Effects of substitutability and asymmetry on natural resource management with centralized governance structure

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Abstract

Many resource management studies focus on one resource. Humans, however, rely on multiple resources in a complicated way. A person may derive more well-being from one unit of a resource than from another; one resource may be substituted by another to some degree. How should one manage such coupled natural-human systems? In this work, we build on recent research that focuses on developing conceptual frameworks and mathematical models to understand such interactions. The multiple resource condition injects the concept of substitutability into models of coupled human-natural systems and affects how such systems should be governed. Substitutability has been mostly mentioned in the field of economics for a substitution of natural and human capitals. Similarly, one resource may substitute for other scarce resources in coupled human-natural systems since some of these resources are not completely independent. In this study, we revise and expand an existing conceptual framework to include two natural resources, resource users, governing agency and public infrastructure in a centralized governance structure, i.e., all the natural resources are managed by the same governing entity. We then devise a set of dynamical equations and relationships from different fields, such as a replicator equation, a population equation, and a CES production equation, to capture the dynamics of this coupled system. This analysis can provide a decision-support tool to design policies to sustainably govern the built environment where human, natural resources, and infrastructure are interconnected. Model analysis takes a multi-faceted perspective of both resource users and governing entities to assess policies against different levels of disturbance. The results reveal how substitutability and asymmetry in resource use affect the viable policies needed to maintain the system.

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INTRODUCTION

Coupled system thinking

Recent years have witnessed a growing interest in the "interdisciplinary thinking" related to the coupling of human and other systems (e.g., coupled human-natural systems, socio-ecological systems, socio-hydrological systems, socio-technical systems). In the era of Anthropocene, humans actively engage in the natural processes, thereby adding more nonlinearities and uncertainties to the system analysis. Infrastructure (both hard and soft) is often involved in these complex linkages by either facilitating or hindering interactions between them. Understanding these interactions is essential for policymakers to successfully manage natural resources.

Current research

- Many empirical studies were established by social scientists (represented by Elinor Ostrom) in small-scale local communities.
- Natural scientists and engineers studying socio-ecological systems (SES) using diverse methods to illustrate underlying mechanisms between humans, natural resources and infrastructure.

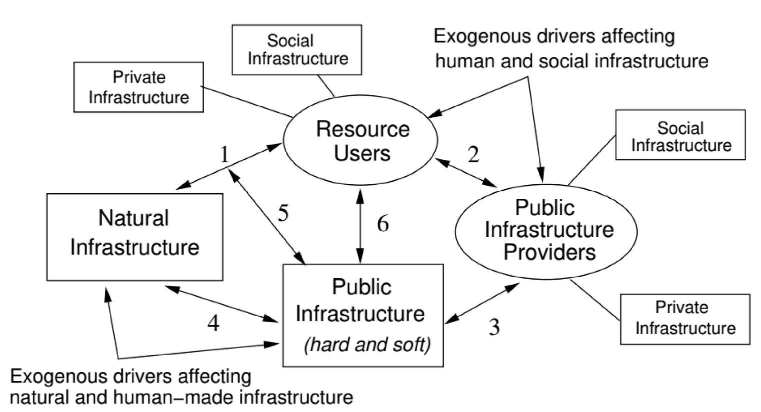

Figure 1. SES robustness framework. *Adapted from Anderies et al., 2004 and Muneepeerakul & Anderies, 2017*

Settings in this study

- There exist two natural resources, each with individual infrastructure (overall two infrastructure) to represent a multiple-resource condition and both infrastructures are managed in a centralized structure, governed by a single PIP (as in Fig. 3).
- The research is rather interaction-focused. Therefore, it clears out a power of entities' heterogeneity (e.g., initial conditions or parameters of two resources) to remove their critical effect to the results, simplifying and clarifying the analysis
- Resource users may share a different portion of efforts on natural resource harvest

A concept of "substitutability" in economics

- Substitutability has been researched in economics to understand an elasticity of substitution between human and natural capitals.
- Such concept is applied to many different substitutions (e.g., human-natural capital substitution, natural capital-energy substitution, import-export goods substitution and information technology-labor substitution)

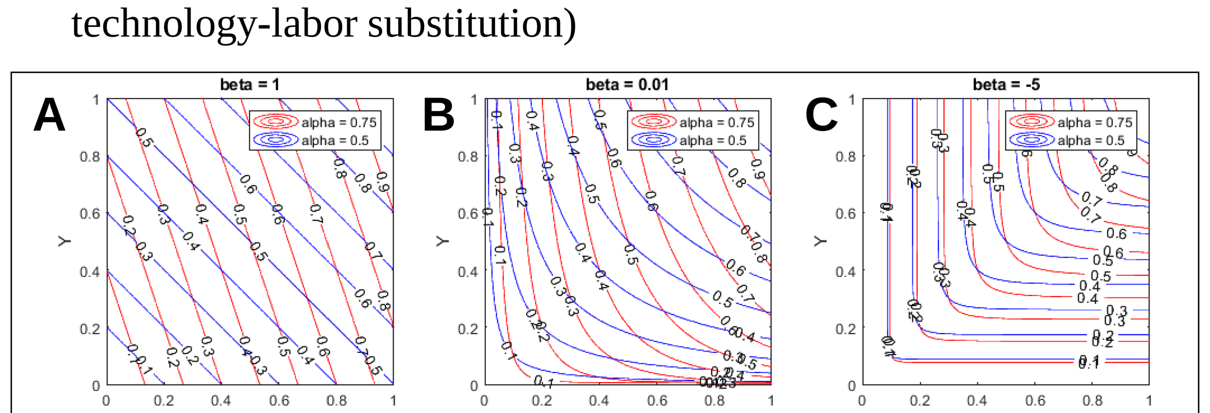

Figure 2. Contours of utilities between two substitutable capitals using CES production function from traditional economics. Contours follow an equation of $f(X,Y) = [\alpha X^{\beta} + (1-\alpha)Y^{\beta}]^{\frac{1}{\beta}}$. A: perfectly substitutable resources, B: imperfectly substitutable resources, and C: complementary resources.

OBJECTIVES

I. Revise/expand the framework and construct a dynamical model with multiple resource conditions and their substitutable relations in a centralized governance structure.

II. Analyze how substitutability of natural resources and asymmetry of resource users' effort shares to multiple resources effect to the management of coupled systems.

III. Compare single-resource and multiple-resource conditions and provide a need for more complexity.

A REVISED FRAMEWORK

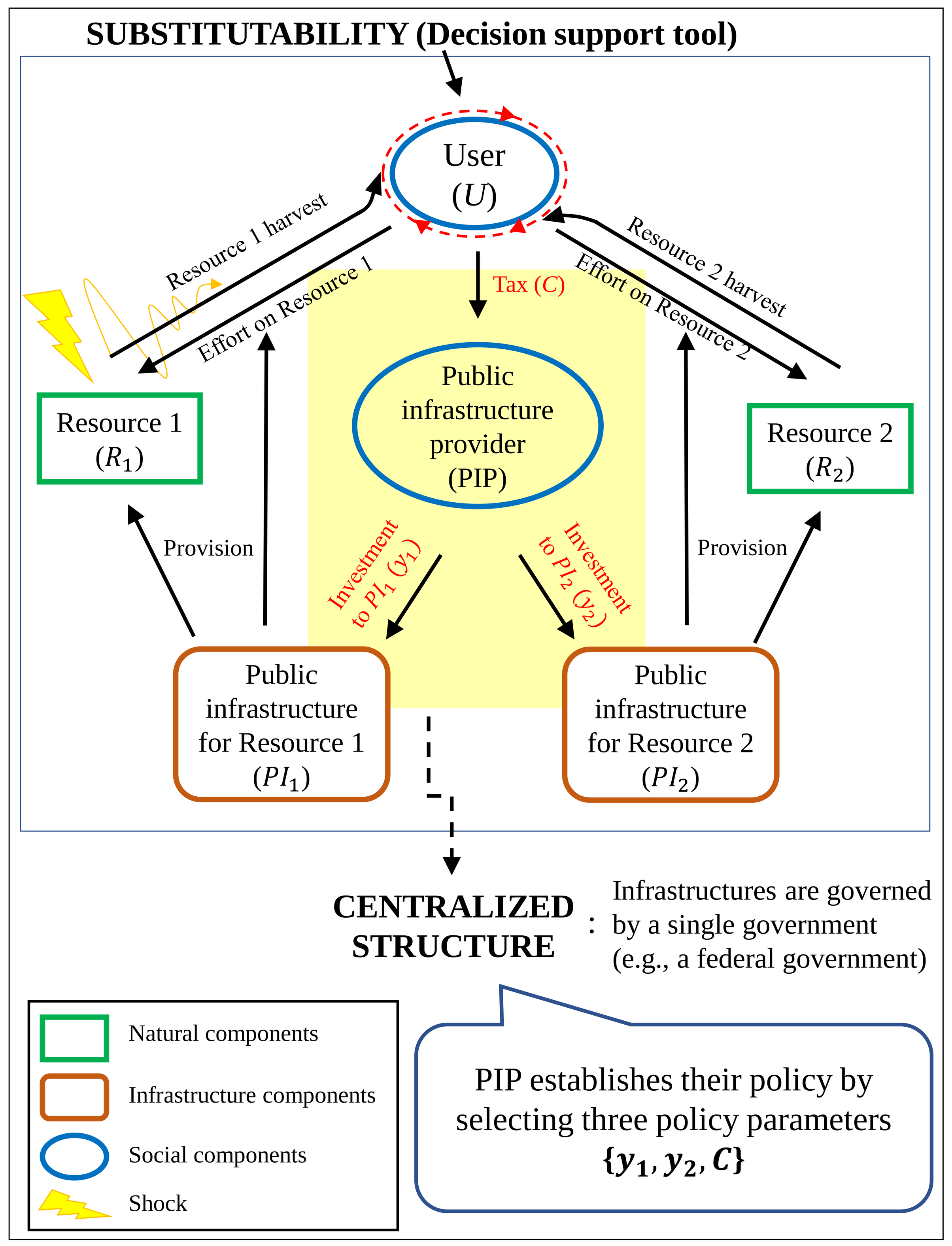

Figure 3. A expanded framework with a multiple resource condition

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METHOD: STYLIZED MODELING

DYNAMICAL SYSTEM MODELING OF THE COUPLED HUMAN-NATRUAL SYSTEMS

Infrastructure dynamics

$$\frac{dI_{HM,i}}{dt} = \underbrace{\mu_{2,i} y_i C p_i \gamma_i U N R_i H_i(I_{HM,i})}_{\text{Maintenance}} - \underbrace{\delta I_{HM,i}}_{\text{Decay}}$$

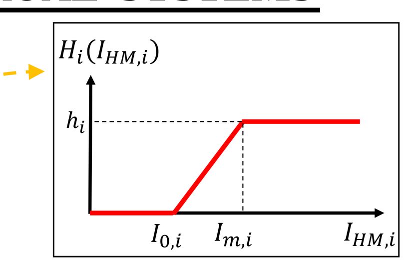

Figure 4. A piecewise function for the productivity of infrastructure i

Natural resource dynamics

$$\frac{dR_i}{dt} = \underbrace{g_i - d_i R_i}_{\text{Natural dynamics (Growth-decay)}} - \underbrace{\gamma_i U N R_i H_i(I_{HM,i})}_{\text{Human harvest}}$$

Social dynamics (replicator eq.)

$$\frac{dU}{dt} = rU(1-U)(\pi_U - w)$$

TWO STRATEGIES

FARMING (STAY INSIDE) *vs* WORK OUTSIDE (GO OUT)

If employment wage > farming profit

$\frac{dU}{dt} < 0 \rightarrow U$ will decrease

SUBSTITUTABILITY MODELING

From CES production equation

$$\pi_U = (1-C)A\left[\sum_{i=1}^{2} \alpha_i \underbrace{\left(p_i R_i H_i(I_{HM,i})\right)}_{\text{Payoff of Resource i in a user perspective}}^{\beta}\right]^{1/\beta}$$

A: an efficiency parameter
α_i: distribution parameter
- $\alpha = 0.5$: symmetric
- $\alpha \rightarrow 0$ or 1: asymmetric

β: a substitution parameter
- $\beta \rightarrow 1$: high substitutability
- $\beta \rightarrow 1$: low substitutability

$$\pi_{PIP} = \underbrace{(1-y_1-y_2)}_{\text{Not invested fraction from tax}} CUNA\left[\sum_{i=1}^{2} \alpha_i \left(p_i R_i H_i(I_{HM,i})\right)^{\beta}\right]^{1/\beta}$$

Model will produce two outputs:

1. *Number of viable policies*: How many possible policy parameter combinations exist to sustain the coupled systems
2. *Expected values of infrastructures*: How well policy parameter combinations build infrastructure performances

ANALYSIS ON POLICY VIABILITY

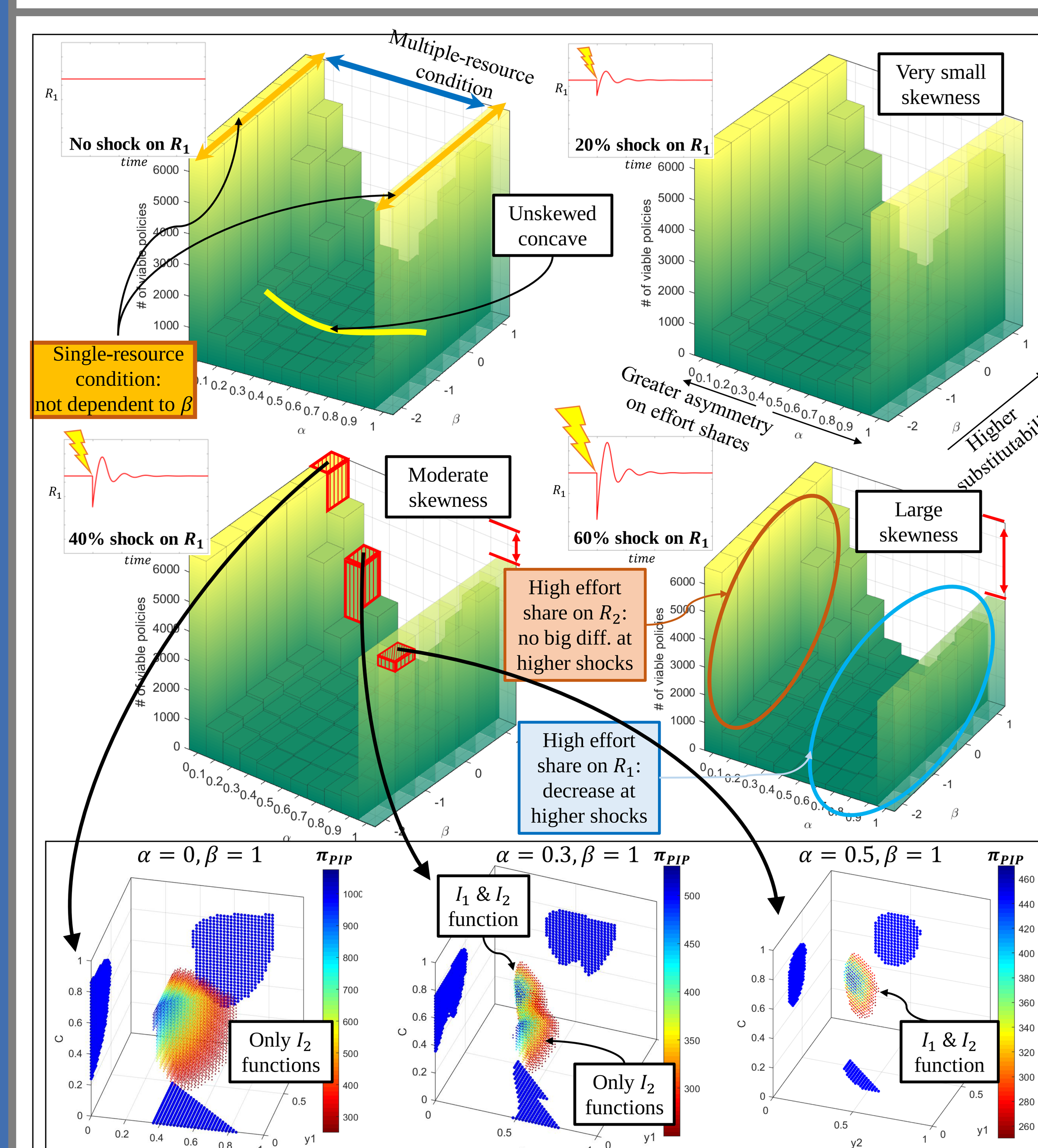

Figure 5. Graphs of the number of viable policies with different α and β values. It also displays policy space ($y_1 - y_2 - C$) at $\alpha = 0, 0.3, 0.5$ when the system experience 40% shock.

ANALYSIS ON POLICY PERFORMANCE

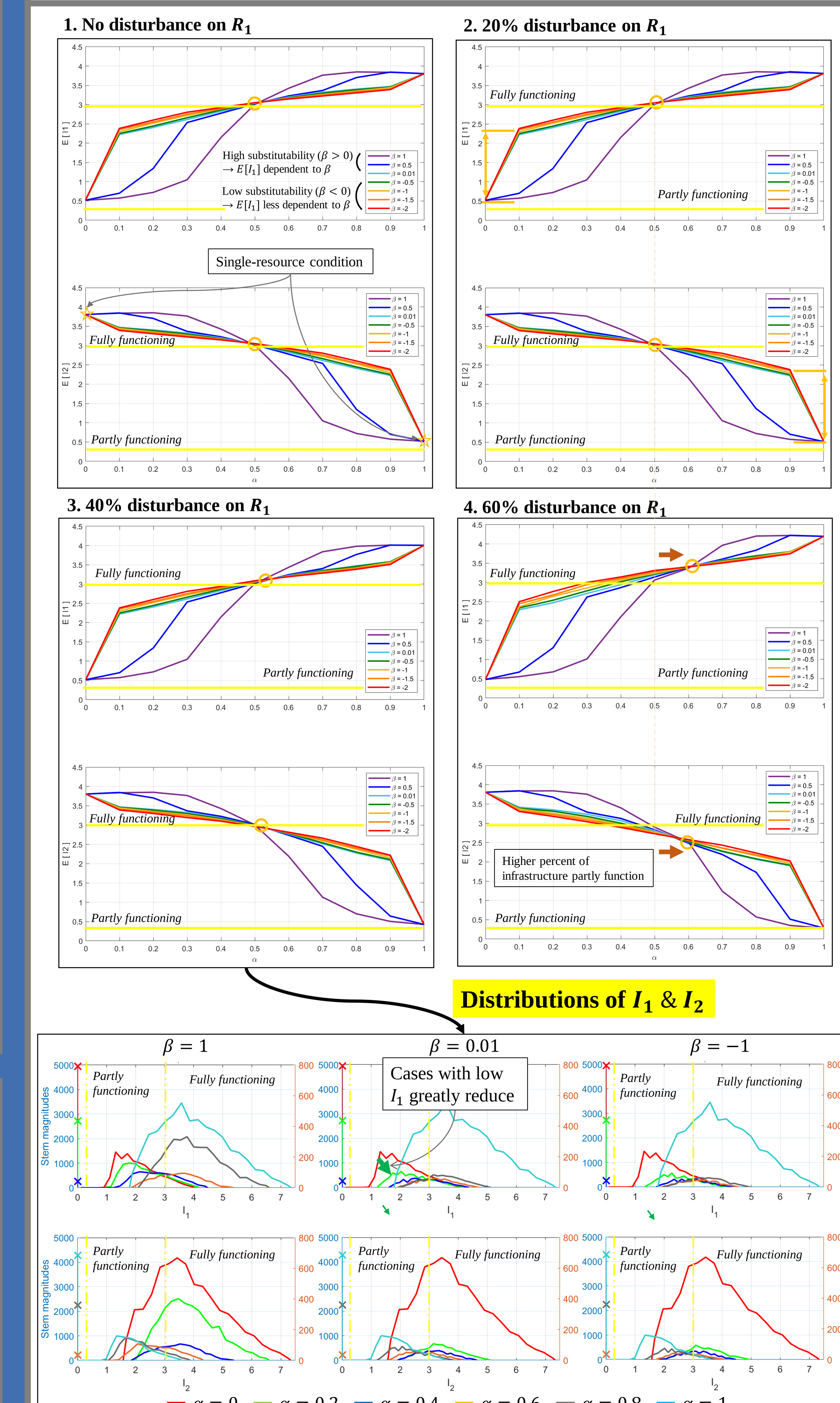

Figure 6. Graphs of the expected values of I_1 & I_2 ($E[I_1]$ & $E[I_2]$) with different α and β values. It also displays distributions of I_1 & I_2 at $\beta = 1, 0.01, -1$ when the system experience 40% shock.

DISCUSSION

- The model simplifies the interactions to clearly explore the mechanism of human-environmental interactions.
- Multiple-resource ($0 < \alpha < 1$) and single-resource conditions ($\alpha = 0,1$) exhibit different behaviors so that modeling multiple resources is critical.
- High substitutability ($\beta > 0$) and higher asymmetry of effort shares (α far from 0.5, close to 0 or 1) helps system to sustain better to the natural shocks.
- This framework can be expanded to the field related to energy or other technologies. For example, R_1 may represent traditional energy, while R_2 may represent renewable energy..
- Ultimately, this research will broaden not only the study of coupled systems but also economics with non-stationary capitals.