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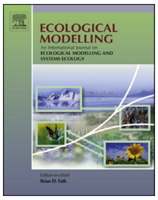

Robust stability mechanism of an artificial ecosystem based on biological mutations and synergies driven by ecological information

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ABSTRACT

The ecosystem stability was significantly underestimated in traditional mathematical models described by continuous-time ordinary differential equations (ODEs), irrespective of the influence of intricate biological behaviors on the dynamic characteristics of ecosystem. The goal of this study is to discuss the perspective and method of modeling complicated biological behaviors such as mutation and synergy, and compare the sizes of the stability region of two types of ecological model in parametric space through digital simulation. In this research, the inedible plant biomass was processed into soil-like substrate (SLS) for sustainable wheat cultivation under the combined action of earthworm and bacterial communities, and a SLS-based artificial ecosystem (SLSAE) comprising wheat, earthworm, bacterial communities, SLS and artificial environment was therefore established to theoretically investigate the stability mechanism of artificial ecosystem. Based on finite state machine (FSM) principles and methods, the ecological information was considered as discrete-event which could trigger complicated biological responses like mutations and synergies simulated by states transition and actions execution in FSM so as to effectively maintain robust stability of ecosystem in different environmental conditions. The digital simulation results clearly indicated that the SLSAE hybrid model binding continuous-time ODEs model with discrete-event FSM had a larger stable domain to the environmental changes compared to its traditional ODEs ecological models, which was exactly in agreement with the phenomena observed in both artificial and natural ecosystems.

1. Introduction

The highly robust stability of nature ecosystem is largely sustained by complex creatures' behaviors response to ecological information, causing the self-organized formation of intricate relationships between organisms and their surroundings (Haken, 1977; Kauffman, 1993; Camazine et al., 2001). Due to limitation of modeling ideas and methods, however, currently most of mathematical models of ecological processes have not adequately considered these actively biological behaviors such as mutation and synergy acclimating to environmental changes. As is well known, although the traditional continuous-time ordinary differential equations (ODEs) models with rigidly defined parameters and structure can precisely describe the dynamic characteristics of non-living systems like mechanical, electromagnetic and fluid systems, etc., they are not suitable for long-term description and prediction of ecological processes without consideration of organisms adaptive and selective behaviors (Hutchinson, 1961; Nicolis and Prigogine, 1977; Jørgensen and Fath, 2004; Kylafis and Loreau, 2008; Zhang et al., 2013). Similarly, correct evaluation of ecosystem stability cannot also be obtained from such mathematical models (Bartsev and Okhonin, 1999; Pelletier, 2000; Ives and Carpenter, 2007; Ma et al., 2012).

The organisms often actively change their behaviors through proper responses to ecological information for adaption to the environmental variations. In the running process of the ecosystem, ecological information is often discontinuously generated and

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Abbreviations: FSM, finite state machine; SLS, soil-like substrate; SLSAE, SLS-based artificial ecosystem; ODEs, ordinary differential equations.

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hierarchically disseminated on different scales from ecosystems, communities and populations to organs, tissues, cells, protoplasm and even molecules, giving rise to complicated biological behaviors like mutations and synergies buffering ecosystem against environmental variations to keep robust ecological balance. For example, if a biotic community is subject to stress of light, temperature, water and food, some species will take the initiative to change their metabolic rates, diets and foraging behaviors, and even produce gene mutations in order to adapt in the face of the adversity (May, 1971; Baltzis and Fredricson, 1988; Bartsev, 2004; Levine and HilleRis, 2009). Besides, certain species can produce the allelopathic substances to inhibit excessive growth of other species as interspecific competition intensifies in a phytocenosis (Bais et al., 2006). These environmental signals directly or indirectly related to light, temperature, water, food and allelopathic substances could be regarded as ecological information triggering and affecting biological behaviors. Although the ecological information plays very important role in the control and regulation for ecosystem operation, it is also not considered adequately in continuous-time ODEs models widely applied for current ecological studies (Gitelson et al., 2003).

Therefore, how to properly model the complicated biological behaviors driven by ecological information will be the key in description of ecosystem dynamics, otherwise ecological models cannot truly capture the dynamic characteristics of ecosystem reacting to environmental changes. After a long period of research, we have come to realize they could be effectively modeled and simulated by finite state machine (FSM) principles and methods. The ecological information could be taken as discrete event, and ecosystem operating characteristics changes resulting from complicated biological behaviors like mutations and synergies could be sufficiently simulated by states transition and actions execution in FSM.

In this research, the soil-like substrate (SLS) was prepared for sustainable wheat cultivation by processing inedible plant biomass, such as straw, bran, and roots through aerobic bio-compost under the combined action of earthworm and bacterial communities in the artificial environment (Manukovsky et al., 1997; Gros et al., 2005; He et al., 2010). The SLS-based artificial ecosystem (SLSAE), a specific miniature artificial ecosystem including wheat, earthworm, bacterial communities, SLS and artificial environment, was correspondingly constructed and mathematically modeled to carry out computer simulations for theoretically testing the hypotheses and validating the FSM methodology based on observed phenomena from prototype experiments.

The purpose of this study is to discuss the perspective and method of modeling complicated biological behaviors such as mutation and synergy, and compare the sizes of the stability region of two types of SLSAE model in parametric (input) space through numerical simulation, one model is only based on continuous-time ODEs without regard to biological behaviors, and another is hybrid model containing both continuous-time ODEs model and discrete-event FSM taking biological mutations and synergies driven by ecological information into consideration. Like most of ecological models, however, the nonlinear ODEs model developed to describe SLSAE in this study cannot be solved analytically, so its stability also cannot be specified from the analytical solutions. Because Lyapunov stability criterion is widely used in stability analysis of ecosystems (Culshaw and Ruan, 2000; Pykh, 2002; Dambacher et al., 2003; Haddad and Chellaboina, 2005; Regana et al., 2010; Hu and Liu, 2012), Lyapunov indirect method is used here to conduct stability analysis of SLSAE. We found the hybrid system of SLSAE has non-trivial stationary solutions at a wider range of parameters. In the research, the robust stability mechanisms of SLSAE were elucidated to a certain extent, which was also in favor of comprehending that of natural ecosystems.

2. Materials and methods

2.1. Time-continuous ODEs model of SLSAE

The SLSAE composed of wheat, earthworms, bacterial communities, SLS and the artificial environment was constructed, the producer was wheat cultivated on SLS, the consumer was earthworm fed on inedible wheat biomass, the decomposer was aerobic bacterial communities divided functionally into two types, bacterial community-A (*bmA*) and bacterial community-B (*bmB*) responsible for biological degradation of inedible wheat biomass and earthworm coprolites for SLS preparation, respectively.

The continuous-time ODEs state-space model (Eqs. (1)–(12)) of SLSAE was developed by system dynamics and parameter estimation based on related ecological mechanisms and experimental data, describing the process of SLS preparation and the essential relationship between organisms and artificial environmental factors.

$$\dot{x}_1 = \mu_{1m}\left(\frac{E}{E_m}\right)^{\varepsilon} aT^a(T_u - T)^b \prod_{i=5}^{7} \frac{1}{1 + \frac{k_i}{x_i} + \frac{x_i}{k_{ih}}} \frac{x_8}{K_8 + x_8} \times (1 - e^{-wx_{12}})x_1(t - \tau_1) \tag{1}$$

$$\dot{x}_2 = \left[\mu_{2m}x_2\left(\frac{x_{10}}{K_{2\_10} + x_{10}}\right) + \beta x_2 x_3\right] \frac{X_9}{K_o + X_9} - K_{2d}x_2 \tag{2}$$

$$\dot{x}_3 = \left(\mu_{3m}x_3 \frac{x_{10}}{K_{3\_10} + x_{10}} - \lambda x_2 x_3\right) \frac{x_9}{K_o + x_9} - K_{3d}x_3 \tag{3}$$

$$\dot{x}_4 = \mu_{4m}x_4 \frac{X_{11}}{K_{4\_11} + X_{11}} \frac{X_9}{K_o + X_9} - K_{4d}x_4 \tag{4}$$

$$\begin{aligned} \dot{x}_5 = {} & \rho_5 r_{10-3}\mu_{3m}x_3 \frac{x_{10}}{K_{3-10} + x_{10}} \frac{x_9}{K_o + x_9} \langle t - \tau_1 \rangle + \eta_5 r_{11-4}\mu_{4m}x_4 \frac{x_{11}}{K_{4-11} + x_{11}} \frac{x_9}{K_o + x_9} \langle t - \tau_2 \rangle - \\ & r_{51}\mu_{1m}\left(E/E_m\right)^{\varepsilon} aT^a(T_u - T)^b \prod_{i=5}^{7} \frac{1}{1 + \dfrac{k_i}{x_i} + \dfrac{x_i}{k_{ih}}} \frac{x_8}{K_8 + x_8} \left(1 - e^{-wx_{12}}\right) x_1(t - \tau_1) \end{aligned} \tag{5}$$

$$\begin{aligned} \dot{x}_6 = {} & \rho_6 r_{10-3}\mu_{3m}x_3 \frac{x_{10}}{K_{3-10} + x_{10}} \frac{x_9}{K_o + x_9} \langle t - \tau_1 \rangle + \eta_6 r_{11-4}\mu_{4m}x_4 \frac{x_{11}}{K_{4-11} + x_{11}} \frac{x_9}{K_o + x_9} \langle t - \tau_2 \rangle - \\ & r_{61}\mu_{1m}\left(E/E_m\right)^{\varepsilon} aT^a(T_u - T)^b \prod_{i=5}^{7} \frac{1}{1 + \dfrac{k_i}{x_i} + \dfrac{x_i}{k_{ih}}} \frac{x_8}{K_8 + x_8} \left(1 - e^{-wx_{12}}\right) x_1(t - \tau_1) \end{aligned} \tag{6}$$