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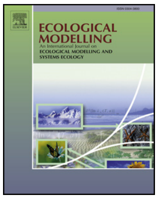

# Robust stability of closed artificial ecosystem cultivating cabbage realized by ecological thermodynamics and dissipative structure system

Dawei Hu[a,b,c,d,*], Kai Wang[a,b,c], Jingfei Hu[a,b,c], Xinming Xu[a,c,d], Yufei Long[a]

[a] *School of Biological Science and Medical Engineering, Beihang University, Beijing 100191, China*
[b] *State Key Laboratory of Virtual Reality Technology and Systems, School of Computer Science and Engineering, Beihang University, Beijing 100191, China*
[c] *Institute of Environmental Biology and Life Support Technology, Beihang University, Beijing 100191, China*
[d] *Beijing Advanced Innovation Centre for Biomedical Engineering, Beihang University, Beijing 100083, China*

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## ABSTRACT

The environmental disturbances often negatively influence normal operation of closed artificial ecosystems (CAE). In this paper, a specific CAE cultivating cabbage (CAECC) was considered as a dissipative structure system (DSS), its highly precise kinetic model was developed by system dynamics and experimental data. Based on ecological thermodynamics (ET) and DSS, the optimal feedback control law of light intensity, temperature and aerating rate was obtained from the stored-energy function and *Odum*'s maximum power principle. The digital simulation results showed that the closed-loop CAECC control system could be stabilized at a prescribed working point with desired dynamic response characteristics, accompanied with conducting eco-work and dissipation of the stored energy generated by environmental disturbances with different strengths. This research will lay a theoretical and methodological basis for construction and operation of CAE.

## 1. Introduction

Closed artificial ecosystems (CAE) is mainly composed of biological community dominated by higher plants and artificial environmental factors such as light, temperature, water, air and fertilizer meeting the ecological requirements of biological community and realizing crops, vegetables, flowers and herb medicines cultivation with high quality and efficiency (Yanata et al., 2015; Becerril and Rios, 2016). In design and construction of CAE, the most crucial criterion is operational reliability and stability, because the operating process of CAE is susceptible to environmental disturbances, which will result in plants yield decrease and ecological functions impairment, and even system breakdown (Ives and Carpenter, 2007). Hence it is indispensable to work out how to effectively control and regulate the artificial environmental factors for CAE to robustly operate in the case of environmental disturbances occurrence.

Currently, the open-loop and linear closed-loop control are used extensively in CAE. The open-loop control is only based on subjective experiences and working specification rather than on-line feedback information on system operation, hence open-loop control is very sensitive to disturbances with low control precision and operating stability (Kozai, 2013). The simple closed-loop control is generally applied for linear systems derived usually by linearization of a nonlinear system at a specific working point and in its neighborhood, and the linear feedback algorithm is obtained from classic cybernetics, such as root locus, Bode diagram, pole placement, quadratic optimal control, and so forth (Ogata, 2012a; Hu et al., 2013).

Nevertheless, the CAE is a highly nonlinear complicated system whose operating state often deviates more greatly from a certain working point under the effect of disturbances, therefore linearization procedure and simple closed-loop controls like PID (Proportional-Integral-Derivative) and LQG (Linear-Quadratic-Gaussian) control for mechanic, electromagnetic and fluid systems are unsuitable for CAE to achieve the desired dynamic performance, and even cause serious control failure (Gitelson et al., 2003).

*Lotka*'s simple but cogent argument had already proposed that, as a principle, "natural selection tends to make the energy flux through the system a maximum". *Odum*'s maximum power principle elucidates that ecosystems prevail that develops designs that maximize the flow of useful energy for maintenance and growth (Odum, 1983). From these viewpoints of ecological thermodynamics (ET), therefore artificial ecosystem can also be considered as a dissipative structure system (DSS) with natural tendency to move away from thermodynamic equilibrium to the largest extent, and gradually acquire the ability to conduct maximum eco-work (Jorgensen, 2012).

According to dissipative structure theory, if a proper stored-energy

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[*] Corresponding author at: Institute of Environmental Biology and Life Support Technology, Beihang University, Beijing 100191, China.
*E-mail address:* dwhu@163.com (D. Hu).

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function (so-called *Lyapunov* function) of a DSS can be found, it is possible to obtain an optimal feedback control algorithm for robustly stabilizing the DSS at a satisfied operation level with good dynamic response performances to control action (Ogata, 2012a; Cuce et al., 2016).

Therefore, in this research, optimal feedback control law derived from ET and DSS was applied for closed-loop control of a specific CAE cultivating cabbage (CAECC). In addition to cabbage, there also exits a common vegetable pest (whitefly) in the CAECC, and three tunable environmental factors, i.e., light intensity, temperature and aeration rate of air inlet pipe (Bergstrand et al., 2016). Firstly, a highly valid kinetic model was developed to describe the internal structure and dynamic behaviors of CAECC. Secondly, a proper stored-energy (*Lyapunov*) function composed of kinetic energy and potential energy was formulated. Thirdly, the optimal feedback control law of light intensity, temperature and aeration rate was obtained based on stored-energy (*Lyapunov*) function and *Odum*'s maximum power principle. Finally the effect of robust control was sufficiently verified and tested through digital simulation under the different kinds of environmental disturbances.

## 2. Materials and methods

### 2.1. Mathematical modeling of CAECC

The kinetic model of CAECC was developed by system dynamics to express and simulate its internal structure and dynamic behaviors (Ogata, 2012b). It is worth mentioning that living activities such as cabbage and whitefly growth are regarded as the fundamentally dynamic mechanisms to drive CAECC operation. In other words, the rates of living activities are taken as the benchmark to determine the rates of nonliving activities such as the rate of gases ($O_2$ and $CO_2$) concentration through coefficient calibration.

### 2.2. Stored-energy and robust control of CAECC based on ET and DSS

Supposed that the pseudo-model of CAECC can be expressed as following generic form:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathrm{x}, \mathrm{p}, \varepsilon, \mathbf{u}) \tag{1}$$

where **x** is biomass or concentration**,** **p** is parameter**,** **ε** is response of **x** to environmental disturbances and **u** is control input. The **f (x, p, ε, u)** is rate equations representing the relationships between species and their biotic/abiotic environmental factors. Hence it is not only the dynamic mechanisms to drive the CAECC operation, but also the dissipative paths to conduct eco-work and release heat (entropy) to environment, maintaining the system equilibrium and further moving it far from the thermodynamic equilibrium (Shieh and Fan, 1982; Jorgensen, 2012). Hence it is crucial to formulate a proper stored-energy (*Lyapunov*) function for CAECC dissipation. Based on this function and maximum power principle, the optimal control law **u*** could obtained correspondingly for closed-loop regulation of CAECC.

From the viewpoint of ODE model, if $\dot{\mathbf{x}} = \mathbf{f}(\mathrm{x}, \mathbf{p}, \boldsymbol{\varepsilon}, \mathbf{u})$ is gradually stable, the system's stored energy continuously decreases or the phase loci gradually converge to an attractor. In other words, CAECC will automatically restore to the attractor from deviations as environmental disturbances occur, which resembles the CAESS is exerted an imaginary stretch and friction force generated by a spring and damper combination (Fig. 1), a proper stored-energy (*Lyapunov*) function for CAECC dissipation could therefore be constructed based on insight on this ecological characteristic.

### 2.3. Model validation and optimal control law verification through digital simulation

After derivation of kinetic model and optimal control law of the CAECC, the simulation model of closed-loop CAECC control system could be constructed through their feedback connection on the platform of MatLab/Simulink. A large number of digital simulations including *Monte Carlo* simulations were carried out for parameter identification, model validation and optimal control law verification. Parameters in the model were identified based on time-domain experimental data via nonlinear least square and genetic algorithm or specified by directly taking from documents (Jorgensen, 1979). The total experimental data were divided into 2 parts, one part (two-thirds of data) applied for parameters identification, and the rest for model validation.

## 3. Results and discussion

### 3.1. CAECC prototype

The CAECC prototype was composed of three interrelated components: the autotrophic unit was cabbage (*Brassica oleracea*), the heterotrophic unit was whitefly (*Trialeurodes vaporariorum*) and the artificial environment factors including light intensity, temperature and aerating rate (Fig. 2). The cabbage cultivation was illumined by LED photo source whose total intensity ranged from 600 $\mu$mol $m^{-2}$ $s^{-1}$ and 2000 $\mu$mol $m^{-2}$ $s^{-1}$. The temperature and the aeration rate varying from 15 °C to 22 °C and 50 L $h^{-1}$ to 200 L $h^{-1}$ were adjusted by an air conditioner and a two-way pump, respectively (Qu et al., 2009; Hu et al., 2013).

### 3.2. Model derivation of CAECC

#### 3.2.1. Hypothesis of modeling CAECC

In order to thoroughly and profoundly investigate the complicated dynamic behaviors of CAECC, it was necessary to develop a grey-box kinetic model based on related mechanisms and experimental data, and the model was derived according to the following assumptions:

1. CAECC was considered as a nonlinear, continuous and lumped parameter system.
2. According to the practical operation of CAECC, the light intensity, temperature, $O_2$ and $CO_2$ concentrations were limiting factors influencing organism growths, and the CAECC operated in relatively normal circumstances.
3. The rates of non-living processes were approximately proportional to those of living activities.

#### 3.2.2. Model derivation of CAECC

*3.2.2.1. State variables.* The kinetic model of CAECC included 4 state variables: cabbage phytomass ($x_1$: kg, wet weight), whitefly biomass ($x_2$: kg), $O_2$ concentration ($x_3$: %), $CO_2$ concentration ($x_4$: %).

Rate equations were obtained from quantifying the relationships between organisms and their biotic/abiotic environmental factors in the CAECC.

*3.2.2.2. Tunable parameters.* Three environmental factors were used as tunable parameters in the kinetic model to control and regulate dynamic behaviors of CAECC, i.e., light intensity ($\boldsymbol{I}$, $\mu$mol $m^{-2}$ $s^{-1}$), temperature ($\boldsymbol{T}$, °C) and aerating rate of air inlet pipe ($\boldsymbol{w}$, L $h^{-1}$) which was equivalent to outflow rate of air outlet pipe, keeping air pressure constant in CAECC.

*3.2.2.3. Rate equations.*

1. Rate equations related to cabbage phytomass dynamics
   In CAECC, three process rates closely related to dynamics of cabbage phytomass ($x_1$) are cabbage growth rate ($v_{1b}$), whitefly predation rate on cabbage ($v_{12}$) and the impact of environmental disturbances on cabbage growth rate ($v_{1n}$), respectively. They could be specified accordingly as follows: