which is determined physically by water supply and food-water efficiency, i.e. $D_j = h_j \times H_j$.

Applying the profitability-investment equation [RR08, RCC11] to build the

[10] Although Zipf's Law initially describes the principle of relative frequency in language [Zip49], George Kingsley Zipf applied it to many phenomena in the bio-social sciences [RJ11a].

relationship between profit and investment, the profitability gap determines the rate of investment, then

$$\frac{\partial I_j}{\partial p_j} = I_j \tag{4.7}$$

where I_j is the investment at which the profitability gap is added onto investment per se positively, and p_j the rate of profit defined as $p_j = P_j/K_j$. The profitability-investment equation shows that only replacement investment will occur when profit-earners expect a profit rate that merely covers the opportunity cost of holding their capital stock constant. If the profitability gap is positive (negative), they will invest more (less) than is needed to keep their capital stock constant.

4.2.3 Water Supply and Efficiency

For a given amount of water supply, the water efficiency reflects technical change, i.e. the accumulation of the capital of the second kind, which makes up the total capital along with the capital of the first kind. For a given technical level, water efficiency also depends on short-run water supply, i.e. if the water supply is sufficient (insufficient) in short run, they will enhance the water use more efficiently (inefficiently), hence

$$\frac{\partial h_j}{\partial H_j} = -\alpha_3 \tag{4.8}$$

where α_3 is the rate at which the increase of water supply weakens the water efficiency. Investment can improve water efficiency with an increasing marginal entropy production [Key36, Dal96] according to

$$\frac{\partial h_j}{\partial I_j} = \alpha_4 \tag{4.9}$$

and

$$\frac{\partial h_j}{\partial S} = \frac{\alpha_5}{h_j} \tag{4.10}$$

respectively, where α_4 is the rate at which the increase of investment strengthens the water efficiency, α_5 is the rate at which the increase of water efficiency is weakened along with the entropy growth. This means that investment enhances the efficiency of water use, however, due to the second law of thermodynamics that matter and energy tend toward a state in which no useful work can be done, because the energy in the system is too diffuse, increasing water efficiency causes the increasing growth rate of entropy production in the system.

Exogenous annual water availability is affected by climate change, and has an impact on annual water supply. The amount of available water supply H_j follows a linear negative function of climate change index G, i.e.

$$\frac{\partial H_j}{\partial G} = -\alpha_6 \tag{4.11}$$

where α_6 is the rate at which the climate change is added onto the change of the water supply negatively.

4.3 Food Consumption

This section covers the simulation for food consumers (agents) at the micro-scale. At time t, for a given agent, their rank determines their wage income and food choice. It follows that lower ranking means higher wage income, and that people with lower ranking choose more expensive food. For heterogeneous consumers, the share of food consumption compared with total consumption depends on wage income according to the Engel ratio that is constant in time in developed countries. Considering that the wage income is far more than the money cost of human energy requirements in developed countries, food share can be more stable than in developing and emerging countries, where the share of food consumption may experience a more severe change along with the rapid economic growth [TD07, Tim12, RTM12] and more volatile food price shock [Ale08, AB11, Caf13, Gou13]. Except for the rate of unemployment, food price and system-based agent ranking, all other variables in the system are closed. Wage income and food consumption occupy the important position: for each agent, wage income determines her share of the total food consumption.

4.3.1 Wage and Food Share

According to Steve Keen [Kee01],

> A microeconomic model which is inconsistent with such things as business cycles, sustained unemployment, commonplace excess capacity, and the importance of credit, is to Post Keynesians an invalid model.

The economic agent's wage here is macro-economy-based, i.e. the aggregate wage is yielded in the macroeconomic system, while the private wage follows a given distribution function, which is independent of the macro wage share, but depends on the given coefficients. Given N consumers (agents) in an economy, the wage income for kth agent ($k = 1, 2, \ldots, N$) follows Zipf's law [Axt01, New05, YRJ09]

$$W_k = W_1\left(1 - \frac{\log k}{\log N}\right) \tag{4.12}$$

where W_1 is the wage for the richest food consumer at time t. At the same time, the share of food consumption $e_k(0 < e_k \leq 1)$ reflects the agents' behavior as it depends on the wage, i.e. the Engel ratio, which is the percentage share of food expenses to the total wage income. This is considered a very important proxy indicator of poverty as it relates to the capacity of humans to access food with their acquired income. Humans having a high Engel ratio have low incomes and a high percentage of those low incomes are used to acquire food for survival. Hence

$$e_k = 1 - \frac{W_k}{W_1} = \frac{\log k}{\log N} \tag{4.13}$$

Hence, given the total population, the Engel ratio depends on the rank of each food consumer.

4.3.2 Food Choice and Consumption

Food choice [Kea10, DGN13, DBSB13] is affected by the rank of food consumer and food price following the assumption that lower ranking consumers choose more expensive food which is produced by smaller land/water users who may use more expensive approaches, such as with organic food that uses less industrial inputs but more labor etc. Therefore, there exists a functional relationship between food choice and wage income, i.e. the kth consumer selects food made by the jth producer, hence

$$\frac{\partial(e_k W_k)}{\partial R_j} = \beta_{j,k} \tag{4.14}$$

where all βs are positive parameters, and $\beta_{j,k}$ is the rate at which the change of wage income for the kth consumer is added onto the change of the consumption of food produced by jth producer positively. Furthermore, it is argued that the matrix $\boldsymbol{\beta} = (\beta_{j,k})_{M,N}$ is sparse, i.e.

$$\boldsymbol{\beta} = \begin{pmatrix} \beta_{1,1} & \beta_{1,2} & \cdots & \beta_{1,N} \\ \beta_{2,1} & \beta_{2,2} & \cdots & \beta_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{M,1} & \beta_{M,2} & \cdots & \beta_{M,N} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & \iddots & \iddots & \iddots \\ 0 & 0 & \iddots & \iddots & \iddots & 0 \\ 0 & \iddots & \iddots & \iddots & 0 & 0 \\ \iddots & \iddots & \iddots & 0 & 0 & 0 \end{pmatrix} \tag{4.15}$$

Hence, for kth agent, food consumption is

$$e_k W_k = \sum_{j=1}^{M} \beta_{j,k} R_j \tag{4.16}$$

The micro food consumption, therefore, can decompose to a set of food items produced at the micro-level.

4.3.3 Saving, Debt Flow and Consumption

By analogy with the effect of the profitability gap on investment decisions [RR08], and due to the paradox of thrift that increasing unemployment leads to an increase in the propensity to save causing a decrease in effective demand causing unemployment to rise, it is proposed that the unemployment gap has an impact on the population's saving behavior. Therefore, the exogenous unemployment rate u affects personal saving/debt behavior through

$$\frac{\partial X_k}{\partial u} = -X_k \tag{4.17}$$

where

$$X_k = \begin{cases} V_k & \text{if saving exists} \\ B_k & \text{if debt flow exists} \end{cases} \tag{4.18}$$

is the saving/debt flow at which the unemployment gap is added onto saving/debt flow per se negatively.

Therefore the kth agent's consumption can be represented by the difference of debt/saving flow and wage income, i.e.

$$C_k = W_k - \frac{\mathrm{d}}{\mathrm{d}t} X_k \tag{4.19}$$

4.4 Macroeconomic System Dynamics

According to Marc Lavoie [Lav11], the usual Kaleckian model consists of three equations: a pricing equation [Dut84, Lav95, HO03, Set09, Ohn13, Kee13], a saving equation [Ste79, Mar84, HLVT11, Pal13a], and an investment equation [Sen63, Ste79, FHP88, Lav95, LRS04, FDP13]. This is established based on three assumptions, i.e. (1) the pricing function in terms of the profit rate depends on the profit share, the rate of capacity utilization, and the capital to capacity ratio; (2) the saving function in growth terms depends only on the profit rate and the propensity to save out of profits; and (3) the investment function in growth terms depends on some constant, the rate of capacity utilization, and the normal profit rate (or the share of profit).

Building on the Kaleckian model, by introducing entropy to modify the accumulation of capital (i.e. accumulation of capital stock depends on investment and entropy production), we develop a model for macroeconomic system dynamics. In the model, it is assumed that entropy exists, and evolves independently of the development of the economy, however, the path of energy consumption has an impact on entropy production. Nicholas Georgescu-Roegen's conception of "useful work" also has been introduced to replace the application of energy [GR79] because the engine of economic growth has been the growing use (thanks to declining costs) of energy service (useful work), not energy per se, according to Robert Ayres and his colleagues [AAW03, AW05, WA12]. Useful work is defined as the sum total of all types of physical work by animals, prime movers and heat transfer systems, and consists of three categories: the first category is muscle work, for which the fuel is food or feed; the second category is fuel used by prime movers to do mechanical work; and the third category is fuel used to generate heat.

4.4.1 Entropy Production and Water Supply

Entropy is a measure of the number of distinct ways in which a system may be arranged, often taken to be a measure of disorder, or a measure of progressing towards thermodynamic equilibrium [PNB72, DC01]. The entropy of an isolated system never decreases, because isolated systems spontaneously evolve towards a maximum at thermodynamic equilibrium, whereas the entropy of an open system can either be maintained at the same level or decreased (negative entropy) [DC01, Dew05, MS06, KMC10, MB10]. According to the second law of thermodynamics, that matter and energy tend toward a state in which no useful work can be done, because the energy in the system is too diffuse, in an open system, change in entropy in a given time interval comprises entropy production due to an irreversible process in the system (an internal component) and entropy flow due to exchange with the environment (an external component). An open system needs to maintain an exchange of energy and resources with the environment in order to be able to continuously renew itself. Under the second law, the energy or matter from the production process will be converted to a less ordered form, i.e. the final products tend to have higher entropy than the raw materials [HBM03, AA10].

Integrating the existence of entropy production, according to the first law of thermodynamics and the conception of useful work, we have

$$\gamma_D D + T = S + \gamma_C C \tag{4.20}$$

where all γs are positive parameters, terms on the left-hand side consist of the solar energy inputs as a constant multiple γ_D of food production $D = \sum_{j=1}^{M} D_j$ by photosynthesis and the useful work T at time t, and the terms on the right-hand side comprise the entropy S generating from energy usage processes and the influence of final actual consumption $C = \sum_{k=1}^{N} C_k$ on energy through a constant multiple γ_C. In a closed ecosystem, entropy production is isolated from the economic process, however, and from the perspective of an open ecological-economic system, it depends on the choice of useful work path [GR79], whereas useful work follows a logistic growth curve [Smi10a, Smi10b], i.e.

$$\frac{\partial T}{\partial Y_A} = \frac{T}{Y_A}\left(1 - \frac{T}{\boldsymbol{T}}\right) \tag{4.21}$$

where the useful work growth in ideal conditions with an exponential growth rate at which the growth rate of actual output adjusts it, and $\boldsymbol{T}$ is the existing useful work stored in fossil fuels. Therefore despite entropy being isolated from the economic system and economic development, the entropy production is path dependent on the useful work consumption. As mentioned in chapter 3 in this thesis, the flow of entropy production can be determined by two factors: the waste arising from capital stock and the waste from labor stock. Hence, the rate of capacity utilization and the rate of unemployment become two core concepts in our analysis.

As above, development on water supply and efficiency in micro-scale, we use a similar way to develop a dynamics for water supply in macro-scale. Indeed, agricultural water supply is determined by climate change index G and its ratio of water-climate g, where G is exogenous variable and the ratio depends on investment I, i.e. $H = gG$, where

$$\frac{\mathrm{d}}{\mathrm{d}t} g = \gamma_g I \tag{4.22}$$

and

$$\frac{\mathrm{d}}{\mathrm{d}t} G = -\gamma_G G \tag{4.23}$$

where G, as mentioned above, is an index for climate, i.e. a bigger index number implies less rainfall and also higher temperature, γ_g is the rate at which the investment increases the water efficiency under climate change, and γ_G is a decay rate with $\gamma_G > 0$.

4.4.2 Capacity Utilization and Unemployment

Effective demand is seen to be a central, if not the central, issue of Keynes's *The General Theory of Employment, Interest and Money* [Key36]. The Kaleckian model has progressively become quite popular among heterodox economists concerned with macroeconomics and effective demand issues [HLVT11]. Michał Kalecki's ideas on income distribution are necessary additions to Keynes's arguments regarding the determination of the level of effective demand [LM99]. As mentioned in chapter 3 the fluctuation in effective demand is responsible for business cycles.

Denote Y_E is expected aggregate output, after decomposing, P_j is individual profit for jth agricultural agents in agricultural sector, P_{M+1} is aggregate profit in non-agricultural sector, and W_k is individual wage for kth agents, i.e.

$$Y_E = \sum_{j=1}^{M} P_j + \sum_{k=1}^{N} W_k + P_{M+1} = P + W \tag{4.24}$$

where $P = \sum_{j=1}^{M+1} P_j$ is aggregate profit income, $W = \sum_{k=1}^{N} W_k$ aggregate wage income. By similar technique, the actual aggregate output Y_A can be decomposed as

$$Y_A = \sum_{j=1}^{M} I_j + \sum_{k=1}^{N} C_k + I_{M+1} = I + C \tag{4.25}$$

where C_k is the individual consumption of the kth agent, and I_j the individual investment for the jth agricultural agent in the agricultural sector, I_{M+1} the aggregate investment in the non-agricultural sector, $I = \sum_{j=1}^{M+1} I_j$ the aggregate investment, and $C = \sum_{k=1}^{N} C_k$ the aggregate consumption. The difference between actual and expected output can be represented by the aggregate difference between profit and investment for producer and the difference between wage and consumption for consumer, i.e.

$$Y_E - Y_A = (P + W) - (I + C) = (P - I) + (W - C) \tag{4.26}$$

Hence, the rate of capacity utilization is defined as the ratio between actual output and expected output, therefore $y = Y_A/Y_E$, where Y_E is expected output[11] that may be bigger than actual output. Denoting L is the amount of labor supply including agricultural labor and non-agricultural labor, and L_E as employed labor, unemployment rate u is defined as the ratio between unemployed labor and total labor supply, i.e. $u = (L - L_E)/L$ and the labor productivity l is defined as actual

[11] Capacity utilization is the ratio between actual output and full capacity output [Kal57]. We here assume that the sum of profit and wage proxies full capacity output.

output produced by per worker, i.e. $l = Y_A/L$.

The amount of employed labor grows with capital stock at a constant rate γ_E, i.e.

$$\frac{\mathrm{d}}{\mathrm{d}t}L_E = \gamma_E K L_E \tag{4.27}$$

The growth of labor productivity responds positively to the rate of capacity utilization, and negatively to the rate of unemployment, therefore involuntary unemployment is likely, namely so-called technological unemployment [Key30], hence

$$\frac{\mathrm{d}}{\mathrm{d}t}l = (\gamma_l - \gamma_y(1-y) - \gamma_u u)l \tag{4.28}$$

where γ_l is the exponential rate at which the growth of labor productivity grows under the condition of full employment and full capacity utilization, γ_y is the rate at which labor productivity is weakened by idle capacity, and γ_u is the rate at which labor productivity is weakened by unemployment.

4.4.3 Investment and Consumption

Investment is a core activity that is critical for achieving sustainable development. Jerry Courvisanos [Cou05, CJ06] develops a sustainable framework which begins with an identifiable goal and then designs a strategy of public intervention in order to implement the goal. Innovation is stimulated with supportive public policies for the attainment of sustainable economic and ecological development. Furthermore, he [Cou09] argues that, "neither will deliver sustainable development unless market uncertainty can be ameliorated through public investment strategies that create a predictable but strategic focus to induce innovation that is cumulatively changing towards an ecologically sustainable investment program." In this context, Colin Richardson and his colleagues [RCC11] argues that investment "needs to shift away from the existing techno-economic paradigm (e.g., fossil fuel energy) to a new techno-economic paradigm that is ecologically sustainable (e.g., renewable energy)."

Capital stock, profit and investment decisions are viewed as integrated in the Kaleckian investment equation, and the profitability gap [RR08] links these variables together. When the upper boundary of capital flow is reviewed and defined by introducing the conception of entropy, the definition of profitability can be modified, and then investment decisions can be changed according to the profitability-investment equation.

As mentioned above, for the jth ($j = 1, 2, \ldots, M$) agricultural producer capital stock is denoted by K_j, and non-agricultural capital stock is K_{M+1}, hence, the aggregate capital stock $K = \sum_{j=1}^{M+1} K_j$ follows that aggregate investment $I = \sum_{j=1}^{M+1} I_j$ contributes its accumulation while the entropy depletes it, namely

$$\frac{\mathrm{d}}{\mathrm{d}t} K = I - \gamma_S S \tag{4.29}$$

where γ_S is the rate at which the entropy reduces the capital flow. The investment dynamics follows, with the growth of investment being determined by the profitability gap [RR08, RCC11], i.e.

$$\frac{\partial I}{\partial p} = I \tag{4.30}$$

where the rate of profit is defined as a ratio between aggregate profit $P = \sum_{j=1}^{M+1} P_j$ and aggregate capital stock K, i.e. $p = P/K$.

Denote the share of agricultural capital stock κ as the ratio between agricultural capital stock to the aggregate capital stock, i.e.

$$\kappa = \frac{\sum_{j=1}^{M} K_j}{\sum_{j=1}^{M+1} K_j} \tag{4.31}$$

Increasing actual output decays the share of agricultural sector, furthermore, it is assumed as

$$\frac{\partial \kappa}{\partial Y_A} = -\gamma_\kappa \kappa \tag{4.32}$$

where γ_κ is the rate at which the marginal increasing output decays the share of agricultural capital stock. According to Equation (4.5), therefore, for jth food producer, capital stock can be represented as

$$K_j = \frac{\kappa K(\log M - \log j)}{M \log M + \sum_{j=1}^{M} \log j} \tag{4.33}$$

4.4.4 Income Distribution

The most famous Post Keynesian model is on growth and distribution [12] and was developed in 1956 by such Cambridge economists as Joan Robinson and Nicholas Kaldor to explain the distribution of income [Lav09a]. The Cambridge model is a hybrid of Keynesian and pre-Keynesian features whereas the neo-Kaleckian model is Keynesian [Pal13a]. Recent literature on the mechanism of income distribution

[12] A good survey on the Post Keynesian models of economic growth and income distribution is given by [KS11] highlighting that "the adjustment of savings to investment, rather than the other way round, is seen to be a central, if not the central, message of Keynes's General Theory".

and economic growth from Post Keynesian and Kaleckian perspectives has also been impressive, with class conflict and the Cambridge theory of income distribution being surveyed from an international perspective [Pal06]. Furthermore, the paradox of an unprecedented deteriorative change in income distribution and a stable growth in capital stock and output is reviewed [Lav09b], the link between rising shareholder power, increasing pressure on labor, and redistribution at the expense of wages, with the macroeconomic effects on capacity utilization, profits and capital accumulation is established [HVT10]. Managerial pay is introduced into the Kaleckian model [Pal13c], while the stability of the Kaleckian model of economic growth and income distribution is surveyed [HLVT11, Lav11, HLVT12], together with the increasing role of financial motives, financial markets, financial actors and financial institutions in the Post Keynesian model of growth and distribution is developed [HVT11], and the relationship between income distribution and capacity utilization in the Kaleckian model is examined [NF12]. Post Keynesian economists also have explained many economic phenomena, such as inflation being a consequence of conflicts between social classes over the proper distribution of income [Cas03].

Denoting $W = \sum_{k=1}^{N} W_k$ as aggregate wage income, the share of wage income is defined as the ratio between wage and expected output[13], i.e. $\omega = W/Y_E$, while the share of profit is defined as the ratio between profit and actual output $\phi = P/Y_E$.

The share of profit can determine the rate of mark-up [Ble89, BM90] in the short run by

$$m = \frac{\phi}{1-\phi} \tag{4.34}$$

where the share of profit is closer to 1, the rate of mark-up is closer to positive infinite, whereas if the share of profit is closer to 0, the rate of mark-up is closer to 0. Therefore

$$\frac{\partial m}{\partial \phi} = \frac{1}{(1-\phi)^2} \tag{4.35}$$

The determinants of income distribution are complicated. First of all, the ratio between the number of producers M and the number of consumers N determines the degree of monopoly for the long run, which affects the shares between profit and wage, i.e. $\exists \epsilon > 0$, s.t.

[13] Indeed, it is reasonable and more convenient here to use expected output instead of actual output that consists of investment and consumption, because for every two continuous time periods the former actual output is the latter expected output, which is not always equal to the latter actual output; however, the gap between expected and actual outputs will tend to zero under a different system environment.

$$\left| \frac{M}{N} - \frac{1}{\gamma_\omega} \frac{\phi}{\omega} \right| < \epsilon \tag{4.36}$$

where γ_ω is a constant to link two ratios, hence

$$\left| \phi - \frac{\gamma_\omega M}{\gamma_\omega M + N} \right| < \epsilon \tag{4.37}$$

An increasing unemployment rate can weaken the bargaining power of workers, then decrease the share of wages and increase the share of profits [Cas03], i.e.

$$\frac{\partial \phi}{\partial u} = \frac{\gamma_\phi \phi}{u} \log \left(\frac{\gamma_\omega M}{(\gamma_\omega M + N)\phi} \right) \tag{4.38}$$

where γ_ϕ is the rate at which the change of the unemployment rate is added onto the change of the profit share positively, and the logarithmic item is used to represent a long run tendency of profit share as defined by Equation (4.37).

4.4.5 Sizes of Firm and Population

In ecology, the size of the ecosystem has become an important variable related to biodiversity. In 1972, Robert May [May72] gave a sophisticated and important analysis of the trade-off between stability and biodiversity, showing that larger communities were less likely to be stable, and he dispelled absolutely the idea that greater diversity necessarily begets stability.

Due to recognizing the sophistication of the size of firm and population, the model introduces the pattern of firm and population sizes to represent a possible path simulating the degree of monopoly that affects macroeconomic behavior. Additionally Malthusian spirits can be reflected by the influences on the growth rate of useful work in the ecosystem, and capital stock and wage income in the macroeconomic system.

The classical model of the dynamics of population size is the Verhulst logistic equation[14] [CL03, PSS08, Sak13, SRMD13]

$$\frac{\partial N}{\mathrm{d}W} = \frac{N}{W} \left(1 - \frac{N}{\gamma_N Y_A} \right) \tag{4.39}$$

where γ_N is treated as a variable to account for the ratio at which the fluctuations in available resources depend on actual output that is used as a variable to account for limitations of population growth. Indeed, the equation is not able to be

[14] The Verhulst system is an ecological model for managing resources, where in this model the exploitation rate of the resource is proportional to the biomass and the economic activity [CQSP07].

used to do cross-country analysis because of how complicated is the relationship between economic growth and population. However, for the regional model in a given country, a constant ratio between output and population is acceptable. Furthermore, the Verhulst equation reflects a Malthusian perspective. Generally economic growth is limited by increasing entropy production and by an unstable intake of useful work.

Applying the Verhulst logistic equation to model firm size, the number of firms depends on the size of the economy as measured by the capital stock, hence

$$\frac{\partial M}{\partial K} = \frac{M}{K}\left(1 - \frac{M}{\gamma_M Y_A}\right) \tag{4.40}$$

where γ_M is the rate at which the change of the agricultural capital stock is added onto the change of the amount of firms.

Finally assuming that population growth and growth of labor supply share a similar dependency in the long run, we can have

$$L = \frac{N}{1 + \gamma_L} \tag{4.41}$$

where γ_L can be understood as demographic dependency ratio, i.e. an age-population ratio of those typically not in the labor force (the dependent part) and those typically in the labor force (the productive part). Indeed, a static dependency ratio is assumed here.

4.5 A Simulation Model for the Murray-Darling Basin Economy

The Murray-Darling Basin Economy Simulation Model, aims to develop new theoretical approaches that relax some of the conflicting assumptions of economic theory, to move towards a more self-consistent approach to understanding and predicting future trends in an economy that values both production and protection of scarce environmental resources, and to test a new theoretical model against one of Australia's most drought-stressed agricultural regions.

The model is built on a foundation of sustainability economics and complex systems theory. It assumes that the presence of moderate or extreme water scarcity affects economic growth, and that scaling and universality may hold in complex social, economic and ecological systems. We will assume that complex dynamical ecological and economic systems can be integrated in a framework that develops the concept of the profitability gap [RR08] as the endogenous driver of the economic growth trajectory.

System Dynamics modeling [Hom06, RGMS07, PSS08, VGR+11, LS12, RS12a] studies systems from the top down by establishing a set of ordinary differential equations on the precondition that complex behaviors of the system (e.g., involuntary unemployment) result from the interplay of feedback loops, stocks, and flows, all occurring within the bounded endogenous system. The method arose originally in management science [FMR76] from the recognition of the need to explicitly model non-linear processes that are characteristic of complex phenomena such as policy resistance, the law of unintended consequences, and the often counter-intuitive behavior of social systems. Computer simulations are used to track accumulations of stocks (e.g., capital, entropy, population), which are determined by flows (e.g., profitability), and feedback loops (causal loops with either balancing or reinforcing effects).

Agent-based modeling [EA96, Eps99, Eps02, Hom06, RGMS07, EPH11, GMA+11, VGR+11, LS12] is used to study complex systems from the bottom up by examining how their individual elements (agents) behave as a series of functions of individual properties, their environment, and their interactions with each other. Through these behaviors, emergent properties of the overall system are revealed. The method arose originally in computational mathematics in the context of simulating individual behaviors that are characteristic of heterogeneous evolution and are often interactive or interdependent with each other.

The model includes three separate parts, i.e. a Post Keynesian Ecological Macroeconomic part modeled using a system dynamics approach and Kaleckian micro-investment behavior and micro-consumption behavior modeled using an agent-based approach. These parts are linked together by aggregating micro individual behavior into the behavior of the macro system, and feedback of macro behavior on micro behavior by introducing an entropy production function based on exogenous climate change.

In this section, we fuse the ideas developed above and apply our model to the specific case of the Murray-Darling basin, Australia. We propose an 11 differential equations system as below

$$\frac{\mathrm{d}}{\mathrm{d}t}L = \alpha_L L(t) \tag{4.42a}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}L_E = \alpha_E L_E(t)\left(1 - \left(\frac{L_E}{L} - (1-u)\right)\right) \tag{4.42b}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}K = \alpha_I I(t) - \frac{\alpha_G}{G(t)} \tag{4.42c}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}K_E = \alpha_K K_E(t)\left(1 - \left(\frac{K_E}{K} - y\right)\right) \tag{4.42d}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}I = (\alpha_P - \alpha_K)\frac{P(t)}{K(t)}I(t) \tag{4.42e}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}G = \alpha_G G(t) \tag{4.42f}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}P = \alpha_P P(t)\left(1 - \left(\frac{P}{Y} - \phi\right)\right) \tag{4.42g}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}Y = \alpha_Y Y(t) \tag{4.42h}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}u = \alpha_u u - \alpha_{u\phi} u\phi - \alpha_{uy} uy \tag{4.42i}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\phi = -\alpha_\phi \phi + \alpha_{\phi u}\phi u - \alpha_{\phi y}\phi y \tag{4.42j}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}y = -\alpha_y y + \alpha_{yu} yu - \alpha_{y\phi} y\phi \tag{4.42k}$$

where Equations (4.42a)-(4.42b) represent the dynamics of labor force supply and employed labor. We do not model population growth explicitly and assume that labor supply can be represented by a simple exponential growth curve [BBB+12, NAB+13, Sak13]. Employed labor growth is regulated by the entire labor supply growth and the rate of unemployment in the macroeconomic system because we do not assume that full employment is automatically achieved (Equation (4.42i)). Equations (4.42c)-(4.42d) show the dynamics of capital stock and utilized capital in the macroeconomic system (where the rate of change of capital is determined by current capital stock, investment and climate change, and the rate of change of utilized capital flow) is regulated by the rate of capacity utilization, again because we do not assume that full capacity utilization is automatically achieved (Equation (4.42k)). Equation (4.42e) is the Richardson profitability-investment gap equation [RR08] which describes the relation between investment and the difference between the rate of profit between contiguous periods, and where the rate of change of profit is given by Equation (4.42g) which is limited by the share of profit. Equation (4.42f) describes the change of climate through potential annual rainfall, i.e. the rainfall in the Murray-Darling basin has been predicted by three scenarios - a high global warming scenario, a medium global warming scenario, and a low global warming scenario. These represent dry extreme, median and wet extreme weather according to a report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project, *Water availability in the Murray-Darling Basin*, where we neglect hydrodynamics per se, but highlight the influence on the economy of changing annual rainfall. In Equation (4.42h) the output which follows an exponential growth is reliable because we use current price to measure all variables related to the macroeconomic system. Equations (4.42i), (4.42j) and (4.42k) are integrated to describe the nexus of the rate of unemployment, the share of profit, and the rate of capacity utilization using a three-dimensional Lotka-Volterra differential equation system. Water security in the Murray-Darling Basin depends on the Australian macro-economy, and on the climate features in the Basin. In an open ecological-economic system, the failure of coordinating the parameters in equation system (4.42) will result in a lose-lose situation.

4.6 Parameter Estimation

In this section, we use ABS data for the period 1978-2005, where all macroeconomic variables are based on current price, to estimate the parameters in equation system (4.42).

Other than the last three equations (4.42i), (4.42j) and (4.42k) which simulate the rate of unemployment, profit share and the rate of capacity utilization respectively, we can induce closed-form or analytical solutions for each equation if all other variables are seen as parameters. Based on these analytical solutions, we estimate the baseline parameter values as shown in Table 4.2.

Table 4.2: Parameter values for the model (I)

Parameter	Description	Value
α_L	The growth rate of labor supply	0.0186
α_E	The growth rate of employed labor	0.0186
α_I	The rate at which investment increases capital stock	0.3069
α_G	The rate at which climate change diminishes capital stock	-1.2533×10^7
α_K	The growth rate of utilized capital	0.0722
α_P	The growth rate of profit	0.0811
α_Y	The growth rate of output	0.0697

Figure 4.5 shows the difference between observed and predicted data in the ordinary least squares sense where blue scatter plots are the observed data, the

green line plots the simulated, and blue bar plots the differences. labor supply (as shown in Figure 4.5a) and actual output (as shown in Figure 4.5f) are assumed to follow an exponential growth curve; employed labor (as shown in Figure 4.5b), utilized capital (as shown in Figure 4.5d) and profit (as shown in Figure 4.5e) are assumed to follow an exponential logistic growth curve, i.e. saturation exists and depends on the rate of unemployment, the rate of capacity utilization, and profit share respectively; and capital stock (as shown in Figure 4.5c) is assumed to follow a linear growth trend, where the rate of growth depends on investment and climate change.

4.7 Hypothesis Validation

In this section, we use ABS data for the period 2006-2012, where all macroeconomic variables are based on the current price, to validate the model described by equation system (4.42).

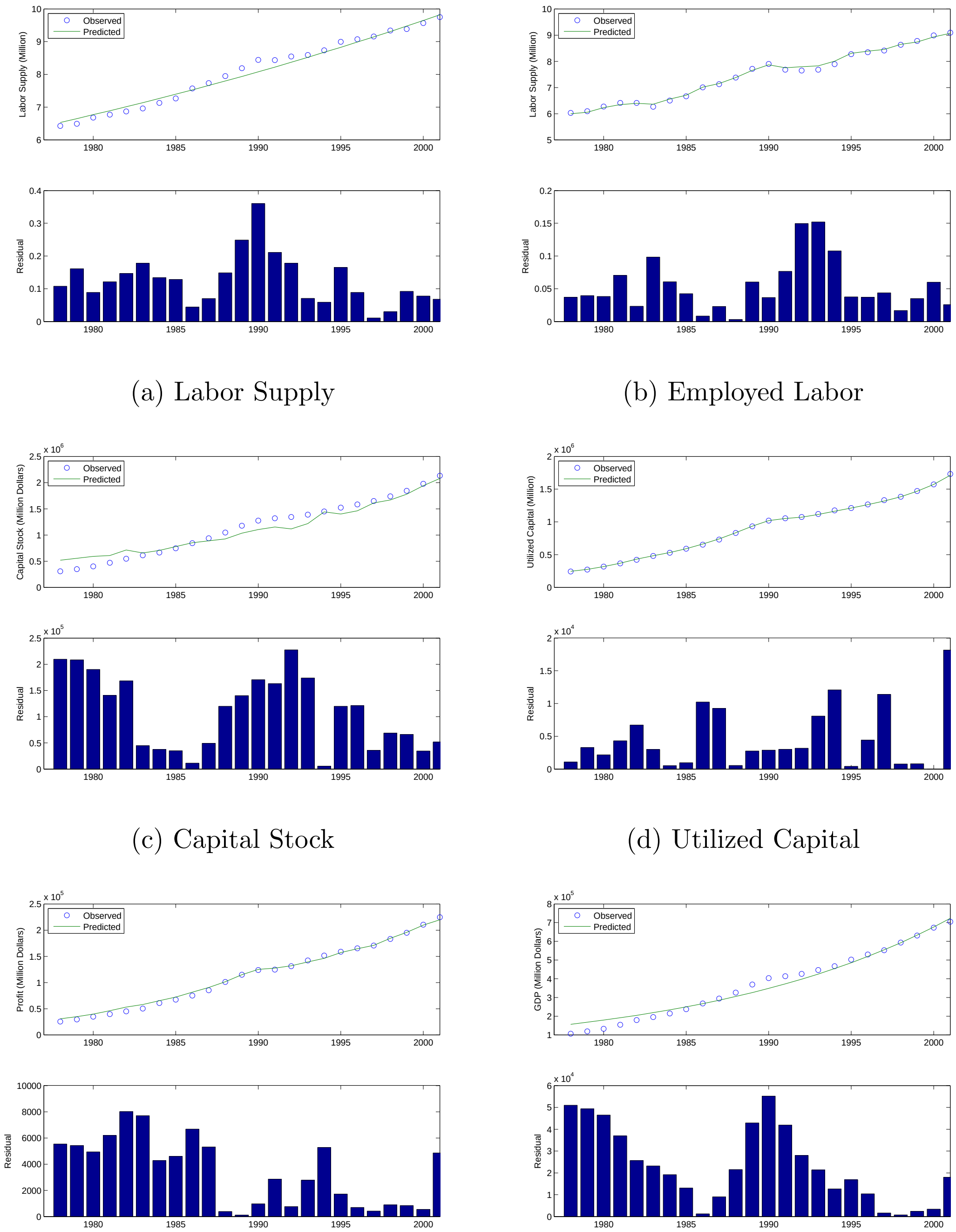
Figure 4.6 shows the comparison between real-world and simulated data where green line plots are diagonals, and the coefficients of determination (R^2) are available. The results of the hypothesis validation show that equation system (4.42) provides a consistent prediction for the dynamics of labor supply, employed labor, capital stock, utilized capital, profit, and output when we use the coefficients estimated by historical data, and control the other parameters (the rainfall, the rate of unemployment, the share of profit, and the rate of capacity utilization) using actual (i.e. not historical) data.

Particularly Figure 4.6c and Figure 4.6d show the real and simulated value for capital stock and the utilized capital stock respectively based on Equation (4.42c) and Equation (4.42d), and indicate that both are underestimated. The lower than average rainfall (other than the year of 2010) over the period 2006-2012, and hence an atypically severe climate constraint is responsible for the underestimation.

4.8 Results

In this section, we apply the parameters shown in Table 4.2 which are validated by the real-world data over the period of 2006-2012. Additionally, we provide some unvalidated parameters that appeared in Equations (4.42f) (4.42i), (4.42j), and (4.42k), i.e. the rainfall, the rate of unemployment, the share of profit, and the rate of capacity utilization. As mentioned above, without government intervention, intrinsic business cycles are represented by the interaction between the rate of unemployment, the share of profit, and the rate of capacity utilization

Figure 4.5: Parameter estimation



(a) Labor Supply

(b) Employed Labor

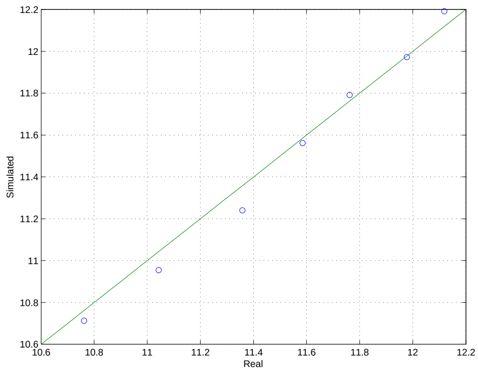
(c) Capital Stock

(d) Utilized Capital

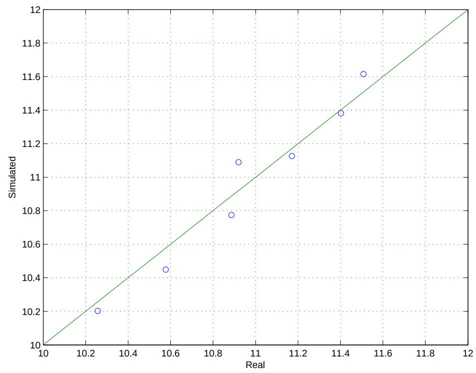
(e) Profit

(f) Actual Output

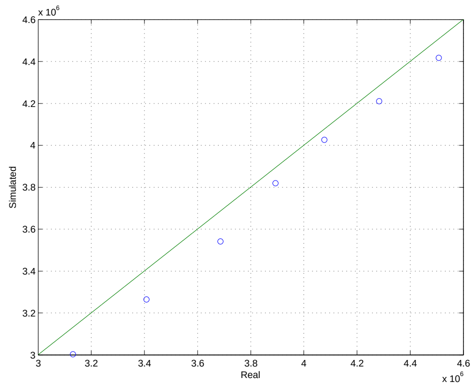
Figure 4.6: Hypothesis validation



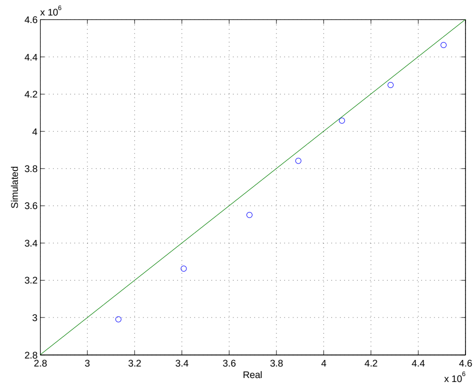
(a) Labor Supply $R^2 = 0.9933$



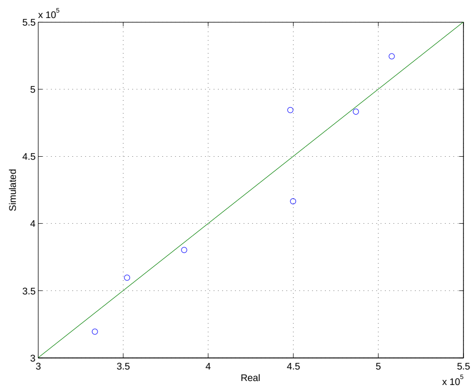
(b) Employed Labor $R^2 = 0.9603$



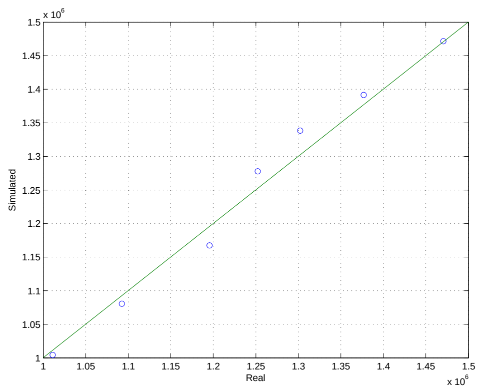
(c) Capital Stock $R^2 = 0.9972$



(d) Utilized Capital $R^2 = 0.9972$



(e) Profit $R^2 = 0.9178$



(f) Actual Output $R^2 = 0.9858$

under the Lotka-Volterra system. In effect, we argue here that annual rainfall forecasts are impossible when the best accessible resources are CSIRO's climate change scenarios data, and that the last three equations reflect the Post Keynesian economic idea while regressed parameters are unstable due to the characteristics of three-dimension Lotka-Volterra equations. Table 4.3 gives the parameters, and Figure 4.7 shows the curves in the corresponding three-dimension phase space.

Table 4.3: Parameter values for the model (II)

Parameter	Description	Value
α_u	The growth rate of unemployment	1.5714
$\alpha_{u\phi}$	The rate at which the profit share reduces the unemployment	3.6667
α_{uy}	The rate at which the capacity utilization reduces the unemployment	1.8333
α_ϕ	The growth rate of profit share	0.2895
$\alpha_{\phi u}$	The rate at which the unemployment increases the profit share	131.2667
$\alpha_{\phi y}$	The rate at which the capacity utilization reduces the profit share	11
α_y	The growth rate of utilized capital	0.1375
α_{yu}	The rate at which the unemployment increases the capacity utilization	1.8333
$\alpha_{y\phi}$	The rate at which the profit share increases the capacity utilization	0.3548

We use initial values taken from the ABS data for the labor force of 6.3554 million[15], employed labor 5.8281 million[16], capital stock 394111 million dollars[17], utilized capital 308692 million dollars[18], investment 33165 million dollars[19], annual rainfall 457mm[20], profit 33190 million dollars[21], and output 128341 million dollars[22]. Three scenarios of climate change have been used following the report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project[23], *Water availability in the Murray-Darling Basin* which predicts

[15] 6202.0 - labor Force [Aus13e]

[16] 6202.0 - labor Force [Aus13e]

[17] 5204.0 - Australian System of National Accounts [Aus13d]

[18] 5204.0 - Australian System of National Accounts [Aus13d]

[19] 5206.0 - Australian National Accounts: National Income, Expenditure and Product [Aus13c]

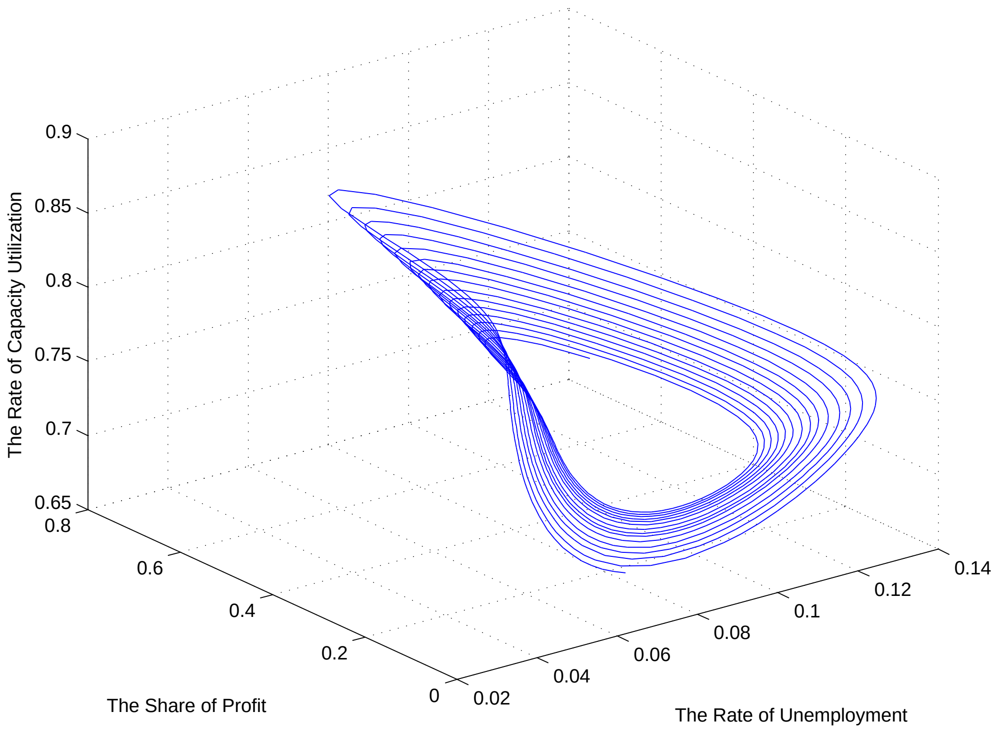
[20] Australian Climate Variability & Change [Bur13b]

[21] 5206.0 - Australian National Accounts: National Income, Expenditure and Product [Aus13c]

[22] 5206.0 - Australian National Accounts: National Income, Expenditure and Product [Aus13c]

[23] The Southern Oscillation [Aus12] refers to a massive see-sawing of atmospheric pressure

Figure 4.7: The nexus of unemployment, profit share and capacity utilization



a 13% decrease under a dry extreme 2030 climate, a 3% decrease under a median 2030 climate, and an 8% increase under a wet extreme 2030 climate relative to a baseline of 457mm which is the average annual rainfall from 1895 to 2006 (averaged across the entire Murray-Darling basin). Two scenarios of government intervention are compared. The first consists of minimizing business cycles and macroeconomic fluctuations through the stabilization of unemployment, profit share and capacity utilization to full employment and full capacity utilization The second consists of no intervention i.e. following intrinsic business cycles where the rate of unemployment, the share of profit, and the rate of capacity utilization interact according to a Lotka-Volterra scheme (Figure 4.7).

Figure 4.8 shows that from a long run perspective, government intervention can increase the working opportunities for a labor force facing climate change.

Figure 4.9 shows that government intervention can increase the utilization of

between the northern Australian-Indonesian region and the central Pacific Ocean, links to sea surface temperatures in the Pacific Ocean, and affects the climate of the Murray-Darling Basin. The Southern Oscillation Index, measuring the strength of the Southern Oscillation, is defined by fluctuations in the surface pressure difference between Tahiti and Darwin, and relates closely to the main weather features of the Basin. Severe and widespread drought over the Basin generally accompanies an extreme in the Oscillation when the pressure is abnormally high at Darwin and abnormally low at Tahiti and vice versa. Dry extreme years are called El Niño years while wet extreme years are called La Niña years.

Figure 4.8: Predicted employed labor. Government intervention can increase the working opportunities for a labor force facing climate change.

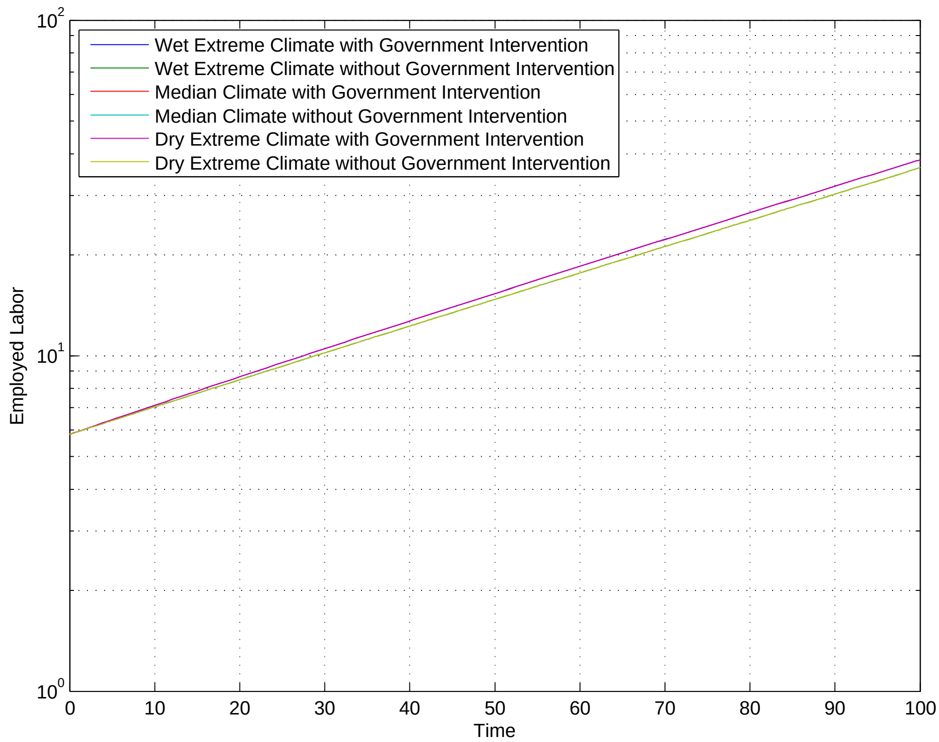
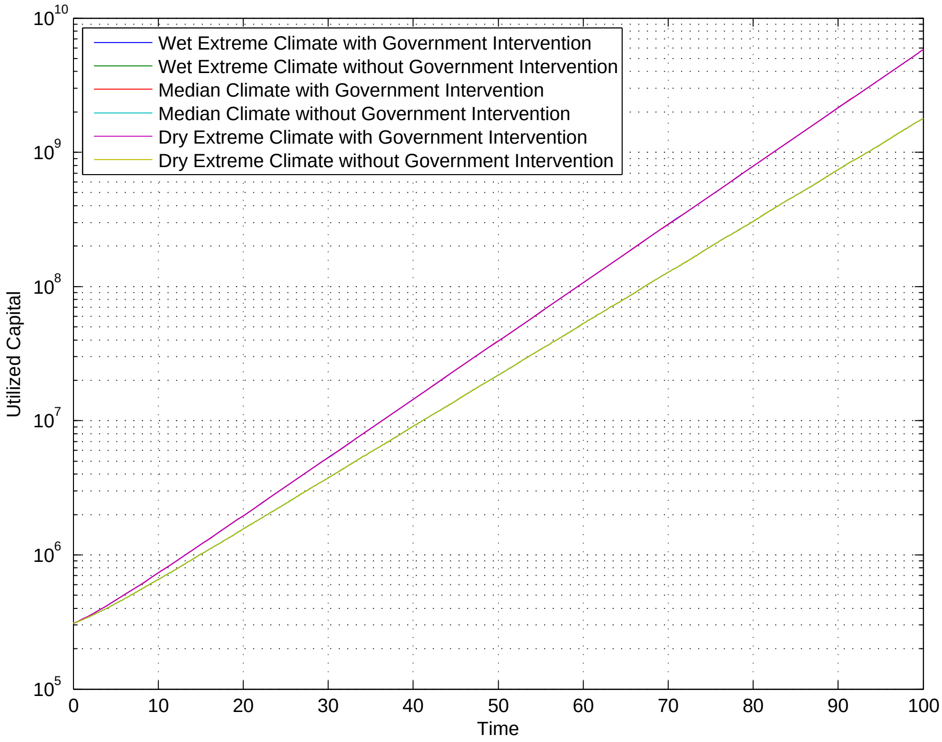


Figure 4.9: Predicted utilized capital. Government intervention can increase the utilization of capital stock.



capital stock comparing with the scenario without government intervention.

Figure 4.10 shows that investment remains stronger with government intervention.

Figure 4.11 shows that the profit is stronger with government intervention than without it in a long run perspective.

4.9 Conclusion and Discussion

This chapter constructs an ecological macroeconomic model based on a Post Keynesian model of economic growth and income distribution to simulate the combined macroeconomic system and water ecosystem under the influence of climate change. The predictions account for the response of the Murray-Darling basin economy to water availability and climate change as well as to potential government interventions. The focus of our analysis is on how the macroeconomic system responds to these shocks. Significantly, our model does not assume that capital accumulation is isolated from nature. Instead, we derive the impact of natural capital from our specification of how ecological economic insights can

Figure 4.10: Predicted investment. Investment remains stronger with government intervention.

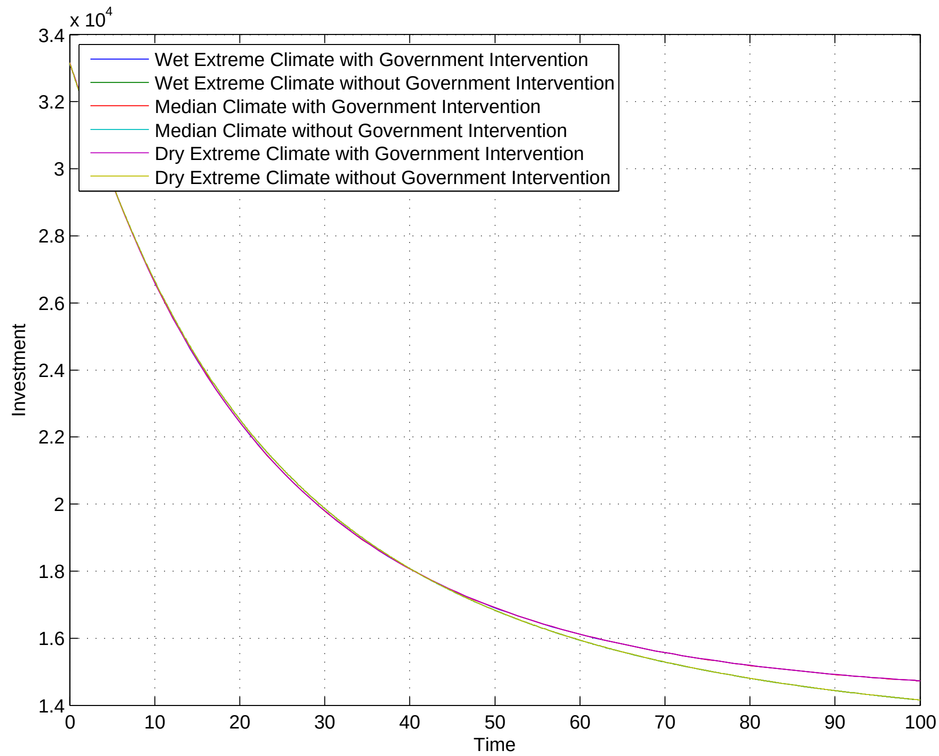
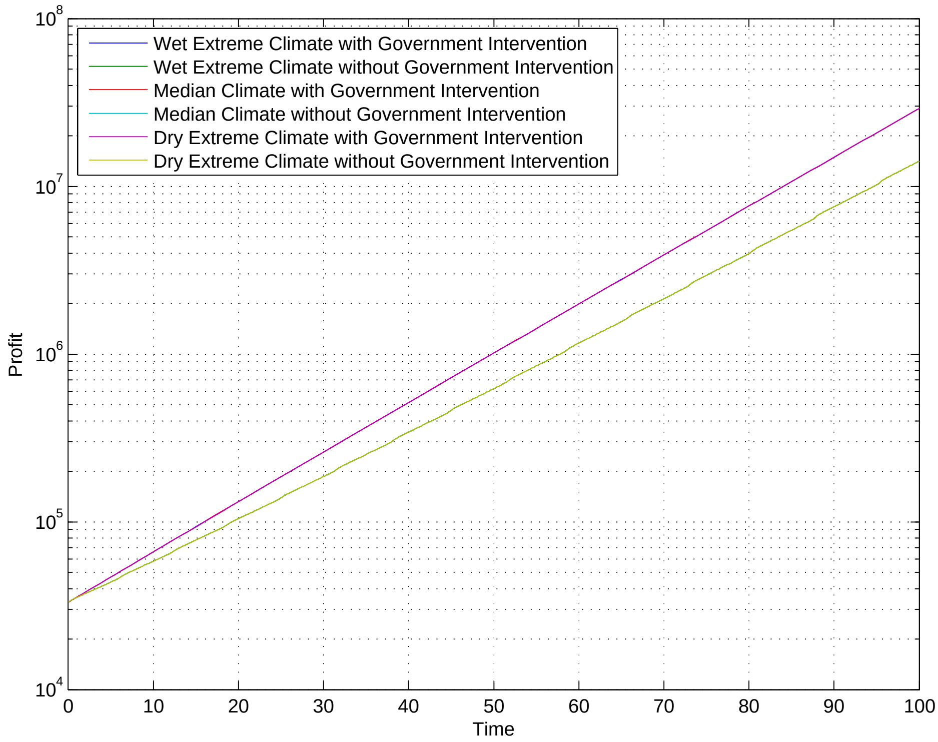


Figure 4.11: Predicted profit. Profit is stronger with government intervention.



be fused into Post Keynesian traditions. This can be interpreted as entropy production diminishing capital accumulation, or diminishing the present stock of capital at the time that investment contributes to capital.

From this ecological economic aspect on the theory of production and supply, complementarity between capital inputs replaces substitution, and most significantly, the second law of thermodynamics is applied, and entropy is introduced. From the Post Keynesian viewpoint on the theory of expenditure and demand, effective demand lies at the core of the economic system, and involuntary unemployment exists, therefore the paradox of thrift and insufficient demand can accompany business cycles.

Our model fuses the work of Herman Daly [Dal96] on complementarity of inputs, Nicholas Georgescu-Roegen on entropy generation [GR79], Robert May on biodiversity and stability [May72], Michał Kalecki on investment [Kal71], Marc Lavoie on distribution [Lav92], Jerry Courvisanos on business cycles [Cou96], and Colin Richardson on the role of the profitability gap [RR08]. Under this framework the case of the Murray-Darling basin is studied based on data over the period of 1978-2010. We apply the model to the prediction over the next century of the impact of climate change and government intervention on capital accumulation and investment dynamics, as well as on profit.

Due to the lack of data on useful work supply and entropy production within a given region, we replaced this with future water supply using the report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project, *Water availability in the Murray-Darling Basin*. Future work can build on this simulation of the water ecosystem based on more available data, and incorporate a deeper fusion with the macroeconomic system.

Chapter 5

Food Riots

In chapter 4 we proposed an ecological-economic framework based on Post Keynesian ecological economic methodology to integrate the food and water economy, and applied it in a case study of the Murray-Darling basin in Australia. Clearly water is not just a constraint in Australia, but is a growing constraint on global food production, especially in areas of the highest population densities. Australia is fortunate in producing more food than it consumes and neighboring countries rely on these exports for food security. The performance of Australian agriculture is also a determinant of global food commodity prices, which in turn are known to impact on social unrest. The Asian region, particularly the south and east, is having an increasing influence on Australian politics. The developing economies of Asia are experiencing serious environmental and social problems that threaten to undermine future development, food security, and regional stability. Rapid economic transformation, increasing income and rising populations in developing countries have been key drivers behind the rapidly growing global demand for food. As water and other natural resources (like the availability of chemical elements for making fertilizers[1]) increasingly limit the potential of agriculture, the economic and social impacts of loss of food security will increase. It is therefore essential not just to understand the links between ecology and economics, but also to understand the consequences for social stability.

Food security is a growing concern worldwide. More than one billion people are estimated to lack sufficient dietary energy availability [Bar10]. Food-related riots may take place after absolute food shortages arising from physical food production and accumulation shortages or economic shortages due to inefficient food distribution. We call physical shortage “absolute shortage”, and economic

[1] An NPK fertilizer is one that contains three key constituent chemical elements that are Nitrogen (N), Phosphorus (P) and Potassium (K). The three elements promote plant growth in three different ways. In simple terms, these are: Nitrogen that promotes the growth of leaves and vegetation, Phosphorous that promotes root growth and Potassium that promotes flower and fruit growth.

shortage "relative shortage". Absolute food shortage may take place because of hysteresis effects from relative shortage and natural shocks in the short run. However from the long run viewpoint, absolute shortage does not exist because Malthus's theory that food production can limit the growth of population has been proven false due to technical progress raising crop yields. Therefore relative food shortage is of greater concern, as a large part of the population cannot access food even if the total amount is more than is needed for population subsistence. Food trading and food exchange contribute to the population's low capacity to access food. According to the seminal work of Amartya Sen, *Poverty and Famines: An Essay on Entitlement and Deprivation* [Sen81], unequal food distribution can cause famine even when aggregate food production levels are more than sufficient for subsistence, that is

> starvation is the characteristic of some people not having enough food to eat. It is not the characteristic of there being not enough food to eat. While the latter can be a cause of the former, it is but one of many possible causes.

For example, local weather shocks can reduce local food production and income as well, since incomes in developing countries often depend on agriculture, so that those in affected areas cannot purchase food from unaffected regions [Sen81]. Institutional limits, like an economy-wide centralized plan, may undermine collection and respond to new information in the presence of an aggregate shock to food production, so that even regions with higher per capita food production can suffer higher famine mortality rates [MQY10]. Therefore, a famine can occur even if aggregate food production is high [Sen81, Til83, Bar10, MQY10, Wan11].

However, food shortages, including physical and economic, do not necessarily lead to food riots. Besides physical factors and economic factors, there are political explanations, social situations, and demographic structures activating food riots depending on a specific path. For example, some food riots can be most meaningfully explained, not in a simple economic formula of food shortage, but within a political context of changing governmental policy and in terms of secular economic changes in marketing arrangements for grain [Til71, Til76]. In relation to the physical environment, recent quantitative studies have causally linked climatic environmental events to human conflict [BTN+11, HMC11, OWL+12, SBK+12, HBM13]. The direct causes of food riots and conflicts are still controversial across a range of spatial and temporal scales, for example environmental changes may increase the risk of violent conflict, but not necessarily in a systematic way and unconditionally, and the effects of environmental changes on violent conflict are likely to be contingent on a set of economic and political conditions that determine adaptation capacity [BBK12]. In the context of social situations, positive and negative forms of religious coping are related to positive and negative psychological adjustment to stress [AV05], and religion increases within-group trust but also may increase mistrust and conflict with external groups [AG12]. Demographic structures play a role where, for example, violence and war connects the low social status of women and gender inequality to conflicts ranging from international aggression to civil war [Hvi12].

Instead of pursuing direct causes of food riots, an indirect path is explored to evaluate the threat arising from food riots by introducing a basal characteristic index based on principal component analysis across Asian developing countries. The index can measure the relative long term status for food security between countries, but cannot capture the temporal evolution of conflict. Therefore, the concept of flow of anger is introduced to represent the temporal dimension in each country. The index represents the change in the propensity for violence that is based on the country's basal characteristic index. Finally, by applying Richardson's index system [RZ13] for threat severity, trigger potency and policy effectiveness, we fuse these five variables (i.e. basal characteristic index, dynamic factors index, threat severity index, trigger potency index and policy effectiveness index) into a three-dimensional first-order autonomous differential equation system.

The chapter proceeds as follows. Section 5.1 presents previous models on food-related conflicts prediction. Section 5.2 summarizes the Asian Food Security Risk Engine. Section 5.3 describes the basal characteristic index by applying principal component analysis that includes the data sources and reports summary statistics. Section 5.4 constructs the dynamic factors index by introducing the concept of the flow of anger. Section 5.5 presents the threat-trigger-policy nexus model and its parameters, and section 5.6 describes the results for parameter estimation and interprets them. Section 5.7 demonstrates the validation of the model, and section 5.8 discusses the findings and concludes.

5.1 Methodology and Previous Literature

In econometrics, a static model is a time series model where only contemporaneous explanatory variables affect the dependent variable, while a dynamic model is a time series model where no further lags of either the dependent variable or the explanatory variables help to explain the mean of the dependent variable. From a system dynamics point of view, solving a dynamic model means determining how much material or information has accumulated in each of a system's stocks[2] at every point in time [Rad11]. This can be accomplished in one of two ways - analytically or via simulation. Linear dynamic models can be solved either way. Nonlinear models, except for a few special cases, can only be solved via simulation whereas, static models concentrate on modeling a closed system, and estimate the character of the future observation is the same as estimating any existed observation.

Static models concentrate on the finding of possible explanations for the dependent variable, such as unrests, conflicts, riots, and wars, including food-related ones.

There exists the possibility that civil unrest activities, across countries and over long time periods, are governed by universal mechanisms and that social unrest contagion is governed by the same mechanisms despite the idiosyncrasies of individual countries and geographic regions [Bra12]. This has been explored by using the modified tail-weighted Kolmogorov-Smirnov statistic (wKS), defined as the maximum distance between the cumulative distribution functions of the observed data and the fitted simulation model.

Both high and low food prices hurt the poor [SS12]. In low income countries[3] increases in the international food price leads to a significant increase in the incidence of anti-government demonstrations, riots, and civil conflict. In high income countries variations in the international food prices have no significant effects on measures of intra-state conflict [AB11].

Food price changes also have recently been linked to riots and political unrest, and civil unrest is correlated, not to food price volatility, but to food price spikes [Bus10, SPD^{+}11, LBBY11, Bel11, Gou13]. The causal relationship between food prices and political unrest is studied by regressing the level of political unrest in a particular month on the food price level, three-month food price volatility, and political unrest in the previous month [Bel11]. The causal relationship between food prices and the incidence of natural disasters is studied by regressing the food price level on the number of natural disasters, three-month food price volatility, and political unrest in the previous month [Bel11].

[2]Stocks, which are sometimes referred to as "levels" or "states", accumulate (i.e. sum up) the information or material that flows into and out of them. Stocks are thus responsible for decoupling flows, creating delays, preserving system memory, and altering the time shape of flows. Flows of information or material enter and exit a system's stocks and, in so doing, create a system's dynamics. Stated differently, the net flow into or out of a stock is the stock's rate of change. When human decision making is represented in a system dynamics model, it appears in the system's flow equations. Mathematically, a system's flow equations are ordinary differential equations and their format determines whether or not a system is linear or non-linear.

[3]The group of low income countries is identified using the World Development Indicators (WDI) classification scheme and includes both countries classified by the World Bank as Low Income as well as those classified as Lower Middle Income.

The dominant causes of food price increases are investor speculation on commodity markets and conversion of corn to ethanol. These two are the most prominent of six possible factors including (a) weather, particularly droughts in Australia, (b) increasing demand for meat in the developing world, especially in China and India, (c) biofuels, especially corn ethanol in the US and biodiesel in Europe, (d) speculation by investors seeking financial gain on the commodities markets, (e) currency exchange rates, and (f) linkage between oil and food prices. These factors were studied by reconstructing a supply and demand equilibrium price model with Walrasian adjustment [LBYBBY11].

The effect of financial speculation on food price increase or food price volatility is very controversial. In effect, besides the above argument [LBYBBY11] that investor speculation causes food price rises, there are also claims that unprecedented buying pressure from new financial index investors created a massive bubble in agricultural futures prices at various times in recent years, and financial index investors were one of the main drivers of spikes in food commodity prices that have occurred since 2007. For example, a technical report published by the International Food Policy Research Institute[4] *When speculation matters*, a briefing note shown by srfood[5] *Food Commodities Speculation and Food Price Crises. Regulation to reduce the risks of price volatility*, and a policy paper developed by Oxfam[6] *Not a Game: Speculation vs Food Security: Regulating financial markets to grow a better future*. However, the argument that buying pressure from financial index investment in recent years did not cause massive bubbles in agricultural futures prices has been also considered [AIG13].

Climate change may undermine global food security and increase human conflicts [CA79, HMC11, SFT+12, SBK+12, HBM13]. Food production in middle income countries was found to be especially vulnerable to droughts by using a quantitative harvest vulnerability index based on annual soil moisture and grain production data as the dependent variable in a Linear Mixed Effects model with national scale socio-economic data as the independent variables [SFT+12]. Higher temperatures and lower rainfalls have little effect in rich countries but substantially reduce economic growth and have wide-ranging effects in poor nations, reducing agricultural output, industrial output, and aggregate investment, and increasing political instability [DJO08].

Dynamic models, based on static modeling, are supposed to reflect the sys-

[4] The International Food Policy Research Institute (IFPRI) is an international agricultural research centre founded in the early 1970s to improve the understanding of national agricultural and food policies to promote the adoption of innovations in agricultural technology.

[5] The srfood is a Special Rapporteur who works for the United Nations and reports on the right to food.

[6] Oxfam is an international confederation of 17 organizations working in approximately 90 countries worldwide to find solutions to poverty and related injustice around the world.

tem's change across a time scale. Food-related production, consumption, shortages and riots can be viewed as an ecosystem that may respond in a smooth, continuous way to changing conditions or may switch abruptly to a contrasting alternative stable state.

Recent application of analytical procedures to various aspects of non-equilibrium dynamics that involves economics [Set98, Kee03, GKLO06, Cou12, Kee13], sociology [Eps99], ecology [SBB+09, BWAJ+10, MB10, FL13], and physics [Cro99, Kee03, Dew05, GKLO06, Guj10, Ves12], provides some capacity to quantify patterns. In the context of ecosystem behavior, for instance, the following components have broad application: (1) dramatic ecosystem change may result from small changes in conditions or drivers; (2) these changes are not readily reversed by proportional changes to the conditions or drivers; and (3) ecosystem resilience is altered as a result of these changes [SCF+01]. Also, catastrophe theory studies endogenous discontinuities in certain kinds of dynamical systems that arise as given control variables change continuously [RJ11a].

Considering the lack of static models and the insufficiency of application of nonlinear dynamical models, we identify the basal characters and dynamic factors based on the previous literature, and design a nonlinear dynamic model to predict the Asian food security risk.

5.2 An Asian Food Security Risk Engine

An Asian Food Security Risk Engine is being developed as a computable model for scenario planning and for predicting, one month ahead, the threat severity to internal security and stability occurring within any of 27 Asian developing countries[7].

The risk engine uses a basal characteristic index to distinguish countries from each other. Next, the risk engine uses a dynamic factors index to measure the flow of anger, i.e. to describe the dynamics of a poor Asian nation's stock of anger based on basal characteristic index. Finally, based on dynamical stocks of anger,

[7] Referring "composition of macro geographical (continental) regions, geographical sub-regions, and selected economic and other groupings" by United Nations [Uni10], the 27 Asian developing countries consist of 3 Caucasus countries (Armenia, Azerbaijan, Georgia); 5 Central Asian countries (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan); 7 South Asian countries (Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka); 9 South East Asian countries (Cambodia, East Timor, Indonesia, Laos, Malaysia, Myanmar, Philippines, Thailand, Vietnam); and 3 East Asian countries (China, Mongolia, North Korea). The country sets exclude 15 West Asian countries (Bahrain, Cyprus, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, State of Palestine, Syrian Arab Republic, Turkey, United Arab Emirates, Yemen) and 2 South Asian countries (Afghanistan, Iran) due to selective geographic factors, and developed Asian countries (Brunei, Singapore, Hong Kong, Japan, Macao, South Korea) because of economic factors.

threats take place once the stocks break through the threshold, triggers amplify the anger, and policies give a positive or negative feedback. At the same time, triggers and policies are dynamical, depending on the threats and on themselves.

At the heart of the model that drives the risk engine lies a three-dimensional first-order differential equation system that calculates the threat effects, as caused by the relevant basal, dynamic, trigger, and policy variables. Time lags that recognize such facts as local prices taking one month to reflect world prices have been built in. There are 27 sets of such equations, one differential equation system per country.

As for the calculation of basal characteristic index across countries, data collection ranges from 1990 to 2010 annually, and the average values are used to measure cross-section components. Cross-country difference measurement depends on principal components analysis (PCA) that also gives a way to identify the key factors that reflect the initial stock of anger for each country.

As for selection of dynamic factors determining the flow of anger, in this model, both food price and energy price are included, given that food price is a double-edged sword for the poor [SS12], although a recent tendency shows higher correlation between food price and energy price.

As for evaluation or data collection on threats, triggers and policies for each country in a given month, they comprise only those due to food-related problems, as occurred from January 2006 to December 2012. Security problems due to border disputes and tribal, ethnic, religious, self-determination, or separatist movements within Asian countries were excluded from the analysis, unless they were responsible for triggering food-related threats.

Finally, threats, triggers, and policies data over the period 2006-2008 are used for parameter estimation, while the 2009-2012 data are reserved for hypothesis testing.

5.3 The Basal Characteristic Index: Initial Stock of Anger

A basal characteristic index is used to distinguish countries from each other, in order to measure the basis for the food-related problems coming from both cross-country and within-country variation.

5.3.1 Development of the Dataset

In several Asian developing countries, the polity seems almost permanently to inhabit the first, second, etc. rung on a kind of “threats ladder”. This initial "rung number" (with its associated "anger thermometer reading") is hypothesized to be due to certain, almost permanent, enviro-socio-politico-economic structural features, termed the basal characteristic index (see Table 5.1 for the variables and their categories and sources, and Table 5.2 for the definitions of variables) of that nation. These may include such long-duration features as autocratic ruling elites, repressive regimes and lack of press freedoms.

Table 5.1: Basal characteristic index: sources of variables

Category	Variable	Source
Economic	Gini Index	UNDP
Economic	GDP % in Agriculture	WDI, World Bank
Economic	GDP growth per capita	WDI, World Bank
Economic	GDP per capita PPP	WDI, World Bank
Ecological	Distance to the equator	Bansal and Ochoa [BO11]
Ecological	Geographic group	Author calculation
Ecological	% Agricultural land	FAO
Ecological	% Arable land	FAO
Ecological	Cereal	WDI, World Bank
Ecological	Precipitation	WDI, World Bank
Political	Political system ranking[8]	Author calculation
Political	Press freedom rating	Freedom House
Political	Polity2[9]	Polity IV project
Social	Culture index	Williamson and Mathers [WM11]
Social	% Adult literacy	UNESCO
Social	Total adult literacy rate	UNESCO
Social	% Population under 25	US Census Bureau
Social	Total age dependency	US Census Bureau
Social	% Males aged 15-24	WDI, World Bank
Social	% Urban population	WDI, World Bank
Social	Fertility rate	WDI, World Bank
Social	Mortality rate	WDI, World Bank
Social	Population density	WDI, World Bank
Social	Telephone lines	WDI, World Bank
Social	Google news hits	Author calculation

[8]The authors assign the rankings between 0 and 10 discretely to Asian countries in means of the similarity and difference between two selected countries.

[9]The Polity2 variable from the Polity IV project measures the level of democracy, which is identical to the polity variable with the exception of periods of interruption, interregnum, and transition [PN10].

The time series data coming from the United Nations Statistics Division and World Bank are almost all available over the period 1990-2010. Hence, the average over this period is available and provides a stable basal characteristic index. However, some political variables cannot be accessed annually, and it is still reasonable to measure a basal characteristic index by using data of a specific year due to decades of stability for almost every country.

Table 5.2: Basal characteristic index: definitions of variables

Variable	Definition
Gini Index	Gini Index in 2005.
GDP % in Agriculture	Share of Agricultural GDP in GDP in 2000.
GDP growth per capita	GDP per capita growth (annual %). Average over 1990-2010, when available.
GDP per capita PPP	GDP per capita, PPP (constant 2005 international dollar). Average over 1990-2010, when available.
Distance to the equator	Countries grouped by distance to the equator.
Geographic group	Central Asia = 1, East Asia = 2, South East Asia = 3, South Asia = 4, Caucasus = 5.
% Agricultural land	Share of Agricultural area in Land area. Average over 1990-2010, when available.
% Arable land	Share of Arable area in Agricultural area (in %). Average over 1990-2010, when available.
Cereal	Cereal yield (kg per hectare). Average over 1990-2010, when available.
Precipitation	Precipitation (mm pa) in 2008.
Political ranking	Political system ranks assigned by authors (0 to 10).
Press freedom	Index of quality of the legal environment.
Polity2	Political stability indicator institutionalized autocracy minus democracy score (-10 to 10).
Culture index	The sum of three positive beliefs (control, respect, trust) minus the negative belief (obedience). The index uses PCA to extract the common variation among all four components, and then it is normalized to range between 0 and 10.
% Adult literacy	Population share of literate people aged 15 and above. Average over 1990-2010, when available.
Total adult literacy	Number of literate people aged 15 and above. Average over 1990-2010, when available.
% Population under 25	Population share of males under 25. Average over 1990-2010, when available.

Variable	Definition
Total age dependency	Number of persons under age 15 plus persons aged 65 or older per one hundred persons 15 to 64 in 2009. Average over 1990-2010, when available.
% Males aged 15-24	Population share of males aged 15-24 years. Average over 1990-2010, when available.
% Urban population	Percentage of total population living in cities. Average over 1990-2010, when available.
Fertility rate	Number of children per woman. Average over 1990-2010, when available.
Mortality rate	Infant mortality rate (per 1000 live births). Average over 1990-2010, when available.
Population density	Population density (persons per km^2) in 2009. Average over 1990-2010, when available.
Telephone lines	Number of telephone connections. Average over 1990-2010, when available.
Google news hits	The annual amount of news item hits by Google search engine (<country name> AND food AND riots OR protests OR strikes). Average over 1990-2010.

The analysis of basal characteristic index was based on Table 5.1 above, i.e. a dataset of 25 variables drawn from the World Development Indicators (WDI) database of the World Bank, plus other databases published by the FAO, the UN Educational, Scientific and Cultural Organization (UNESCO), the US Census Bureau, the Asian Development Bank (ADB), and the author's calculations, describing the degrees of difference for 27 Asian developing countries. Indicator values were computed as 21-year averages over the period 1990-2010. Table 5.3 below provides summary statistics from across 27 nations for the 25 variables in four categories, i.e. ecological (6 variables), political (3 variables), economic (4 variables), and social (12 variables).

Table 5.3: Summary statistics for basal characteristic index

Variable	Mean	Std. Dev.	Minimum	Maximum
% Agriculture GDP	26.4291	13.1768	8.5990	57.2387
GDPPC growth	3.4641	2.5786	-1.5714	9.6460
GDPPC PPP	2754.5270	2145.1273	731.2237	10451.6131
Gini	0.3823	0.0582	0.1850	0.4850
Agricultural land	41.1534	19.9840	7.9584	78.0413
Arable land	44.8323	28.7824	0.9155	91.1085
Cereal	2580.3924	953.0950	831.5333	4949.6944

Variable	Mean	Std. Dev.	Minimum	Maximum
Distance to the Equator	2.0741	0.8286	1.0000	3.0000
Geographic Group	3.0000	1.2710	1.0000	5.0000
Precipitation	1338.5185	849.0592	161.0000	2875.0000
Political System Ranking	5.9630	4.1183	1.0000	12.0000
Polity2	-0.4466	6.2858	-9.0000	9.7647
Press Freedom Rating	67.0000	18.4161	33.0000	99.0000
% Adult literacy	82.7189	20.9083	38.5160	99.9983
% Males aged 15-24 years	9.8421	0.8915	7.4684	12.2168
% Population under 25	53.0507	7.2391	36.0155	62.1363
% Urban population	37.2759	15.6402	13.3929	65.2271
Culture index	4.5807	1.6224	2.1100	8.0400
Fertility rate	3.1329	1.1112	1.7488	6.5176
Mortality rate	45.0337	20.3410	8.5125	80.8625
Population density	200.3118	291.4693	1.7193	1246.2223
Telephone lines	6.4895	5.1794	0.1853	18.3171
Total adult literacy rate	78.9598	26.7680	0.8605	99.9983
Total age dependency	53.6528	11.6686	39.3980	92.1152
Google news hits	59.7743	86.0192	2.4762	347.2381

5.3.2 Principal Components Analysis

Principal components analysis (PCA) is used to extract the common factors underlying variations in the basal characteristic index of 27 Asian developing countries in the period 1990 to 2010. Whenever the characteristics for different countries changed independently, we inferred that they were driven by country-specific factors. Whenever they moved together, we inferred that all countries are subject to common factors. The raw data used to construct the basal characteristic (BC) index comprised that set of $n = 25$ basal characteristics, variables or indicators listed in Table 5.1 above. These were standardized, i.e. measured as the deviations from the means and divided by the standard deviations. Not all trend patterns are alike, but they do appear to comprise relatively independent components.

A correction for correlated system noise in the 25 Basal indicators is applied. In computing the principal components (PCs) we reduced the dimension of the data by finding those few ($m < n$) orthogonal linear combinations of the $n = 25$ original variables that exhibit the largest variance. The purpose of PCA is to cut through variation within the sample to see whether certain members of the dataset of Basal variables are truly related to one another. Briefly, PCA is a statistical method for extracting those factors or components responsible for the co-movement of a group of variables, and it allows the synthesizing of such information.

By running the PCA, we integrated the 25 ecological, social, political, and economic indicator values into a single BC Index, which then was normalized to range from 1 to 100 (cf. minimum to maximum base stock of anger) for 27 Asian developing countries. An index that aggregates more than one indicator facilitates the use of complex information by non-experts. For example, decision-makers need a global, long term, "first-cut" evaluation of food security vulnerability, but they may not have the knowledge necessary to understand the complexity of, and trade-offs among, the components of complex social-political-economic-ecological systems. These are easily synthesized by an over-arching metric like the BC Index [CB10].

Differently from conventional food security index, we did not rely on some arbitrary and ad-hoc selection of weights/loadings to compute the aggregate measure for each country. Instead, we determined these weights using PCA. In a nutshell, the procedure involved an orthogonal linear transformation of n possibly-correlated indicators into a far smaller number m of uncorrelated variables called principal components. The first PC accounts for as much of the variation in the original data as possible, with each succeeding component accounting for as much of the remaining variation as possible.

The matrix of basal characteristics sub-indexes (SI) can be written as follows, where the ith row represents one of the 27 Asian nations and the jth column represents one of the 25 sub-indexes of basal characteristics:

$$\begin{pmatrix} SI_{1,1} & SI_{1,2} & \cdots & SI_{1,25} \\ SI_{2,1} & SI_{2,2} & \cdots & SI_{2,25} \\ \vdots & \vdots & \ddots & \vdots \\ SI_{27,1} & SI_{27,2} & \cdots & SI_{27,25} \end{pmatrix} \tag{5.1}$$

The weighting vectors are referred to as eigenvectors in PCA. The overarching index can be expressed in terms of these eigenvectors as follows: the ith country's basal characteristic index (BC_i) is calculated as

$$BC_i = \sum_{j=1}^{n} \frac{SCORE_j \times (SI_{ij} - SI_j)}{SD_j} \tag{5.2}$$

where $SCORE_j$ is the factor score for factor j, SI_{ij} is the ith country's basal characteristics sub-index for factor j and SI_j and SD_j are the mean and standard deviation, respectively, of the factor j variable over all 27 countries. To compute the factor score for a given case for a given factor, one takes the case's standardized score on each variable, multiplied by the corresponding factor loading of the variable for the given factor, and sum these products.

5.3.3 Empirical Results

Once defining BC_i for the ith country as a combination of the first N_{PC} principal components, and choosing $N_{PC} = 4$, Table 5.4 below shows that the first principal component (PC_1) of the basal characteristic dataset is positively correlated (= 0.6612) with annual GDP per capita growth. The second principal component (PC_2) of the basal characteristic data was positively correlated (= 0.6175) with GDP per capita, PPP (constant 2005 international dollar). The third principal component (PC_3) of the basal characteristic data was positively correlated (= 0.4991) with annual GDP per capita growth and positively correlated (= 0.4969) with the share of agricultural GDP in GDP. The fourth principal component (PC_4) of the basal characteristic data was positively correlated (= 0.5993) with the cereal yield productivity (kg per hectare) and positively correlated (= 0.4339) with geographic group.

Table 5.4: Principal component analysis of 27 Asian developing countries in the 25 basal characteristics

Characteristics	Vectors			
	PC_1	PC_2	PC_3	PC_4
Eigenvalue	6.6910	3.7772	3.6360	2.0140
% of variance explained	26.7639	15.1089	14.5439	8.0559
Correlations:				
% Agriculture GDP	-0.3129	0.0938	0.4991	-0.2391
GDPPC growth	0.6612	-0.2467	-0.4969	-0.2354
GDPPC PPP	0.3696	0.6175	-0.2534	0.2971
Gini	0.0559	0.0486	-0.3201	-0.1656
Agricultural land	-0.4214	0.3837	0.2796	-0.0517
Arable land	0.0108	0.2245	-0.2232	-0.2380
Cereal	0.1438	-0.0514	-0.1599	0.5993
Distance to the Equator	0.1129	0.4801	0.0369	0.2881
Geographic Group	0.0997	0.1867	0.0866	-0.4339
Precipitation	-0.0374	-0.1533	-0.0336	0.0069
Political System Ranking	0.0436	0.0495	0.3633	-0.1208
Polity2	0.0479	0.0352	0.1567	0.2490
Press Freedom Rating	0.1925	0.1368	-0.0478	-0.0337
% Adult literacy	-0.1054	0.1458	-0.0177	0.0034
% Males aged 15-24 years	0.1494	0.0840	0.0099	0.0166

Characteristics	Vectors			
	PC_1	PC_2	PC_3	PC_4
% Population under 25	-0.0709	0.0507	-0.0625	0.0152
% Urban population	0.0682	-0.0487	0.0566	-0.0393
Culture index	0.0914	0.0163	0.0595	-0.0201
Fertility rate	-0.0983	-0.0104	0.0170	0.0253
Mortality rate	0.0138	-0.0053	0.0495	0.0309
Population density	-0.0043	-0.0336	0.0108	0.0085
Telephone lines	-0.0129	0.0146	-0.0067	-0.0085
Total adult literacy rate	0.0071	-0.0032	0.0299	0.0048
Total age dependency	0.0030	-0.0090	-0.0009	0.0035
Google News Hits	0.0026	-0.0068	-0.0004	-0.0010

The first two rows of the table refer to the principal components. The eigenvalues and the explained variance proportions are displayed. The variance proportion is calculated as the ratio of each eigenvalue to the sum of all eigenvalues. All other rows display the weights corresponding to each principal component (eigenvector corresponding to each principal component). Additionally, the empirical results identify the key factors that contribute the initial stock of anger in the top, i.e. annual GDP per capita growth, GDP per capita measured by the purchasing power parity (PPP) method, the share of agricultural GDP in total GDP, the cereal yield productivity, and geographic group (Central Asia, East Asia, South East Asia, South Asia, and Caucasus).

Table 5.5 below shows the basal characteristic index, where Column "Original BC" is the basal characteristic that originates from Equation (5.2), Column "Standardized BC" developed by standardizing the original basal characteristic by standard deviation, and Column "Index for BC" arose by normalizing standardized basal characteristic index to the range 1-100, where 1 means minimal initial stock of anger, and 100 maximal.

Table 5.5: Basal characteristic index

Country	Original BC	Standardized BC	Index for BC
Armenia	61.0141	0.7536	28
Azerbaijan	80.1432	0.9899	22
Bangladesh	-92.0386	-1.1368	77
Bhutan	-67.3081	-0.8314	69
Cambodia	-58.5554	-0.7232	66
China	144.2426	1.7816	2
East Timor	-165.7366	-2.0471	100

Country	Original BC	Standardized BC	Index for BC
Georgia	55.3750	0.6840	30
India	-75.7708	-0.9359	71
Indonesia	-18.2078	-0.2249	53
Kazakhstan	93.3358	1.1528	18
Kyrgyzstan	34.3488	0.4243	37
Laos	-20.0938	-0.2482	54
Malaysia	-34.5000	-0.4261	58
Maldives	-82.5723	-1.0199	74
Mongolia	21.9718	0.2714	40
Myanmar	57.0323	0.7044	29
Nepal	-99.7901	-1.2326	79
North Korea	146.2851	1.8068	1
Pakistan	-89.3587	-1.1037	76
Philippines	-78.8794	-0.9743	72
Sri Lanka	-26.1944	-0.3235	56
Tajikistan	0.2280	0.0028	47
Thailand	-13.2331	-0.1634	52
Turkmenistan	87.4111	1.0797	20
Uzbekistan	84.7808	1.0472	21
Vietnam	56.0703	0.6925	30

5.4 Dynamic Factors Index: The Flow of Anger

In thermal physics, Fourier law states that the rate of heat flow depends on a temperature difference, but it also depends on the resistance or conductance of the intervening medium. For the simplest condition, Fourier's equation is represented by

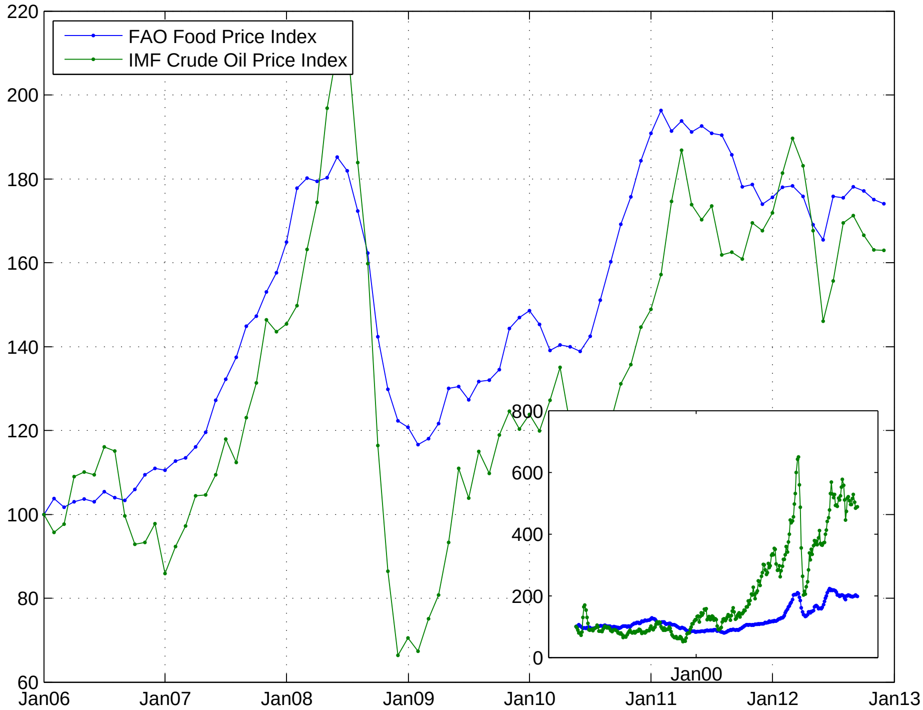
$$q = -k\frac{\mathrm{d}}{\mathrm{d}x}T \tag{5.3}$$

where k is the thermal conductivity, T is the temperature, x is the spatial displacement, and q is the rate of heat flow.

By analogy, Dynamic Factors $DF_1, DF_2, \ldots, DF_n$ are viewed as temperature (T) and the basal characteristic BC_i as thermal conductivity (k). For spatial displacement (x), we can use temporal displacement (t) instead, that is

$$FA_i(t) = -BC_i\sum_{k=1}^{n}\frac{\mathrm{d}}{\mathrm{d}t}DF_k \tag{5.4}$$

Figure 5.1: FAO food price index and IMF crude oil price index



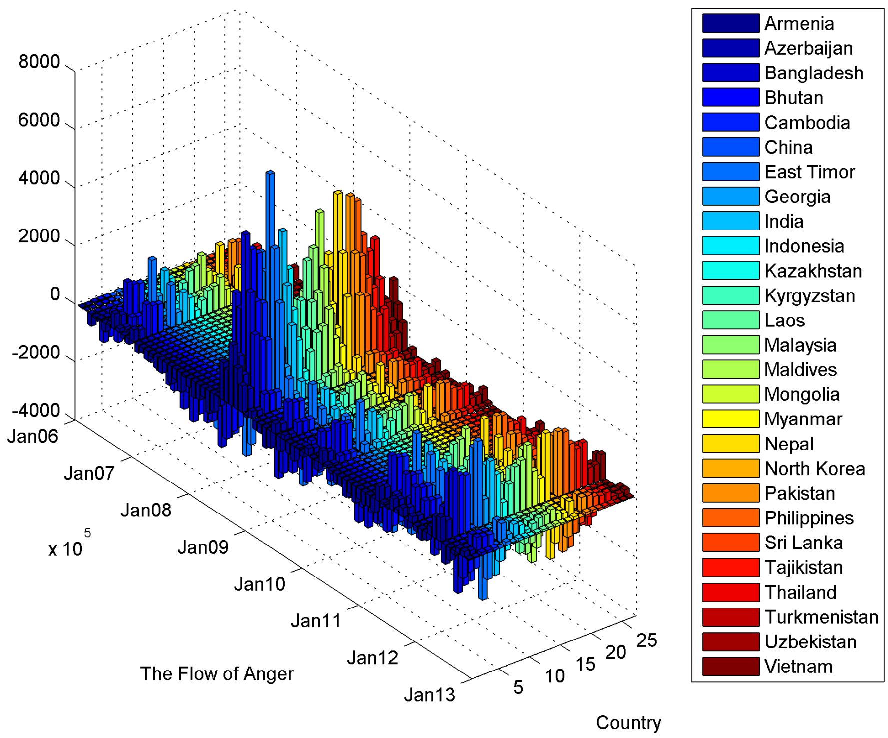
where heat flow (q) is replaced by FA_i, the flow of anger that alters the polity's initial stock of anger, i.e. stock of discontent, in country i. When $n = 2$, so that $DF_1(t)$ is the FAO food price index[10] and $DF_2(t)$ is the International Monetary Fund (IMF) crude oil price index[11], Figure 5.1 shows the period for further parameter estimation and hypothesis testing, that is a time series of the index from January 2006 to December 2012 where index for January 2006 = 100. The inset figure shows a time series of the index from January 1990 to June 2013, which is the latest available data, where the index for January 1990 = 100. We are aware that there is a strong correlation between the FAO food price index and the IMF crude oil price Index. However, we argue that less analysis on cause and effect between food price and energy price would lead to the potential insufficiency on dynamic regression if we omitted the energy price.

The flow of anger $FA_i(t), i = 1, 2, \ldots, 27, t \in [01/2006, 12/2012]$ can be tracked as plotted against time in Figure 5.2 below following Equation (5.4).

[10]FAO food price index takes the average of five monthly spot price indexes (meat, dairy, cereals, oils and sugar) covering a total of 55 commodity quotations deemed representative of international food prices. Local food price indexes in developing countries track this global food price index closely, with a time lag of one month [OCC11].

[11]IMF crude oil price index is average of three spot prices: Dated Brent, West Texas Intermediate, and the Dubai Fateh.

Figure 5.2: The flow of anger of 27 Asian developing countries in the period 2006 to 2012



5.5 The Differential Equation System

Differential equation systems often are complex and always are dynamic. The flip of a complex dynamical system from one state to another is called its "tipping point" and there is increasingly popular interest from the fields of ecology and ecosystem [MLS08, Cos09, SBB+09, WDL+12, SCL+12, FSJ13, SLH13], economics [LT12, FKMO13, DE13], sociology [US05, LGK12, SWD12], physics [Sor02, Sor03, SH03, SDGA04, Ves12] and biology [DMB+12, FL13]. There is a potential for trigger events to push elements of the food-related civil unrest system past a critical threshold or tipping point, beyond which they would change state dramatically, leading to larger-scale threat severity. Different types of threats have qualitatively different effects on governments' choice of policies.

While many approaches to explaining civil strife hypothesise mechanisms that operate at short time scales [PSX07, Bel11, LBBY11, HMC11, Bra12, BBK12, SBK+12, OWL+12, HBM13], we propose that the underlying cause of food-related troubles often should be searched for months earlier. In my view, there can be a progressively increasing build-up of external turbulence upon the internal socio-economic environment, which translates into accelerating fluctuations of the local food price along a rising trend. According to this point of view, a specific trigger event is not always the spark that immediately sets off a conflagration. A food riot also can occur because the society has entered an unstable phase, so almost any small disturbance may have ignited this instability.

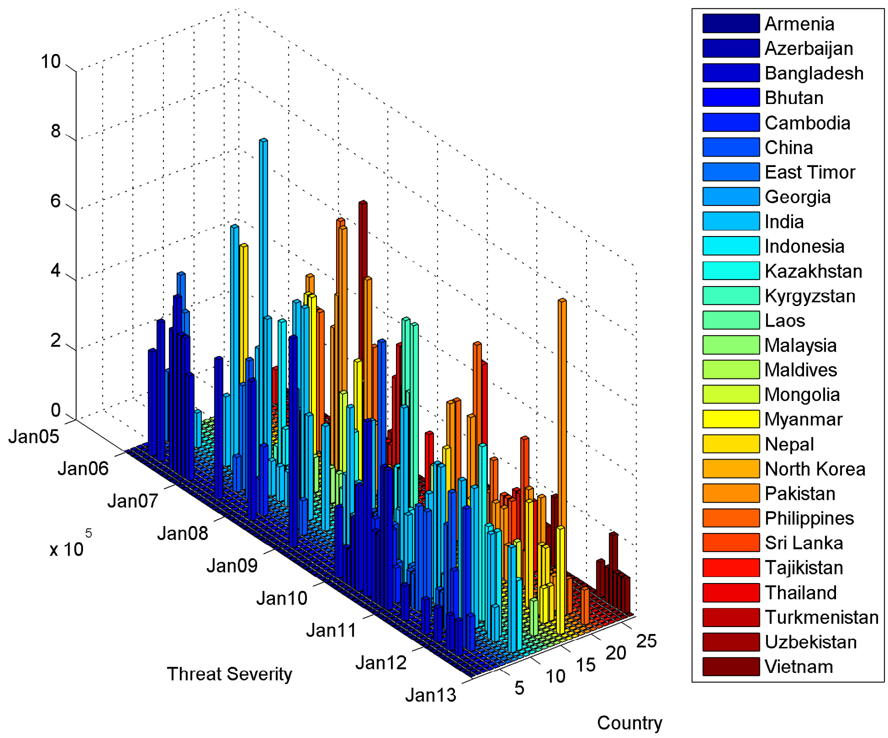
There is an analogy with an active volcano: this very unstable situation eventually will lead to its eruption, as the result of a small earthquake or any tiny change of heat flux. The eruption is fundamentally due to the unstable situation, with the instantaneous cause of the eruption being secondary. In the same way, the increasing discontent and the growing instability of the society close to such a critical point can explain why attempts to model the local (country-level) origins of food-related civil strife have been so diverse. We explore here the concept that a threat fundamentally has an endogenous origin, with exogenous shocks serving only as instantaneous triggers. As a consequence, the origin of threats is far more subtle than often thought because such situations progressively build up in the society as a whole: there is a self-organizing process at work, which could be termed a "systemic instability", a frequently-used concept in financial system studies [CMV09, HM11, HK12b, AKM12, May13].

Real complex systems are almost never in equilibrium, i.e. frequently they may be "out of equilibrium" [Art99, RJ99, SFS+09] and behave in non-stationary ways, where the complexity of the situation forces elements in system to reflect and update their behavior according to their performance. For instance, governments may modify the food policies to moderate the threat of food riots and the situation can fluctuate within the domains of attraction of one or more system states [EA96, KMC10, FJPS04].

A "regime shift" occurs when a system crosses a threshold, after which it is governed by a different set of processes and feedbacks [FZG+10]. The presence of internal system feedbacks also explains why regime shifts exhibit hysteresis: once the system is in a particular regime it tends to remain there, even if the change in inputs that caused the shift is reduced or removed. Because different sets of dominant feedbacks are associated with different regimes, the critical threshold for a shift from Regime 1 to 2 often differs from the critical threshold for a return shift from Regime 2 to 1. In the food security case, internal system feedbacks consist of threats accumulated through international dynamic factors getting stacked on top of the underlying basal characteristic index of each country; also triggers that abruptly change the system and policies that reduce the influence of the inputs as internal system feedbacks. There is a situation in which, when one regime has low food security risk, the other regime cannot smoothly reach the regimes having high food security risk. Food security risk will increase suddenly if the trigger reaches the threshold.

According to Colin Richardson and William Zhao [RZ13], firstly, we define

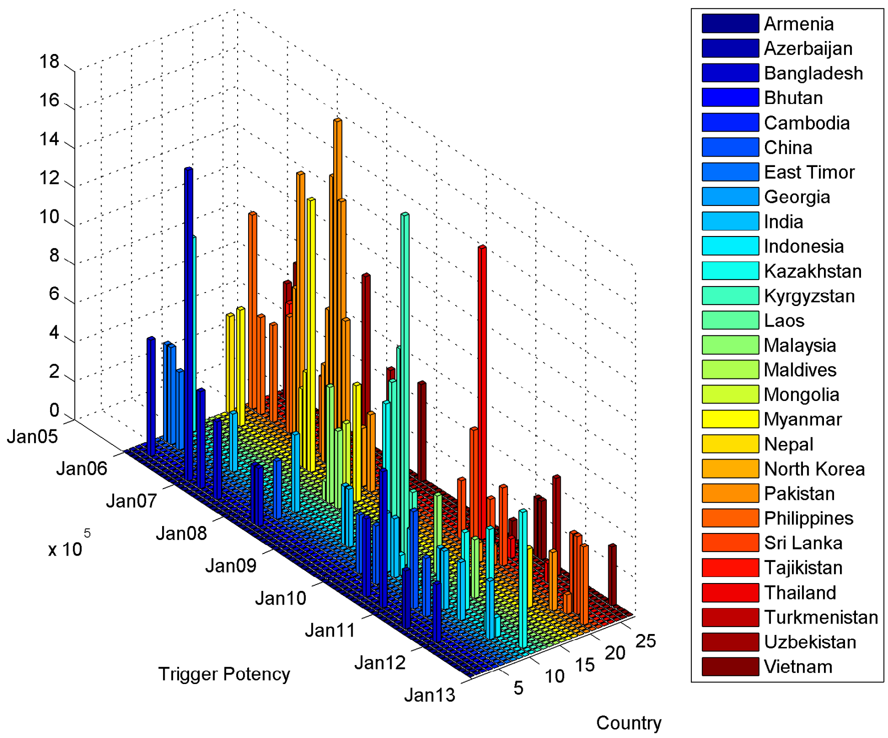
Figure 5.3: Threat severity of 27 Asian developing countries in the period 2006 to 2012



the threat severity as a ladder from 1 to 10 where as the rung number increases the threat severity rises following (1) protests, e.g. posters, petitions, on-line anger, marches, rallies, sit-ins, occupations, barricades, effigy burnings (minor property damage, injuries); (2) extensive protests, strikes (minor property damage, injuries), and/or sieges; (3) violent protests, and/or extensive strikes (major property damage, injuries); (4) violent protests, and/or violent strikes (1+ killed in one month); (5) riots (10+ killed in one month); (6) extensive riots (100+ killed in one month), and/or mutiny; (7) mass riots (500+ killed in one month), and/or putsch; (8) insurgency, rebellion, and/or coup d'etat; (9) extensive rebellion, and/or revolution; and (10) extensive revolution, and/or civil war. Figure 5.3 shows a monthly time series of the threat severity over the period 2006-2012 for 27 Asian developing countries.

Secondly, we define the trigger potency as a ladder from 1 to 10 where as the rung number increases the trigger potency rises following (1) land grabs, price rises, lower subsidies/rations, and/or urban wage cuts announced; (2) intensification of fiscal, monetary or trade discipline, i.e. austerity or free trade or privatization; and government limits or bans entry of external food aid; (3)

Figure 5.4: Trigger potency of 27 Asian developing countries in the period 2006 to 2012



C-list citizen(s) TAJH[12]; curfew declared; and/or trigger #1 implemented; (4) head of state/government attempts to extend term of office; local media crackdown; state of emergency declared; and/or so-called anti-terrorism law(s) passed or toughened; (5) B-list citizen(s) TAJH; unrest in the military, security or police forces; Internet selectively blocked or shut down; elections postponed; and/or foreign media crackdown; (6) opposition political parties banned; military coup; opposition fears rigged election; foreign journalists denied entry; and/or state purchases food from domestic sources to boost government reserve stocks; (7) A-list citizen(s) TAJH; government or business corruption scandal; and/or head of state/government decrees direct rule; (8) C-list citizen(s) KSEDT[13]; and/or massacre(s) of ¡ 10 women/children or ¡50 men; (9) B-list citizen(s) KSEDT; and/or massacre(s) of 50+ men; and (10) A-list citizen(s) KSEDT; and/or massacre(s) of 10+ women/children. Figure 5.4 shows a monthly time series of the trigger potency over the period 2006-2012 for 27 Asian developing countries.

Finally, we define the policy effectiveness as a ladder from 1 to 10 where as the rung number increases the trigger potency rises following (1) state switches military/police/civil service, etc. rations from expensive to cheaper staples; state

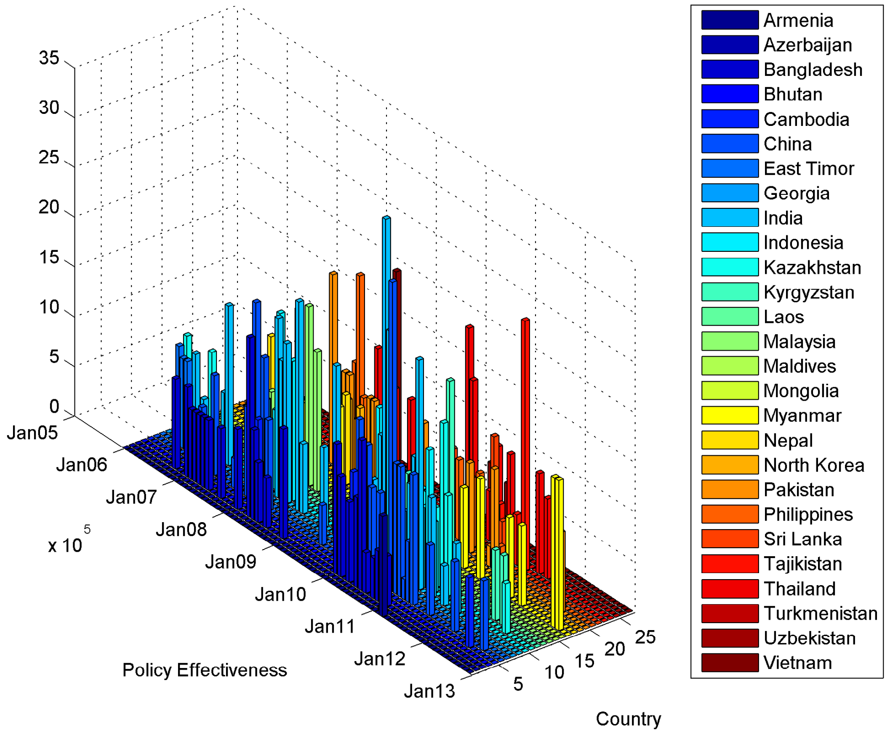
[12]TAJH is short for targeted, arrested, jailed, or on hunger strike

[13]KSEDT is short for killed, suicide, executed, disappeared, or tortured.

limits food purchases per shop visit; and/or state orders smaller portions served in all cafes and restaurants; (2) state controls food prices by fiat; and/or state rations food consumption; (3) impose/lift penalties for food smuggling, price fixing, hoarding, cheating, price gouging, etc.; and/or state subsidizes wholesale food prices; (4) state of emergency lifted; state subsidizes retail food prices; and/or state encourages switching of diets from imported to domestically produced food; (5) police/military/security punished for actions against protesters; targeted transfers of cash, cash for work or subsidized food to the poorest families; and/or control panic buying of food; (6) state suspends purchasing food from domestic sources of supply; state auctions more food from government reserve stocks; and/or state rationalizes food reserves procurement from overseas; (7) head of state/government lifts direct rule; release surviving C-list citizens from prison; crackdown on government/business corruption; raise wages and/or employment of urban workers; ban/limit futures trading and commodity speculation in food; raise interest rates or required reserve ratios of banks; and/or state gifts food from government reserve stocks to local WFP/NGOs to distribute; (8) release surviving B-list citizens from prison; remove/lower import tariffs, quotas and/or domestic taxes on food; state purchases more food imports; and/or state accepts more food aid from donors; (9) change head of state/government; adopt new constitution; release surviving A-list citizens from prison; and/or ban/limit food exports by raising food export taxes, imposing food export quotas or setting minimum export prices; and (10) intervention by UN, adjacent nation(s), etc.; complete change of government; ban/limit foreign land grabs or conversion of farmland for non-agricultural purposes; and/or other actions to increase domestic food production, e.g. debt relief/waiver, cheaper credit, minimum support prices, subsidized inputs for farming or other key activities along the food supply chain. Figure 5.5 shows a monthly time series of the policy effectiveness over the period 2006-2012 for 27 Asian developing countries.

Given the threat severity index $TS_i(t)$, trigger potency index $TP_i(t)$, and policy effectiveness index $PE_i(t)$ at time t in country i, we assume that the change in threat severity depends on 4 factors, with 2 of these 4 factors being weighted by the flow of anger. The first is previous threat severity itself accelerated by previous trigger potency, and we assume that the rate of increase is proportional to the current threat severity. Thus, when the trigger is more potent, the previous threat contributes more. Then, the previous threat severity is decayed by previous policy effectiveness, and we assume that the rate of decrease is proportional to the current threat severity. Thus, when policy is more effective, previous threat contributes less. Next we assume that the change in threat severity is also proportional to the trigger potency, but weighted by the flow of anger. The modification

Figure 5.5: Policy effectiveness of 27 Asian developing countries in the period 2006 to 2012



assumes that if the flow of anger is low, then the impact of trigger potency will be reduced in proportion. For simplicity we assume the interdependency is linear. Finally, we assume that the change in threat severity is proportional to policy effectiveness. Because policy has a relatively slow impact on social dynamics, we assume that the change in threat severity depends on the current month's value for the policy effectiveness. However, we assume that policy has a limited impact on threat severity as the flow of anger increases. To reproduce this behavior, we represent the weighting of policy effectiveness by flow of anger using the Hill equation that describes the non-linear saturation of biochemical reactions. Thus when the flow of anger is low, the impact of policy is low. However, as flow of anger increases, the impact of policy does not increase in proportion, but the weighting increases more slowly up to a maximum value. Therefore, the threat severity equation is written as

$$\begin{aligned}\frac{\mathrm{d}TS_i}{\mathrm{d}t} &= \alpha_1 FA_i(t)TP_i(t) + \alpha_2 TP_i(t-1)TS_i(t-1) \\ &+ \frac{\alpha_3 FA_i^2(t)}{FA_i^2(t)+F^2}PE_i(t) + \alpha_4 PE_i(t-1)TS_i(t-1) \qquad (5.5)\end{aligned}$$

where $F = 10$ is constant comprising the Hill function to affect the acceleration of the Hill transformation part, α_1 is the rate at which the acceleration of current trigger potency by the flow of anger is added onto TS_i; α_2 is the rate at which the previous threat severity (accelerated by previous trigger potency) is added onto TS_i; α_3 is the rates at which the current month's policy effectiveness, weighted by the Hill transformation of the flow of anger, is added on to TS_i; and α_4 is the rate at which the previous threat severity (decayed by the previous policy effectiveness) is deleted onto TS_i.

Furthermore, we assume that the change in trigger potency depends on 3 factors. The first is the level of trigger potency itself, and we assume that the rate of increase in the trigger potency is proportional to the current trigger potency. Next we assume that the change in trigger potency is also proportional to the current and previous month's value for the trigger potency, but weighted by policy effectiveness. The modification assumes that if the policy is effective, then the impact of trigger potency will be reduced in proportion. For simplicity we assume the interdependency is linear. Therefore, the trigger potency equation is written as

$$\frac{\mathrm{d}TP_i}{\mathrm{d}t} = \beta_1 TP_i(t) + \beta_2 TP_i(t)PE_i(t) + \beta_3 TP_i(t-1)PE_i(t-1) \tag{5.6}$$

where β_1 is the rate at which new trigger potency is added onto TP_i per se. trigger potency is assumed to grow exponentially while current and previous policy effectiveness reduce the growth of trigger potency at the rate of β_2 and β_3 respectively.

Finally, we assume that the change in policy effectiveness also depends on 3 factors. The first is the level of policy effectiveness itself, and we assume that the rate of increase in the policy effectiveness is proportional to the current policy effectiveness. Next we assume that the change in policy effectiveness is also proportional to the current and previous month's value for the policy effectiveness, but weighted by trigger potency. The modification assumes that if the trigger potency is high, then the impact of policy effectiveness will be reduced in proportion. For simplicity we assume the interdependency is linear. Therefore, the policy effectiveness equation is written as

$$\frac{\mathrm{d}PE_i}{\mathrm{d}t} = \gamma_1 PE_i(t) + \gamma_2 TP_i(t)PE_i(t) + \gamma_3 TP_i(t-1)PE_i(t-1) \tag{5.7}$$

where γ_1 is the rate at which new policy effectiveness is added onto PE_i per se. policy effectiveness is assumed to decay exponentially while current and previous trigger potency increase policy effectiveness at the rate of γ_2 and γ_3 respectively.

5.6 Parameter Estimation

The Parameter Estimation Spreadsheet in the report paper written by Colin Richardson and William Zhao [RZ13] reveals much about the 2006-08 episode of widespread food-related civil unrest, which affected all but 9 of the 27 countries across 5 regions of Asia. For a start, there were 197 items or monthly mentions of these 24 countries in the 36-month time span.

In terms of total mentions per year, there were 231 in 2006, rising to 412 in 2007 then almost doubling to 702 in 2008. This hints at how the the stock of anger and government attempts at amelioration ramped up as the FAO world food price index approached its first episode peak of 224.4 (nominal food price index) in June 2008.

This section estimates the model's parameters (i.e. those αs, βs and γs in the above equations (5.5), (5.6), and (5.7)) using multivariate regression analysis on data from the period 2006-08. Once a set of ideal equation parameters has been estimated, in next section, they are re-named as coefficients to recognize they are merely statistical approximations to the ideal numbers.

Considering that the index of threat (Figure 5.3), the index of trigger (Figure 5.4), and the index of policy (Figure 5.5) are sparse matrices (consisting of lots of zeros), before regressing the coefficients of Threat-Trigger-Policy system, we transfer all 0 into 1 in order to avoid the disappearance of the parts with the flow of anger through

$$y = \log(x + 1) + 1 \tag{5.8}$$

where x is original definition of index for threat, trigger, and policy, and y is its transformation for clearing away zeros. We estimate α_j $(j = 1, 2, 3, 4)$, β_j and γ_j

($j = 1, 2, 3$) by seeking the least squares solution based on

$$\partial\left(\frac{\mathrm{d}TS_i}{\mathrm{d}t}(t)\right)\Big/\partial(FA_i(t)TP_i(t)) \sim \alpha_1 \tag{5.9a}$$

$$\partial\left(\frac{\mathrm{d}TS_i}{\mathrm{d}t}(t)\right)\Big/\partial(FA_i(t-1)TP_i(t-1)) \sim \alpha_2 \tag{5.9b}$$

$$\partial\left(\frac{\mathrm{d}TS_i}{\mathrm{d}t}(t)\right)\Big/\partial\left(\frac{FA_i^2(t)PE_i(t)}{FA_i^2(t)+F^2}\right) \sim \alpha_3 \tag{5.9c}$$

$$\partial\left(\frac{\mathrm{d}TS_i}{\mathrm{d}t}(t)\right)\Big/\partial(PE_i(t-1)TS_i(t-1)) \sim \alpha_4 \tag{5.9d}$$

$$\partial\left(\frac{\mathrm{d}TP_i}{\mathrm{d}t}(t)\right)\Big/\partial TP_i(t) \sim \beta_1 \tag{5.9e}$$

$$\partial\left(\frac{\mathrm{d}TP_i}{\mathrm{d}t}(t)\right)\Big/\partial(TP_i(t)PE_i(t)) \sim \beta_2 \tag{5.9f}$$

$$\partial\left(\frac{\mathrm{d}TP_i}{\mathrm{d}t}(t)\right)\Big/\partial(TP_i(t-1)PE_i(t-1)) \sim \beta_3 \tag{5.9g}$$

$$\partial\left(\frac{\mathrm{d}PE_i}{\mathrm{d}t}(t)\right)\Big/\partial PE_i(t) \sim \gamma_1 \tag{5.9h}$$

$$\partial\left(\frac{\mathrm{d}PE_i}{\mathrm{d}t}(t)\right)\Big/\partial(TP_i(t)PE_i(t)) \sim \gamma_2 \tag{5.9i}$$

$$\partial\left(\frac{\mathrm{d}PE_i}{\mathrm{d}t}(t)\right)\Big/\partial(TP_i(t-1)PE_i(t-1)) \sim \gamma_3 \tag{5.9j}$$

Table 5.6 reports the results for the estimation of coefficients of the Threat-Trigger-Policy system, and shows that the exponential parts for trigger, and policy have a higher R^2 (between 0.71-0.73) while other parts share a similar value of R^2 (between 0.23-0.37) other than the parts for explaining the threat with the flow of anger and its Hill transformation.

Table 5.6: Coefficients for the Threat-Trigger-Policy system. The robust t-statistics for each estimated coefficient are given in right columns.

	Coefficient		Residual		N	R^2	Adj-R^2
α_1	-3.59E-5	-1.94625	-0.00075	0.040575	972	0.287015	0.286237
α_2	-0.31633	-19.2026	0	-0.03917	972	0	0
α_3	0.039808	1.284315	-0.00112	-0.04958	972	0.001797	0.000708
α_4	-0.2107	-14.9908	-0.00084	-0.04166	972	0.197002	0.196125
β_1	1.504792	50.34963	0.005574	0.360212	972	0.734576	0.734286
β_2	0.329378	16.77368	-0.00394	-0.14981	972	0.234981	0.234146
β_3	-0.33617	-17.257	-0.00672	-0.2577	972	0.245349	0.244525
γ_1	1.427	47.93961	0.001115	0.051293	972	0.715015	0.714704
γ_2	0.564934	23.50268	0.007982	0.248226	972	0.376182	0.375501

	Coefficient		Residual		N	R^2	Adj-R^2
γ_3	-0.52484	-21.0228	0.003431	0.102601	972	0.325457	0.324721

The results do hint that we are on the right track. There are several other options available for further development of this first attempt at a differential equation system, or for adopting some alternative, but strictly hypothesis-consistent, equation set. The aim is to comprehensively validate the stock of discontent hypothesis using the best possible system of equations.

5.7 Hypothesis Validation

In order to validate the stock of discontent hypothesis, we employ the data on threat severity, trigger potency, and policy effectiveness in 27 Asian developing countries using the same dataset belonging to Colin Richardson and William Zhao's report paper [RZ13], and spanning the period 2009-12, to parameterize the differential equations (5.5), (5.6) and (5.7) according to Figure 5.3, Figure 5.4 and Figure 5.5. In terms of total mentions per year, there were 115 in 2009, rising more than 7 times to 845 in 2010 before falling to 357 in 2011 and 201 in 2012.

The differential equation system is a one-month-ahead prediction model and includes a one-month-lag element in order to reflect policy's hysteresis effect, plus the delay differential equations covering the threat severity, trigger potency, and policy effectiveness for 48 months over the period of 2009-12. Therefore, the tests start with the threat-trigger-policy index in December 2008, and use two continuous months' index values in the differential equation system to predict the third month then compare with its true value. Finally comparison between solutions of 48 delay differential equation system and 48-month true values for each one of 27 countries reveals the robustness of the model.

Figure 5.6 displays the comparison of known real-world and model-simulated threat severity. The ideal result would be distributed around the line having a slope of 45 degrees.

As mentioned before, introducing the flow of anger combines basal characteristic index and dynamic factors with the threat-trigger-policy differential equation system, and reflects a change of anger accumulation from the aspect of viewpoint on historical time (not ergodic time) which is difficult to be fused in a closed differential equation system. Given the flow of anger is zero, the differential equation

Figure 5.6: Comparison between predicted and actual threat severity with dynamical flow of anger

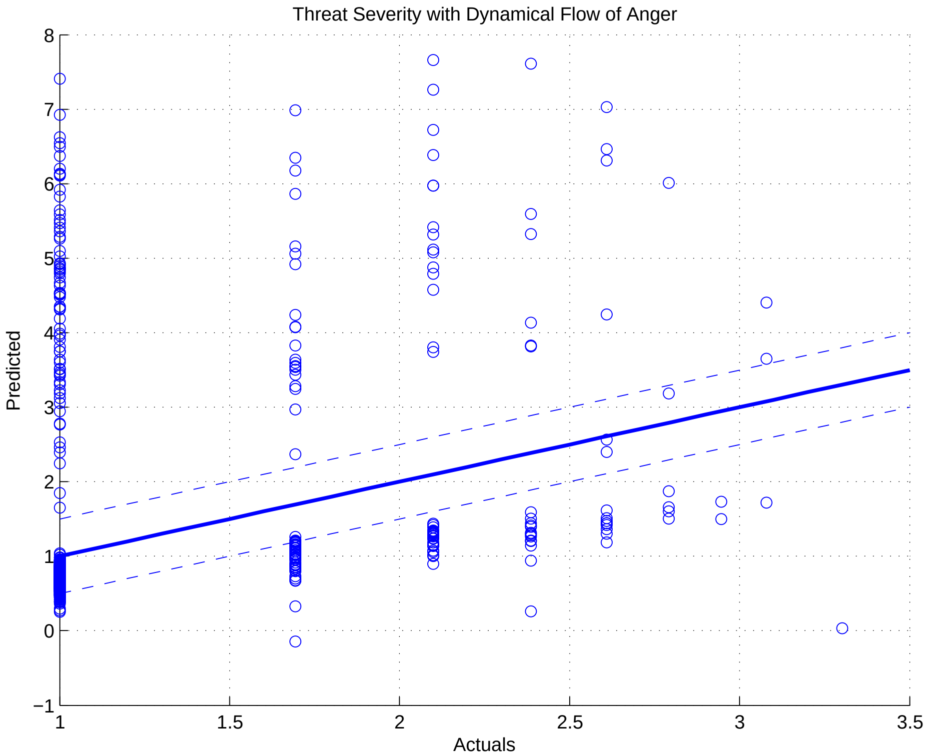
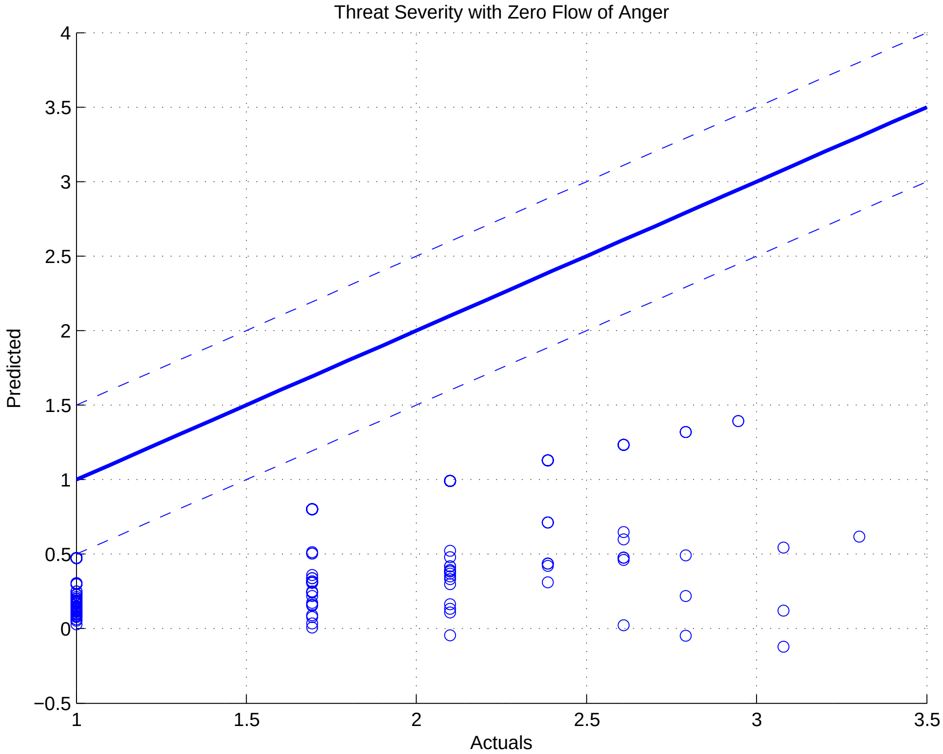


Figure 5.7: Comparison between predicted and actual threat severity with zero flow of anger



system (5.5), (5.6), and (5.7) become

$$\frac{\mathrm{d}TS_i}{\mathrm{d}t} = \alpha_2 TP_i(t-1)TS_i(t-1) + \alpha_4 PE_i(t-1)TS_i(t-1) \tag{5.10a}$$

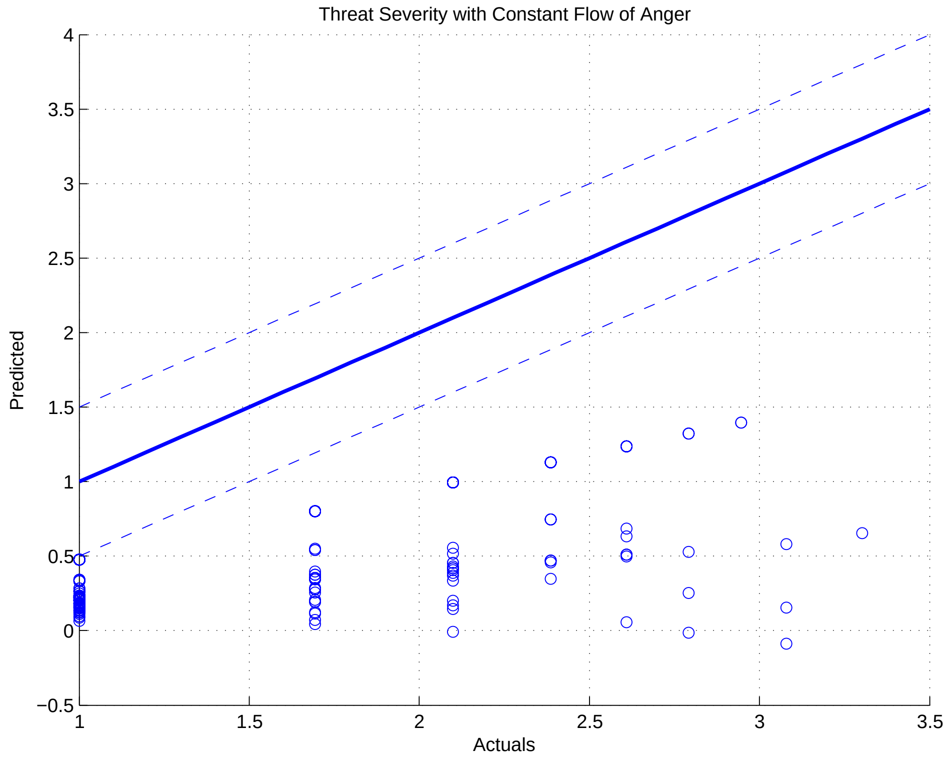
$$\frac{\mathrm{d}TP_i}{\mathrm{d}t} = \beta_1 TP_i(t) + \beta_2 TP_i(t)PE_i(t) + \beta_3 TP_i(t-1)PE_i(t-1) \tag{5.10b}$$

$$\frac{\mathrm{d}PE_i}{\mathrm{d}t} = \gamma_1 PE_i(t) + \gamma_2 TP_i(t)PE_i(t) + \gamma_3 TP_i(t-1)PE_i(t-1) \tag{5.10c}$$

Figure 5.7 displays comparison known real-world and model simulated threat severity with zero flow of anger. The ideal result would be distributed around the line with slope of 45 degree.

In order to highlight the advantage of the introduction of the flow of anger, we assume the flow is a constant other than zero, i.e. the flow of anger exists but is exogenous to the threat-trigger-policy system. Given the flow of anger is a

Figure 5.8: Comparison between predicted and actual threat severity with constant flow of anger



constant, say one, the differential equation system (5.5), (5.6), and (5.7) becomes

$$\frac{\mathrm{d}TS_i}{\mathrm{d}t} = \alpha_1 TP_i(t) + \alpha_2 TP_i(t-1)TS_i(t-1) + \frac{\alpha_3}{1+F^2}PE_i(t) + \alpha_4 PE_i(t-1)TS_i(t-1) \tag{5.11a}$$

$$\frac{\mathrm{d}TP_i}{\mathrm{d}t} = \beta_1 TP_i(t) + \beta_2 TP_i(t)PE_i(t) + \beta_3 TP_i(t-1)PE_i(t-1) \tag{5.11b}$$

$$\frac{\mathrm{d}PE_i}{\mathrm{d}t} = \gamma_1 PE_i(t) + \gamma_2 TP_i(t)PE_i(t) + \gamma_3 TP_i(t-1)PE_i(t-1) \tag{5.11c}$$

Figure 5.8 displays comparison known real-world and model simulated threat severity. The ideal result would be distributed around the line with slope of 45 degree.

Figure 5.6, Figure 5.7 and Figure 5.8 show the threat severity under three system stimulating the nexus of threat, trigger and policy respectively. We can see that (1) three scenarios are not good enough for predicting the threat severity; (2) dynamical flow of anger beats the other two scenarios.

5.8 Conclusions and Discussion

This chapter has developed a dynamic system model to predict the threat severity arising from food insecurity in Asian developing countries. The underlying idea that there is only one small step between "food" and "blood", or that there is small distance from "hunger" to "anger" is old. Therefore the food price index is viewed as one of the most important variables in food security and social conflicts research [LBYBBY11]. Based on Amartya Sen's seminal works [Sen81] that food distribution, not food price, contributes more to social conflicts arising from food insecurity and food shortage, and by analogy with relevant thermodynamic systems, a model with an initial value for "anger", a flow of "anger", and a "tipping point" from anger to social unrests respects the fact that anger dynamics is complex, requires accurate linking between different variables, and needs more data.

In order to measure initial anger level, the model started by developing a basal characteristic index number for each Asian developing country based on 25 basal characteristics covering 4 areas (ecological, economic, social, and political) by using the principal components analysis (PCA) technique which provides a possible way to regress an index for comparable anger levels. Most of these characteristics cover the period of 1990-2010 and their average values are applied. A small subset of them depends on specific annual data because of either the lack of accessible long term data, or credible long term stability of data properties.

Based on this basal characteristic formulation, dynamic factors that include FAO food price index and IMF crude oil price Index in monthly level are applied to 27 Asian developing countries to identify the flow of anger. The flow of anger is analogous to the flow of heat in thermodynamic systems, and plays an important role in the equation set linking threat severity, trigger potency and policy effectiveness. Indeed, a dynamical system without the flow of anger is also developed for comparison which shows the prediction with lower errors cannot reflect the advantage of application on the flow of anger, however, with higher errors, the system fusing the flow of anger gives a better predicted threat severity, trigger potency and policy effectiveness, hence demonstrates the utility of the flow of anger in predicting threats, triggers, and policies.

A first-order three-dimensional differential dynamical system consisting of threat severity, trigger potency, and policy effectiveness is proposed to simulate the internal dynamics and potential tipping points. The system can predict the threat severity for next month in a given country, given the level of threat severity, trigger potency, and policy effectiveness this month and the flow of anger based on the long term basal characteristic index (a constant), FAO food price index and IMF crude oil price Index in the month.

In order to estimate the parameters of the dynamical system, multiple linear regression analyses are performed using the Richardson index for threat severity, trigger potency, and policy effectiveness [RZ13] over the period 2006-2008 which covers the most volatile food price and serious food insecurity situation. In order to validate the system, predictions based on these fitted parameters, are applied to predict the independent values for the Richardson index [RZ13] over the period 2009-2012.

One issue is the shortage of data for some countries. It is important to point out that data shortage limited the components we could select for the basal characteristics. Further data availability can enhance this measure. Another issue is the potential application of localized food and oil prices. It should be emphasized that incorporation of a local price dynamic will improve the simulation accuracy. Unfortunately these considerations are beyond the scope of the current work.

Chapter 6

Conclusions

Complexity is an inevitable part of security for energy, water and food, but most studies report on static modeling within a closed system. Sustainability should be viewed in a broader context than development in the neoclassical sense. A synthesis of complexity and sustainability for the energy, water and food nexus demands a number of stronger methodological features than were available to us. Embracing nonlinear dynamics encourages our better understanding on system's evolution than linear evolutionary than concepts based on static or ergodic systems. Accepting a system as open is a more realistic representation than assuming it is closed. Determinant uncertainty nourishes non-determinant philosophy that implies the need of policy intervention and the possibility of good outcomes through social change. Applying the synthesis framework to the environmental security issues can test the validation of the method, but also deepen the understandings on sustainability. In this thesis, we use the methods of differential equations systems with initial values to discuss three models concerning environmental security - namely energy, water, food.

First, we consider business cycles and macroeconomic volatility contributing to excessive energy consumption and to excessive entropy production, concluding that the more frequent business cycles, the more intensive macroeconomic volatility, then the more energy consumption by humans' economic activities. This, in fact, proves that according to the thermodynamic first law, the energy is conserved, whereas according to the second law of thermodynamics, the energy diffusion process is irreversible, the entropy production is inevitable, but energy expenditure is path-dependent, therefore the different energy usage paths have impacts on the entropy production and entropy accumulation. We also realize that it is difficult to quantify this effect; therefore the model employs a simplified approach, which considers only the unemployment rate and the rate of capacity utilization producing the entropy. The results show that if we do not reduce the frequency of the business cycles, and the intensity of the macroeconomic volatility, both environmental protection and sustainable use of energy would be compromised by the man-made threats.

Second, we establish a system dynamics model comprising three subsystems, i.e. the micro food production, micro food consumption, and macro-economy which couples with the ecological system, but also is relatively independent. At the micro level, both firms' capital stock and personal wealth are assumed to satisfy the Zipf's law, and the Engel ratio is used to connect micro food consumption and the price of the food through introducing the conception of a mark-up rate on costs developed in the macroeconomic system. At the macro level, we follow the Post Keynesian tradition, starting from the income distribution, combining this with ecological economics contributions, i.e. the non-renewable natural capital and the entropy production based on the utilization of capital stock and available labor force to develop a Post Keynesian ecological economics model. In a case study of the Murray-Darling basin, we combine future potential climate change and water security for the macro-economy to present a high-dimensional differential equations system. We use the dataset covering the period 1978-2005 to estimate the parameters in this system, then validate them based on the dataset from the period 2006-2012. We also give a forecast for the long-run based on the system and combined three-dimension Lotka-Volterra equations covering the rate of unemployment, the share of profit, and the rate of capacity utilization.

Third, we develop a framework to predict the severity of civil unrest threats related to food insecurity based on three steps - determining long-run basal characteristic index, introducing the medium-run flow of anger, and forecasting the short-run threat, trigger, and policy variables. In order to determine basal characteristic index, we build a dataset in four areas for each country based on the period of 1990-2010, then use principal component analysis to yield the index of each country's basal characteristic index. In order to introduce the concept of the flow of anger, we use the differences of FAO food price index and IMF energy price index, combined with the basal characteristic index of each country, to get a flow of anger for each country in each month. In order to forecast threats, triggers and policies in the short run, we develop a three-dimension delay differential equations system where the threat is determined by current trigger, current and previous policies, and the flow of anger, with the triggers and the policies following the prey-predator model. We use the dataset covering the period 2006-2008 to estimate the parameters in the system, and validate them based on the dataset from the period 2009-2012. We also compare the forecast without the flow of anger and the forecast with it.

The thesis is underpinned by business cycle and demand-driven economic theories in the Post Keynesian tradition, and entropy production in the ecological economic mainstream. On the one hand, we contribute the nexus of Post Keynesian ecological economics consisting of the first investigation of the impact of business cycles on entropy production, the case study of the Murray-Darling basin economy in the long run, and the case study of the forecast of food insecurity in Asia based on the introduction of the flow of anger. However, on the other hand, we realize that further research is needed from a few aspects including the quantification of business cycles and entropy production, the dynamic networking in micro food production and consumption, and its impacts on macro-economy, the potential application of localized food price and oil price, and the trial of macroeconomic methodology from a critical realist perspective. Unfortunately these considerations are beyond the scope of the current work.

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