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Comparison of an energy systems mini-model to a process-based eco-physiological model for simulating forest growth

Linjun Li[a,b], David R. Tilley[c], Hongfang Lu[a,*], Hai Ren[a,**], Guoyu Qiu[b]

[a] Key Laboratory of Vegetation Restoration and Management of Degraded Ecosystems, South China Botanical Garden, Chinese Academy of Sciences, Guangzhou 510650, China
[b] Key Laboratory of Urban Habitat Environmental Science and Technology, School of Environment and Energy, Peking University, Shenzhen 518055, China
[c] Department of Environmental Science and Technology, University of Maryland, College Park, MD 20742, United States

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ABSTRACT

The mini-modeling technique that H.T. Odum developed in conjunction with his approach to ecological and energy-based systems principles provides a relatively simple, yet powerful way for simulating ecosystem processes at many scales. However, its simplicity presents limitations that should be articulated. This paper developed a mini-model that simulated the biomass growth and soil organic matter accumulation of three subtropical forest plantations typical of South China to compare its simulated results with field observations and the simulated results of a widely applied process-based model of forest ecosystems (Biome-BGC model). The mini-model's simulated results were close to both the observed values and those of the Biome-BGC model over a 23-year record of early growth ($R^2 > 0.90$ for biomass). This indicated that when the key ecosystem components, processes and driving forces were fully considered, the mini-model technique could closely emulate the ecosystem processes using only a few equations. Thus, developing a mini-model from ecological and energetic systems principles is a powerful tool for testing and expanding upon general energy principles applicable to many systems and offers the unique opportunity to perform dynamic emergy accounting. Developing a mini-model, on the other hand, can benefit from exploring a complex process-based eco-physiological model, especially to understand ecosystem structure and processes. Compared with process-based ecosystem models, the mini-model does not include specific eco-physiological mechanisms of material production, but simply simulates the ecosystem processes based on the main flows of energy. However, investigation of energy interactions in the mini-model and sensitivity analysis showed that the parameters of the mini-model need to be set within their confidence intervals to avoid errors and, like most simulations, should be validated with field observations before applying the model further. Energy systems mini-models provide the capability to simulate key ecosystem processes and the dynamics of emergy, which can prove useful for evaluating the temporal change in the accumulated value of ecosystems such as forests for environmental accounting purposes.

1. Introduction

Planetary life exists in a system of interdependence with its environment. A system is composed of components that interact in ways that often provide additional functions unavailable in isolation. Since systems pervade the world, we can learn much about the world through system theories and related methods of investigation. General systems theory emerged along with ecological theories to help answer questions involving complex systems (Odum, 1983, 1994). However, with increasing spatio-temporal scales, the system under study can become so complex that it is difficult to consider every component and interaction simultaneously. Therefore, it is necessary to identify the key components and processes so as to reduce complexity and increase the feasibility of basic emulation (Odum, 1976).

By investigating about 90 different kinds of ecosystem structures and processes (Beyers and Odum, 1993; Odum, 1989, 1994), Odum and his colleagues found that ecosystems of many types had similar structures and network designs and could be abstracted as to support notions in general system theory, *e.g.*, self-sustaining ecosystems were found to be composed of producers, consumers, and decomposers. Based on these general systems principles, we can aggregate the components with similar properties and behaviors in a system to simplify our representation of the system, which

* Corresponding author at: Xingke Road 723, Tianhe District, Guangzhou 510650, China. Tel.: +86 20 37252585; fax: +86 20 37252711.
** Corresponding author at: Xingke Road 723, Tianhe District, Guangzhou 510650, China. Tel.: +86 20 37252916.
E-mail addresses: luhf@scbg.ac.cn (H. Lu), renhai@scbg.ac.cn (H. Ren).

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helps to see the essence of a system's structure and function (Odum, 1983; Odum and Odum, 2000; Brown, 2004).

Energy is the driving force of all system processes, and the operation of all ecosystem processes involves energy use and transformation. The energy pyramid of trophic levels proposed by American ecologist R.L. Lindeman, is a good example of energy use and transformation in ecosystem processes, and the basis of trophic dynamics is the transfer of energy from one part of the ecosystem to another (Lindeman, 1942; Odum, 1968). As H.T. Odum (1971) said, "when systems are considered in energy terms, many types of systems turn out to be special cases of relatively few basic systems, and some bewildering complexity of the world will disappear". This thinking led Odum to develop his energy systems language with its graphical representation of mathematics coupled with energetics as he advanced the field of system ecology. He used the energy systems language (Odum and Odum, 2000) to diagram the components, interactions, flows and storages of material, energy and information within ecosystems of many types (Odum, 1967, 1983, 1996).

The energy systems language is used to create energy systems diagrams of ecosystems, ecological-economic systems, or other systems. The key unit in an energy systems diagram is that of energy. Primary energy is transformed into higher-quality energy by primary production, which is further increased in quality by subsequent energy transformation processes, like herbivory or carnivory. At each transformation step the energy flowing to the next higher level decreases because a portion of the energy is lost *via* the heat sink. These energy transformation processes conform to the laws of thermodynamics, *i.e.*, energy conservation and energy dispersal (entropy). Brown (2004) demonstrated that energy systems diagrams are worth a thousand words, and from a macroscopic viewpoint are helpful in capturing the essence of a whole system, with its component interactions, energetics and kinetics.

Furthermore, energy systems diagrams not only represent many kinds of ecosystem processes, but also involve the corresponding equations of energy use and transformation, which forms the foundation for energy modeling of ecosystem processes. Thus, based on energy systems language, Odum (1976, 1983, 1994) and Odum and Odum (2000) created many kinds of energy systems diagrams and constructed the corresponding mathematical models to successfully simulate the processes in ecological and economic systems.

Since the models constructed are macroscopic in perspective but with reduced complexity, they are often named "macroscopic mini-models" or just "mini-models" (Odum, 1976). The mathematical formulas associated with the energy systems language can be found in the book *Systems Ecology* (Odum, 1983, 1994). For simplicity, it is assumed that the interactions among ecosystem components can be simulated in mini-models using a consistent multiplication rule. If the mini-models fully consider the key parts, processes, and driving forces of the ecosystems under study, then they can closely simulate the energy flow and storage processes of these ecosystems. In addition, Odum believed that the mini-models must adequately represent the characteristics of the original systems to resemble reality, but should be simple enough to be easily understood and used (Odum, 1976, 1998; Brown, 2004). So the mini-models are a form of visual mathematics, which may help with learning about system connectivity and structure. They are also well suited to scenario simulation and analysis. Thus, macroscopic mini-modeling is an effective tool to simulate and explore the dynamic change of all kinds of ecosystem processes with minimal complexity, and continues to gain attention and applicability.

Bayley and Odum (1976) successfully simulated the interrelations of the Everglade's marsh, peat, fire, water and phosphorus by means of a mini-model, and found the water inflow and limited nutrients were the key to manage marshes for long-term stability. Odum (1976) used macroscopic mini-models to simulate the relationships between humanity and nature, including money and energy in the same models; producer–consumer symbiosis and competition; recycling and mining; succession with declining energy reserve; and regional development optima. Odum (1983, 1994) and Odum and Odum (2000) systematically illustrated energy systems theory and language, and developed many mini-models for all scales of ecosystems, including production and recycling, growth, competition and cooperation, succession and evolution, micro-economy, international relations and trade, *etc*. Odum (1995) constructed some mini-models like MATCHUSE and CACAO to explore the relationship between forest management and productivity. Tilley (1999) developed the mini-models EMERGYDYN and EMSPECIE to represent the temporal dynamics of emergy associated with forest storages and tree diversity, respectively. Furthermore, he designed the mini-model MULTIBEN to simulate the empower characteristics of multiple forest benefits under different scenarios of forest management, and found that the maximum empower occurred at an intermediate intensity of resource use. Odum and Odum (2000) and Odum (2007) developed the mini-model CLIMAX to simulate the succession process of an ecosystem to demonstrate that the stages of ecosystem succession first included rapid growth of biomass with low biodiversity, and then slow growth with high biodiversity. Tilley and Brown (2006) used mini-modeling to simulate the emergy and transformity of hydrologic variables in a subtropical wetland watershed to derive temporally dynamic distributions for them as opposed to the commonly used point estimates. Tilley and Comar (2006) employed a mini-model BRAZELECTRIX to simulate and explore long-term paths for Brazil's electricity supply under natural environmental constraints like natural gas and hydro-power. Lei and Wang (2008) used a mini-model to predict the evolution of Macao's development and trends in the coming 20 years, finding that the city's economy will become 15 times larger. By investigating mini-models, Tilley (2011a,b) explored the recycling of emergy in material loops and revised Odum's statements about how emergy and transformity change over time, which have further advanced dynamic emergy accounting. Liu et al. (2012) provided an emergy-based urban dynamic mini-model that accurately emulated the resource consumption, economic growth and environmental impact on Beijing.

However, most of these mini-models did not consider smaller-scale biological processes or physiochemical mechanisms of actual ecosystems. Instead, they are based on principles from ecological and energy systems theory. All mini-models adhere to the first energy law-conservation, the second energy law-entropic degradation of available energy, material conservation, energy transformations that lead to energy hierarchies, autocatalysis as a common feedback control on growth, and typically first-order rate kinetics (Odum, 1996; Odum and Odum, 2000). Despite the broad utility of the mini-modeling approach, there have been few instances where they were compared to process-based, eco-physiological approaches to represent key ecosystem processes (Odum and Odum, 2000).

The aim of this paper is to compare a forest mini-model developed using Odum's approach with a more complex, process-based eco-physiological forest model (Biome-BGC) (Thornton et al., 2002; Thornton and Running, 2002; Li et al., 2013) to determine the capabilities, advantages and disadvantages of the forest mini-model in simulating growth of aboveground biomass and soil organic matter in South China. Such research will address the following two questions: (1) Can the mini-model simulate the major forest ecosystem processes as well as the Biome-BGC? (2) Compared with the Biome-BGC, what advantages and disadvantages does the forest mini-model have?