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Structural Effects and Aggregation in a Social-Network Model of Natural Resource Consumption

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Abstract In this paper we consider a networked system of natural-resource consumption, where the agents are governed by a recently reported model of consumer psychology. Dynamics of the consumption for each agent are influenced by the state of the resource and consumption of her neighbors. The process is parameterized by the psychological characteristics of each agent. This study extends the original model to incorporate the underlying network topology, and explores the effects of aggregation via densely-connected communities present in the network. The exercise yields new interpretations of the predictions made by the original model in context of the influence network. We present aggregation mechanisms first for certain canonical structures of the consuming population and later on for a class of non-canonically structured populations. In the end we present an approximate aggregation scheme for populations where only some inaccurate information of the consumer characteristics is available.

Keywords: Natural resources management, Social Networks, Modeling and identification of environmental systems, Control in economics, Multi-agent systems.

1. INTRODUCTION

In recent years, the controls community has displayed an increasing interest in human-in-the-loop control systems, which are encountered extensively in the real world as complex socio-technical, socio-economic or socio-ecological systems, to name just a few. Conventional approaches commonly treat human influence in these systems either as external disturbances or exogenous inputs. The human-in-the-loop approach offers a new perspective, whereby humans are treated as fundamental components of the system which may or may not adapt to changes in the surrounding environment. Such a method of inquiry not only results in a more accurate representation of reality, but also uncovers hidden relationships and feedback effects which would otherwise not be taken into account. This presents exciting applications in a diverse range of areas which include (but are not limited to) sociology (Friedkin (2015)), energy management (Nguyen and Aiello (2013)), robotics (Schirner et al. (2013)) and economics (Jager et al. (2000)). In this paper we concern ourselves with the control of socio-ecological systems.

One of the major challenges for human-in-the-loop control is the extension of conventional system-identification techniques in order to accurately model human behavior (Munir et al. (2013)). For socio-ecological systems, various models have been proposed which explicitly account for human behavior (see Anderies (2000); Perman (2003)). However a majority of these models assume that humans act as maximizers of certain objectives (for instance financial profit), and that they are constrained by some common notion of rationality. Human psychology is seldom incorporated in such models, which requires investigating the micro-level interactions that exist between humans and the environment and understanding the factors that drive human behavior in such coupled human-natural systems. There exists a plethora of research conducted by the social-psychology community regarding the various determinants that govern the human behavior in a natural resource crisis (Jager (2000)), commonly referred to as the Tragedy of the Commons (Perman (2003)). While multiple computational (Bousquet and Le Page (2004); Hare and Deadman (2004)) and conceptual (Jager and Mosler (2007)) models of natural resource consumption have been put forward in the past, there remains a dearth of relevant mathematical models that are also compliant with the control-theoretic framework.

Our point of departure is a mathematical model of natural resource consumption recently reported by the authors (Manzoor et al. (2016)). This mathematical model is based on the conceptual Social Ecological Relevance model of Mosler and Brucks (2003) which is derived from the psychological first principles of Festinger's theory of social comparison processes (see Festinger (1954)). The

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assumed setting of the model is that of an open-access natural resource (Perman (2003)), shared by a consuming population whose members are henceforth referred to as consumers (or interchangeably as agents). The natural resource is assumed to grow according to the standard model of logistic growth, thus the model is relevant to a wide range of resources which includes fisheries, forests, vegetation, foliage, saffron and so on. While Manzoor et al. (2016) give a detailed introduction and exposition of the model, a focus is placed on a society with two agents, where the agents may either be individual consumers or groups of consumers. Here we extend the model further to include an arbitrarily large number of agents. This makes it possible to incorporate the underlying social network, where consumption of a single agent is influenced only by those agents that are socially connected to her. The resultant model bears much similarity with well known models of opinion formation (Friedkin (2006)), which are derived by the same psychological principles and have been studied extensively by the controls community (see Lorenz (2007)). After introducing the basic model, we present a mechanism whereby groups of similar consumers can be aggregated into a single unit provided that certain conditions of homogeneity hold withing the network. Such block models are studied comprehensively for similar processes in sociology (Borgatti et al. (2009)), as they not only simplify the analysis but also utilize the community structure of the network to present a concise description of the society.

The paper is organized as follows. Section 2 presents the basic model and incorporation of the underlying network. Section 3 introduces the block model for societies with prevailing homogeneous communities. Section 4 presents aggregation mechanisms for partially homogeneous and uncertain populations. We conclude in Section 5.

2. THE CONSUMER BEHAVIOUR MODEL

The complete model is composed of two parts: the ecological sub-model, and the social sub-model. The ecological sub-model describes the dynamics of the resource, whereas the social sub-model describes the dynamics of consumption effort of each individual in the society.

2.1 The Ecological Sub-model

We assume a renewable stock resource (Perman (2003)), whose quantity at time τ is represented by $R(\tau)$. In the absence of consumption, the resource grows at the intrinsic growth rate r when it is near depletion, and continues to grow with a decreasing rate until it reaches the carrying capacity $R_{\max}$, at which point it saturates. The resource-stock dynamics are thus given by

$$\frac{dR(\tau)}{d\tau} = r\,R(t)\left(1 - \frac{R(\tau)}{R_{\max}}\right) - \sum_{i=1}^{n} e_i(\tau)\,R(\tau), \qquad (1)$$

where $i \in \{1, \ldots, n\}$ and $e_i(\tau)$ is the consumption effort of individual i, at time τ, in a society consisting of n individuals. Thus (1) is simply the Gordon-Shaefer model (Gordon (1954)) with the catch coefficient set to unity.

It is important to state here that in the social sub-model to be presented below, the consumption efforts $e_i(\tau)$ can take on both positive and negative values i.e., $e_i(\tau) \in \mathbb{R}$. The interpretation of positive consumption is fairly straight forward i.e., it refers to extraction of the resource. Negative consumption on the other hand, constitutes any measure taken for the sustenance of the resource. This not only includes direct measures like growing trees or breeding fish, but also includes indirect measures such as restoration of soil fertility or restriction of fishing gear. An important implication of negative effort rates which is evident from (1) is that it allows the resource to grow beyond the natural carrying capacity $R_{\max}$. This includes measures such as shifting to intensive agriculture, or adding additional capacity to a fish farm. Manzoor et al. (2016) give detailed interpretations for resource growth beyond carrying capacity as well as negative consumption.

2.2 The Social Sub-model

Here we introduce the cognitive dynamics of the consumers' decision making process. Festinger's social comparison theory (Festinger (1954)) postulates that human beings have the intrinsic drive to evaluate their decisions. They do so by evaluating their decisions against both objective (non-social) information, and social information. Thus in a social-ecological setting, consumers base their use-change decisions on the resource quantity (ecological information) and the consumption of others (social information). What differentiates the decisions of individual consumers is the manner in which they weigh these informations. The ecological information is weighed by $a_i \in (0, +\infty)$, the *attribution* of i, where a low value of a_i represents a consumer who associates responsibility for scarcity of the resource with society and a high value represents one who associates the responsibility with nature. Social information is weighed by $s_i \in (0, +\infty)$, the *social value orientation* of i, where a low value of s_i represents an extremely non-cooperative individual and a higher value of s_i represents a relatively cooperative individual. Psychological studies (Mosler and Brucks (2003)) find that ecological information is given more importance by individuals attributing scarcity to nature, and cooperative individuals give more importance to social information in order to promote equality in consumption. These effects are depicted by the following dynamic model of consumer behavior.

$$\frac{de_i(\tau)}{d\tau} = a_i(R(\tau) - R_i) + s_i \sum_{j=1}^{n} \omega_{ij}(e_i(\tau) - e_j(\tau)), \qquad (2)$$

where R_i is the *scarcity threshold* as perceived by i and ω_{ij} is the tie strength between i and j with the added constraint that $\sum_j w_{ij} = 1$, and $w_{ii} = 0 \ \forall \ i$. Note that R_i is the quantity of the resource above which it is considered abundant by i and below which it is considered scarce. Thus it can also be viewed as a target or set-point that i sets for the resource. A high value of R_i corresponds to a pro-environment individual whereas a low value corresponds to a non-environmental individual. It is also important to realize that this variable depends only on i's perception and does not represent the objective state of the resource.