Achieving Ecological Resilience through Regime Shift Management

M.D. Lemmon

DEPT. OF ELECTRICAL ENGINEERING, UNIVERSITY OF NOTRE DAME

E-mail address: lemmon@nd.edu

ABSTRACT. *Resilience* has come to mean several things in the system sciences. The term is used to describe systems whose function is robust with respect to external disturbances. It is used to describe systems that tolerate faults in some internal component. It is also used to describe systems that have the capacity to recover after a complete collapse of system function. This monograph defines resilience in the last sense. This notion of resilience is often called *ecological resilience*. For a system to be ecologically resilient, one first accept system collapse as being inevitable and then requires that the resources for subsequent system recovery be buried in the wreckage of that collapse.

The ecological concept of a *regime shift* plays an important role in describing abrupt shifts in ecosystem behavior. In particular, the collapse of system function may be seen as an instance of a regime shift. Restoring a collapsed ecosystem often involves walking the system through a specific sequence of alternative states before full recovery can be achieved. The transitions between these alternative states are also regime shifts. But in this case, these regime shifts are purposefully triggered to speed up the recovery process. Managing regime shifts that trigger system collapse provides a way to *conserve* existing system function. Managing regime shifts that systematically rebuild lost system function provides a way to *restore* lost system function. Regime shifts, therefore, play an important role in enhancing the ecological resilience of a dynamical system.

This monograph formalizes the ecologist's regime shift concept by identifying regimes with components (also known as basic sets) of a Morse decomposition of the system's chain recurrent set. This formalization allows the identification of two distinct regime shift mechanisms; one triggered by external shocks (shock-induced regime shift) and the other triggered by bifurcations of the system flow (bifurcation-induced regime shift). This monograph formally defines ecological resilience in terms of a discrete abstraction (called the *regime transition system*) that characterizes the sequences of shock-induced regime shifts that can be triggered in the system. This monograph shows how that transition system can be constructed from the system's differential equation model and demonstrates how it can be used to enhance ecological resilience through the careful management of the system's regime shifts.

Contents

Chapter 1. Introduction - What is a Resilient System? 6

Chapter 2. Regime Shifts 11
1. Regime Shift Mechanisms for Shallow Lake Eutrophication 13
2. Regime Shifts in a Living System 19
3. Food Webs with Consumer-Resource Interactions 24
4. Non-equilibrium Regime Shifts 27
5. Pseudo Regimes 33
6. Summary and Further Reading 38

Chapter 3. Bifurcation Induced Regime Shifts 41
1. Distance to Local Bifurcations (D2B) 42
2. Kinetic Realizations of Consumer-Resource Systems 45
3. Normalized Flux Parameters of Kinetic Systems 48
4. Distance to Local Bifurcation of Kinetic Systems 51
5. Summary and Further Readings 60

Chapter 4. Shock-Induced Regime Shifts 63
1. Jump Diffusion Processes 64
2. Shock-Induced Regime Shift Certificates 68
3. Sum-of-Squares Regime Shift Certificates 72
4. First Passage Times for Intra-Guild Predation System 79
5. Summary and Further Reading 83

Chapter 5. System Restoration through Managed Regime Shifts 85

1. Finding All Equilibria of Consumer-Resource Systems 89
2. Regime Transition System 94
3. Algorithmic Construction of Regime Transition System 97
4. Managing Regime Shifts for System Restoration 103
5. Summary and Further Readings 108

Chapter 6. Conclusion - Are Regime Shifts Real? 110

Acknowledgements 113

Bibliography 114