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편집장 통신

지역시스템 비저니어링: 플럭스 관측에서 지속가능성과학으로의 패러다임 전환

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Rural Systems Visioneering: Paradigm Shift from Flux Measurement to Sustainability Science

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ABSTRACT

Sustainability science is an emerging transdisciplinary research which necessitates not only the communication and collaboration of scientists, practitioners and stakeholders from different disciplines and interests, but also the paradigm shift from deterministic and reductionist approaches to the old basic. Ecological-societal systems (ESS) are co-evolving complex systems having many

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interacting parts (or agents) whose random interactions at local scale give rise to spontaneous emerging order at global scale (i.e., self-organization). Here, the flows of energy, matter and information between the systems and their surroundings play a key role. We introduce a conceptual framework for such continually morphing dynamical systems, i.e. self-organizing hierarchical open systems (SOHOs). To understand the structure and functionality of SOHOs, we revisit the two fundamental laws of physics. Re-interpretation of these principles helps understand the destiny and better path toward sustainability, and how to reconcile ecosystem integrity with societal vision and value. We then integrate the so-called visioneering (V) framework with that of SOHOs as feedback/feedforward loops so that 'a nudged self-organization' may guide systems' agents to work together toward sustainable ESS. Finally, example is given with newly endorsed Sustainable Development Goals (SDG) Lab (i.e., 'Rural systems visioneering') by Future Earth, which is now underway in rural villages in Tanzania.

***Key words*: Sustainability science, Ecological-societal systems, Self-organization, Rural systems visioneering, Sustainable Development Goals Lab**

I. INTRODUCTION

There have been growing concerns on our society's scientific approach to dealing with unsustainable local, regional and global trajectories (e.g., Anthes, 1993; Meadows *et al*., 2004; Folke *et al*., 2011; Janhonen-Abruquah *et al*., 2018). Our ecological-societal systems (ESS) bear severe consequences of accelerating entropic juggernaut in the form of climate change and global capitalism. The juggernaut metaphor is the sacrifice we must pay not only for dissipating energy by unstoppable consumptive use of resources but also for eroding the resilience of the surrounding ecosystems, thereby exacerbating the vulnerability of ESS (Rifkin, 2009; O'Brien *et al*., 2012; Grothmann *et al*., 2017). The success of the agricultural and industrial revolutions, now followed by that of information revolution, has produced its own dearth of the biocapacity of our planet as a whole. As has been exhorted earlier by Meadows *et al*. (2004), success created the necessity for another revolution − a sustainability revolution toward which visioning, networking, truth-telling, learning, and loving are the most important tools for the transition. In tandem, there is a need to accommodate a much wider range of modes of constructing scientific knowledge and understanding about ESS. We must develop a science that allows us to study the coevolution of the natural world and the human-constructed world (e.g., Kay and Boyle, 2008).

Modern science has been structured primarily around Newtonian and Darwinian approaches. In Ulanowicz's term (2009), the former was the first window on the world, captured in mechanistic worldview with its time reversible laws. The latter brought history into the second window on the world, and a third window has been seeking to go beyond both reductionism and even the synthesis of both worldviews to science (e.g., Harte, 2002; Ulanowicz, 2009; Logan, 2013). Considering high levels of uncertainty, epistemological conflicts over facts and values, and a sense of urgency, such a normal paradigm-driven science would be insufficient to sustain our pursuit of finding the governing principles and stewardship for sustainable ESS (e.g. Waltner-Toews and Kay, 2008; Mooney *et al*., 2012).

The co-evolving nature of ESS has become increasingly obvious as human ecological footprint has increased. Yet, the conceptual framework to bridge the societal system dynamics with that of the larger ecological systems within which humanity operates remains deficient to understand their coevolution. The key to understanding the coevolution is to understand processes in nature, which are driven by 'self-organization' (e.g., Kay and Boyle, 2008), and thus we need a new transdisciplinary approach that draws on the theories, concepts, and principles from physical, biological, social and information sciences (e.g., Heylighen, 2011). Integrating these sciences based on the first principles (e.g., the entropy principle and the action principle) provides a first step to bridging ecological and societal systems.

In this letter, we present a conceptual framework which enables not only to bridge nature and human but also to generate useful knowledge for understanding and sustaining the integrity of the combined ESS. First, we revisit fundamental concepts in complex systems, and introduce the first principles that enable such systems to self-organize. We then propose a self-organizing hierarchical open systems framework which is further integrated with the visioneering framework (Kim and Oki, 2011) to guide ESS toward sustainability. Finally, we provide examples on how such frameworks can help realize the sustainable development goals (SDG) Lab of Future Earth (www.futureearth.org/).

II. FOUNDATIONS

2.1. Criteria for a theory

"*A theory is the more impressive, the greater the simplicity of its premises is, the more different kinds of things it relates, and the more extended is its area of applicability. Therefore the deep impression that classical thermodynamics made upon me. It is the only physical theory of universal content that, within the framework of applicability of its basic concepts, it will never be overthrown.*"

Albert Einstein, 1949

The essential for the understanding of coupled ESS dynamics is a scientific theory. The term 'theory' is used to describe most advanced systems of knowledge. Harte (2011) asserts that scientific theories must meet three criteria: (1) falsifiability, (2) comprehensiveness, and (3) parsimony. Falsifiability stresses the point that a scientific theory can never be proven but must be destructible. Theory must stick its neck out, as Harte simply puts, because scientists can only disprove or improve it. Comprehensiveness reminds us that a scientific theory is not a model which has only a limited scope. A successful scientific theory predicts answers that are applicable across a wide range of conditions and phenomena (though it may come at the expense of practicality). Parsimony is measured by the ratio of the number of distinct testable predictions it makes to that of assumptions needed, and thus the ratio should be large. In other words, a parsimonious theory does a lot with a little. To summarize, a scientific theory is based on relatively few, clearly stated, simple assumptions that can be used to make a comprehensive set of falsifiable predictions about the answers to a wide variety of questions from multiple perspectives (Harte, 2011). Here we put forward such a scientific theory - a self-organizing hierarchical open systems (SOHOs) approach with visioneering based on the principles of entropy and action, which may provide hope of unifying the questions and answers under one coherent framework, i.e., sustainability.

2.2. Concepts in complex systems

2.2.1. Defining a system

A system is a collection of things that we perceive to be a whole. Meadows (2008) defines system as an interconnected set of elements that is coherently organized in a way that achieves something. The system components, configured together in a particular structure, constitute the system's organization which allows the system to fulfill its function and purpose. In essence, a system consists of three pillars: elements (or agents), interconnections, and purpose. The least obvious part of the system, its purpose, deserves more attention because it gives birth to a vision which is a crucial determinant of a system's behavior in the process of 'visioneering' − an essential framework in sustainability science (Kim and Oki, 2011).

A system can be categorized into (1) isolated and (2) non-isolated systems (e.g., Jørgensen *et al*., 2007).

An isolated system allows no exchange of energy, matter, and information with the environment. Non-isolated system is further divided into (1) closed and (2) open systems. The former exchanges energy and information but not matter with the environment. Open systems are those that have an environment, which provide energy, matter and information flows into and out of the system. For example, natural and human ecosystems at local to regional scales are all open systems whereas the earth system as a whole may be considered as a closed system.

Ecological-societal systems are combined systems of ecological and social components and drivers that interact and give rise to results which cannot be understood based on ecological or social considerations alone (Chapin *et al*., 2009). For example, societies and their economies are open systems embedded in ecological systems with which they exchange energy, matter and information. Interactions among these systems are vital for each system's development and are believed to be constrained by the laws of physics. Ruth *et al.* (2011) argued that, in contrast to the physical and life sciences, the social and behavioral sciences have not yet organized themselves and connected their theoretical and empirical knowledge in transdisciplinary ways to provide the insights on human with environmental system dynamics across local to global scales.

A conceptual framework that is based on a simple and general theory is needed to couple these two open systems with different levels of complexity. The definition of complexity is like two sides of a coin. As a quantity (hence computable), complexity is the amount of information needed to describe a system. As a quality, complexity may refer to the presence of emergence (i.e., the apparent discontinuity in phenomena between radically different collective behaviors arising from the interaction of subsystems, which are not evident from analysis of each subsystem) (e.g., Standish, 2001; Prokopenko *et al*., 2009). Emergence is distinguished from a flip to a new attractor (i.e., the end-state of a dynamic system as it moves over time) that may be surprising but not novel. The individual component systems as well as the coupled ESS are all complex systems in which large networks of components give rise to complex collective behaviors, sophisticated information processing, and adaptation via learning through self-organization (Mitchell, 2009).

2.2.2. Self-organization

The concept of self-organization denotes open systems, exchanging energy, matter and information with the environment and made up of components whose properties and behaviors are defined prior to organization itself. The term, 'self' implies the absence of centralizing ordering or external forcing whereas 'organization' involves a decrease in internal entropy (or an increase in complexity). As a system self-organizes more, it shows more behaviors, requiring more information to describe its dynamics (Prokopenko *et al*., 2009).

The fundamental properties of self-organization may be summarized as (1) no external control, (2) an increase in order, (3) robustness, and (4) interaction (Correia, 2006). From the information-theoretic perspective, no external control may imply spontaneous arising of information dynamics without any flow of information into the system. An increase in order (or complexity) reflects increased predictive information within the system. In other words, the change in information's gain within the system should be more than that flowing from the environment. Robustness follows from maximizing diversity within the system whereas interaction implies minimization of local conflicts to produce evolutionary stable system. Adaptation (via generating variability, observing feedback, and preferential selection) is considered as a process where system behavior changes to increase mutual information between the system and the environment (Prokopenko *et al*., 2009). For example, Kumar and Ruddell (2011) investigated the principles that characterize the role of the variability in self-organized interaction between various ecosystems and their environment. By examining the network of feedback loops, they found that self-organization arises as a tradeoff where the ability of the total system to maximize information production through feedback is limited by moderate variability of the participating variables. Such a tug of war between variability and information production in open complex systems shed a light on the search for the first principles that drive self-organization processes in nature.

2.2.3. Energy, matter, and information

In open, self-organizing systems, energy of different quantity and quality provides the stimulus for organization, enabling different processes to progress at different rates. Matter is anything that occupies space and has mass. They provide the raw materials for the processes and building blocks for structure. van Benthem (2011) asserts, "*Structure should always be studied in tandem with a process and no information without transformation*." Information acts internally within the system to constrain its behavior, which can also flow into the system from outside. It can catalyze certain processes and not others, thereby prompting the direction of self-organization (e.g., Kay and Boyle, 2008; Ruddell and Kumar, 2009; Yun *et al*., 2014a; Yun *et al*., 2014b).

The interplay of environmental conditions, energy, matter and information defines the context and constraints for the set of processes and structures that may emerge during self-organization. How can we understand the relationship between the external context and self-organization? Dodig-Crnkovic (2012) views that matter is related to energy in a way that structure relates to process, and information relates to computation. The relationship between such complementary pair is analogous to that between being (the persistence of an existing structure) and becoming (the emergence of a new structure through self-organization) (e.g., Prigogine, 1980). The science and education for sustainable ESS should focus not only on energy and matter but also on the fundamental ontological categories: information, computation and telos (i.e., purpose) (e.g., Deacon, 2011; Dodig-Crnkovic, 2012; Sandel, 2009; Mooney *et al*., 2012).

2.3. The two principles

2.3.1. The principle of thermodynamics

A bioeconomist, Nicholas Georgescu-Roegen (1971) said, "*What goes into the economic process represents valuable natural resources and what is thrown out of it is valueless waste. But this qualitative difference is confirmed, albeit in different terms, by a particular (and peculiar) branch of physics known as thermodynamics. From the viewpoint of thermodynamics, matter-energy enters the economic process in a state of low entropy and comes out of it in a state of high entropy*." An astrophysicist, Eric Chaisson (2001) wrote, "*After all, of all the known principles of Nature, thermodynamics has perhaps the most to say about the concept of change*." Likewise, energy-matter-information flows and the co-evolution of ESS are also governed by the two laws of thermodynamics. The first law of thermodynamics is a conservation law – the sum of all energy has been fixed and will remain so until the end of time (Chaisson, 2001). In other words, energy itself can be neither created nor destroyed, though it can change from one form to another. The second law of thermodynamics simply stipulates that there is a price to pay each time energy changes from one form to another. The price is a loss of free energy to perform useful work, which is termed as 'entropy.' Literally, entropy means 'turning toward'; a more insightful translation would be 'transformation in.' Entropy multiplied by temperature (of a system) is a measure of the amount of energy no longer able to convert into useful work. The second law specifies that energy can change in only one direction irreversibly toward a dissipated state of increased entropy (i.e., decreasing quality of energy).

When a system is isolated, energy increase becomes zero and the entropy of the system reaches the maximum, i.e., thermodynamic equilibrium at which all irreversible processes cease. In equilibrium, change has no direction and we cannot distinguish past from future. In an isolated system, we can regard energy flow from ordered to disordered states. Ordered states are where free energy is maximized and entropy is minimized (e.g., organized clean house) whereas disordered states are where free energy is more dissipated and entropy is maximized (e.g., unattended messy house) (Chaisson, 2001). Thermodynamically, order (or organization) can be measured by the number of possible arrangements of a system's elements. Counting all the possible states a system can be organized, the disorderly states far outnumber the orderly states. The latter states have low probability and low entropy. In terms of microstates and macrostates, entropy is regarded as a physical equivalent of probability. The entropy of a given macrostate is the logarithm of the number of its possible microstates. The second law, then, is the tendency of nature to flow from less likely (orderly) to more likely (disorderly) macrostates (e.g., Dincer and Cengel, 2001).

The thermodynamics of open systems allow system's entropy remain constant or even decrease. Localized, open systems (i.e., content) can be sites of emergent order within a global environment (i.e., context) that is largely and increasingly disordered − the essence of non-equilibrium thermodynamics (Chaisson, 2001). When a system begins to exchange entropy with environment through flows of energy, matter and information, it is driven away from thermal equilibrium. The entropy producing irreversible processes begin and the existing structures are replaced by new dissipative structures that capture increasing resources and make more effective use of them. It is the free energy in an open system that moves it away from equilibrium, but nature (which is subject to the second law) resists this displacement (Kay and Boyle, 2008). In other words, equilibrium states are an attractor for non-equilibrium states. Below, we will see that the entropy law alone is not sufficient enough to describe why ecosystems (or nature) choose one path over the other during the course of growth and development.

2.3.2. The principle of least action

The direction of any ecosystem or its trajectory is not known in advance, but one can predict the most probable trajectory of occurrence based on the principle of least action. This principle (having a rich history associated with Maupertuis, Euler, Lagrange, and recently Feynmam, to name a few) had played an important role in the development of classical mechanics, and was employed as a tool to develop the path integral formulation of quantum physics (e.g., Chatterjee, 2016a). Here, action has the dimension of energy multiplied by time, which is a measure to define the functionality of a system and its response to changes in the surroundings, or when a system is in transition from one state to the other. In a networked system, action can be described as the least unit of energy dissipation while navigating from one node to the other. The principle of least action simply states that out of all possible trajectories to move from state A to state B, only that particular trajectory which minimizes action is chosen, or the trajectory which provides least constraint, or along which time taken is minimum (Chatterjee, 2016b).

In a probabilistic framework, the unified notion of entropy and action helps identify the second law of thermodynamics as a force that directs energy dispersal between a system and its surroundings along the paths of least action, or energy gradients being leveled in the least possible time. However, processes in nature do not willingly let systems to disperse off energy. Otherwise, all life forms on earth would have ceased to exist soon after they appeared. As Georgiev and Chatterjee (2016) points out, dissipative systems are resilient to changes in the surrounding because of the presence of feedback loops and response to action mechanisms which make systems to continuously organize, resulting in spontaneous appearance of global order out of local random interactions. The least action state is the attractor for self-organization.

Self-organizing systems have a tendency to establish themselves in thermodynamically nonequilibrium steady states that are capable of persisting even when the environment changes. According to Kay and Boyle (2008), each of these steady states represents an organizational mode (i.e. a particular configuration of components and processes that give rise to specific patterns of behaviors into which the system is capable of locking itself). These organizational modes may be confined to a limited domain in state space about a dynamically stable equilibrium point (i.e. attractor). The capacity of a self-organizing system to maintain its identity (i.e. specific organizational mode) is attributed to the feedback/feedforward loops and the associated dynamic process networks in the system. Recent studies on the relationship between Shannon entropy and information flow demonstrated that information generally flows from high-entropy variables to low-entropy variables, and moderate entropy variables participate in feedback (Ruddell and Kumar, 2009a; Yun *et al*., 2014a; Yun *et al*., 2014b).

A schematic representation of the connectivity of energy, matter, and entropy in the biosphere is illustrated in Fig. 1. We have added an entropy budget to the schematic of Campbell and Norman (1998, Fig. 1). Indeed, our biosphere is a complex continuum, not only in terms of the reality of the interconnectedness of living things and their environments, but also in terms of the physical formulations. Campbell and Norman insightfully and foresightfully wrote, "*Rational exploration of the biosphere is just beginning and it is our hope that this new head knowledge will be woven into your being in such a way that you will have an increased awareness of your dependence on and implicit faith in that which is not known, as well as having some simple quantitative tools at your disposal to enhance a harmonious relationship between yourself and your environment and serve others at the same time*."

It should be noted that climate change and global capitalism are related to the consumption of free energy (associated with the shaded area in Fig. 1).

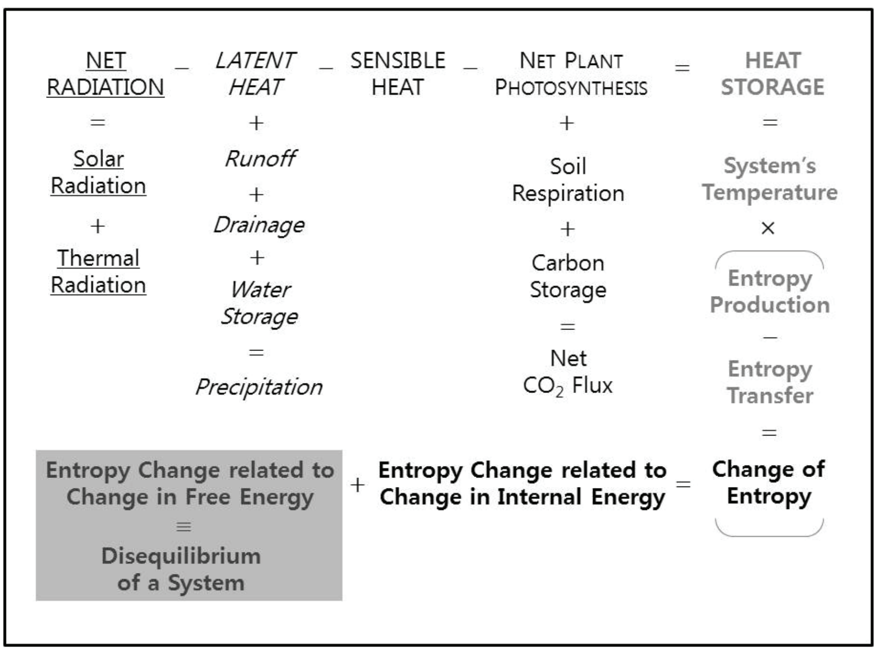

Fig. 1. Schematic representation of the inter-connectedness of radiation (underlined), water (in *italics*), carbon (normal font), energy (in capital), and entropy (**bold**) budgets in a biosphere. (Adapted from Campbell and Norman, 1998).

Considering the rapid increase in demands for free energy by human activity, the pressing question toward sustainability is how human demands may continue to increase without undermining the biocapacity of ecological-societal systems to generate free energy (Kleidon, 2012).

III. Self-Organizing Hierarchical Open Systems Approach

3.1. Basic theory

As a prerequisite to bridging ecological and societal systems, we need a conceptual framework in which diverse concepts can be described and distinguished in a consistent manner for both systems. Ecosystem is defined as an interactive open system comprising communities of organisms/agents and their biogeophysicochemical environment, at any scale desirably specified, in which there are continuous fluxes of energy, matter and information (e.g., Willis, 1997; Ash *et al*., 2010). Based on the assumption that societal systems can be considered as an integral part of ecological systems, three fundamental questions posed by Jørgensen and Fath (2007) serve as a guideline to pursue for the bridging of the two systems: (1) What are the underlying systems properties that can explain their responses to disturbances? (2) Can we formulate building blocks of an ESS theory about processes and properties? and (3) Does such systems theory meet the requirement of falsifiability, comprehensiveness, and parsimony to adequately explain observations with practical application for sustainability?

We believe that the fundamental properties that explain typical ecosystem processes and their responses to disturbances also hold for ESS. Following Jørgensen and Fath (2007), the presumed fundamental properties would be:

(1) ESS are open to energy, matter, and information;
(2) ESS are ontically inaccessible to accurately predict in all detail system behaviors;
(3) ESS have directed development which progressively increases feedback and self-organization;
(4) ESS have network connectivity which gives them new and emergent properties;
(5) ESS are organized hierarchically;
(6) ESS grow and develop in a way that they gain biomass/capital and structure, enlarge networks, and increase information content; and
(7) ESS have complex response to disturbance.

3.2. A conceptual model

The self-organizing hierarchical open systems (SOHOs) approach is basically an ecosystem approach proposed by Waltner-Toews *et al*. (2008). It is a conceptual model to bring together an ecological understanding of the world with human desire to make the world a better place, which manifests the fundamental properties of ESS. Here, we use the term ‘hierarchical’ which means both holarchic (i.e., made up of nested levels of focus) and viewed from different and multiple perspectives (Kay and Boyle, 2008). Our societies as well as ecosystems are open systems and their functions and structures are organized hierarchically (Jørgensen, 2006). A nested system from multiple perspectives is a hierarchical description. According to Page (2008), a perspective is a representation of the set of possible solutions, which creates a landscape where the elevation of each solution equals its value. The better the perspective is, the less rugged the landscape would be. Diverse perspectives create more adjacencies, thus more solutions and the seeds of innovation. Therefore, Complex ESS must be understood from multiple perspectives.

The SOHOs approach is a synthesis between traditional ways of framing both ecological problems and environmental management and complex systems theories. It provides an integrated, nested ecosystem description of the relationship between natural and human systems and serves as a basis for understanding their coevolution (Kay and Boyle, 2008). As a first step to bridging ecological systems

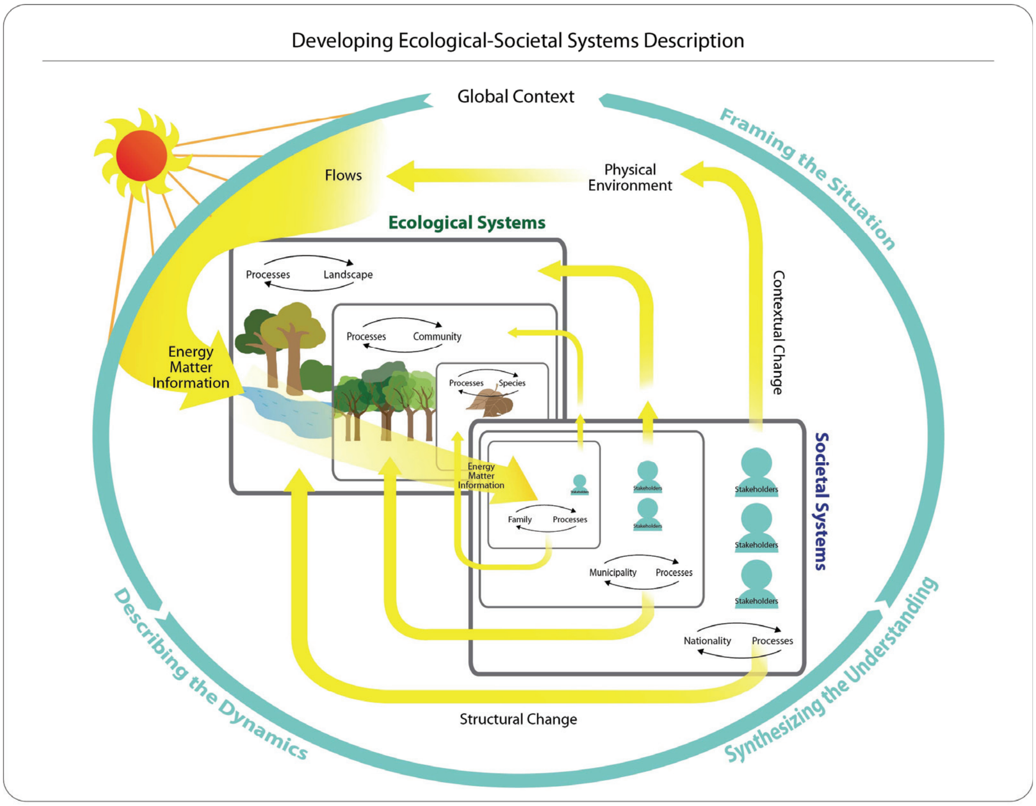

Fig. 2. Interrelationships and influences between ecological and societal systems: The self-organizing hierarchical open systems (SOHOs) framework (Adapted from Kay and Boyle, 2008).

and societal systems, their interrelationships and influences in the biosphere are described in Fig. 2.

The key relationships between ecological and societal systems in Fig. 2 are: (1) ecological systems provide the context (i.e., the biophysical surroundings and flows of energy, matter and information) that are required for self-organization of the societal systems; (2) societal systems can alter the structures in ecological systems, which in turn change the context for the societal systems; and (3) societal systems can change the context for the self-organization of ecological systems and likely their structures, resulting in the altered context for societal systems (Kay and Boyle, 2008).

The SOHOs approach provides a heuristic basis for systems thinking and a better understanding of the interactions between the two systems as coupled self-organizing systems. Of particular importance to note in Fig. 2 is the thermodynamic reality of ESS. That is, a price is paid each time energy changes from one form to another at each step along the way from the sun on the top left to the bottom right of societal systems. The price paid to nature is a gain in entropy, i.e., a loss in the amount of free energy that is needed to maintain a non-equilibrium state for self-organizing processes. To ensure no detrimental effects of human activity on the generation of free energy by the whole systems (e.g., Kleidon, 2012; Kleidon *et al.*, 2013), better understanding and quantification are needed of the roles of the ecological systems as well as societal systems based on the quantitative monitoring of entropy flow and budget in addition to those of energy and matter (e.g., water and CO_2) (see Fig. 1).

The SOHOs framework should be the basis not only for monitoring but also for management and governance for sustainability (e.g., Boyle and Kay, 2008; Kim and Oki, 2011). Nevertheless, few tracks the contextual elements, particularly entropy and information flow, of ecological-societal relationships. In most of modeling and monitoring efforts, we certainly do not think about self-organization and the coevolution of nature and society, let alone our role in these dynamics. The application of the entropy and action principles that have been used to model ecological systems may be applied to social and economic activity (e.g., Ruth, 1996; Hammond and Winnett, 2009). For example, Chen (2005) represented economics as a nonequilibrium thermodynamic process by lognormal process that contains a growth term and dissipation term, thereby presenting a simplified understanding of economic activities including human mind, value, and entrepreneurship. Anttila and Annila (2011) envisioned the possibility that human behavior is governed by the entropy and action priniples that direct natural processes. They formulated concepts of game theory as physical processes that will consume free energy in the least time. Hence, the rate of entropy increase is the payoff function that will subsume all forms of free energy that motivate diverse decisions.

Complex systems approach demands new strategies for experimentation and observation in the natural laboratory rather than in simple controlled environment (Ruddell *et al*., 2013). The central role of information in directing self-organizing processes and structures has only recently been put forward. One of the recent progresses in developing methodologies to describe such role is the information flow process network approach (Ruddell and Kumar, 2009a). Dynamic process network is defined as a network of feedback loops and the associated time series that depicts the magnitude and direction of flow of energy, matter and information between different variables. This approach can be used to formally resolve feedback, time scales, and subsystems that define the complex system's organization by considering mutual information and transfer entropy simultaneously (Ruddell and Kumar, 2009a; Kim *et al*., 2011; Yun *et al.,* 2014b, Kang *et al*., 2017). Furthermore, network statistics can be used to measure the statistical feedback, entropy, and net and gross information production of subsystems on the network (Ruddell and Kumar, 2009b; Kumar and Ruddell, 2010).

3.3. Framing of the Process with Visioneering

The core assumption in SOHOs approach is that a sustainable society maintains itself in the context of the larger ecological systems of which it is a part (Waltner-Toews and Kay, 2008). The SOHOs approach requires the integration of ecological possibilities and wholeness (i.e., ecological integrity) with social values and desires (i.e., societal integrity) into potential narrative descriptions (i.e., scenarios), thereby resolving a shared communal vision for sustainable ecological-societal systems. In essence, it must involve the process of 'visioneering' − the engineering of an integrated vision (Kim and Oki, 2011). Here, engineering implies skillful direction and creative application of scientific principles and experiences to develop structures, processes, and heuristics. Visioneering stands as the cooperative triad of governance (i.e., the process of strategic vision casting, resolving tradeoffs and obstacles, and systematic celebration of progress), management (i.e., translating vision into operation by developing and implementing strategies), and monitoring (i.e., synthesizing observations into narratives, providing feedback, and promoting adaptive learning) (Waltner-Toews and Kay, 2008; Kim and Oki, 2011).

Framing of the SOHOs process with visioneering requires particular key competences in sustainability. Here, competence is defined as a functionally linked complex of wisdom, knowledge, skills, and attitudes that enable successful task performance and problem solving (Wiek *et al*., 2011). First of all, 'systems-thinking competence' must be the basis for combining SOHOs with visioneering. Wiek *et al* (2011) defines it as the ability to collectively analyze complex systems across different hierarchies through comprehensive systems understanding adequate to

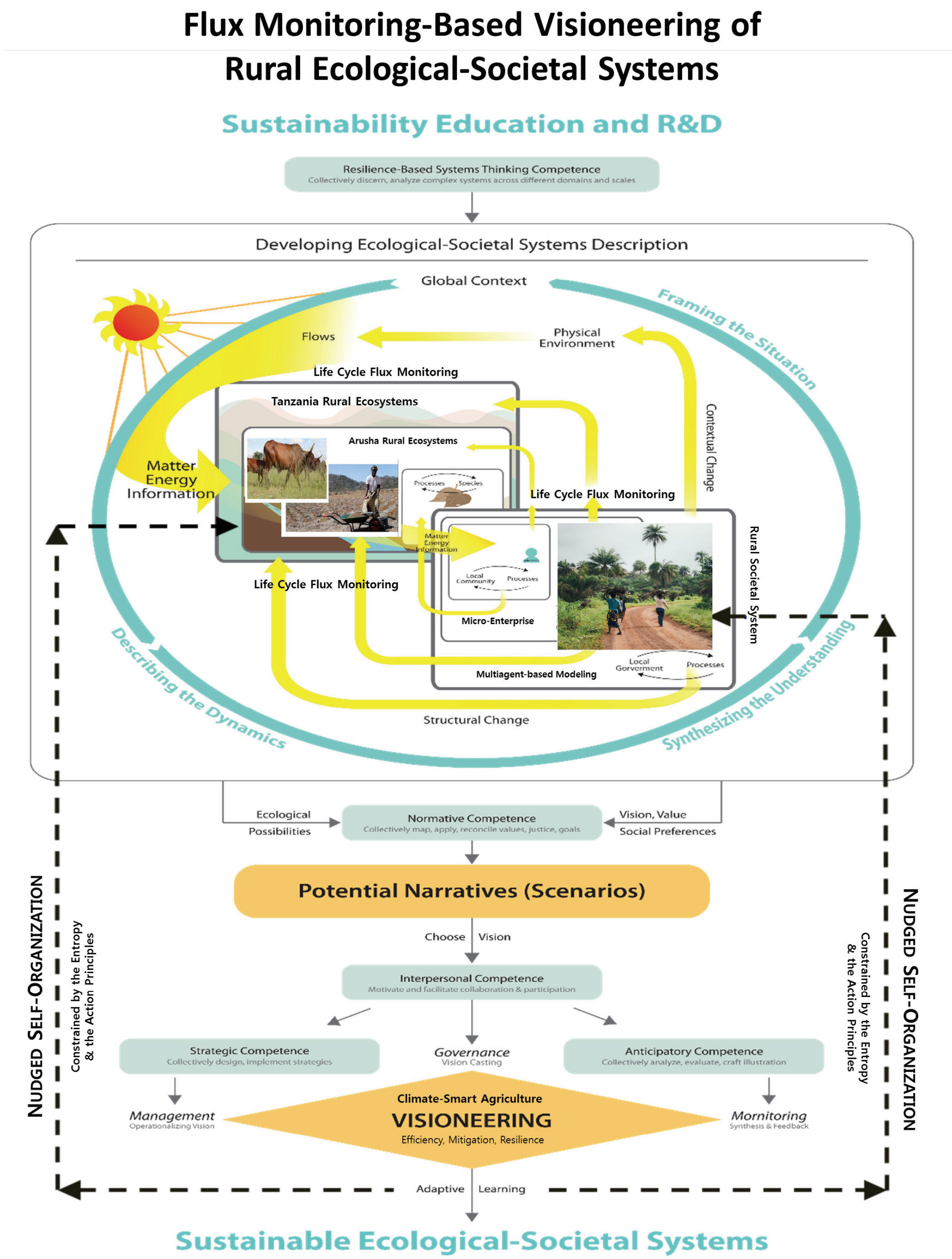

Figure 3. Self-organizing hierarchical open systems with visioneering (SOHOs-V) framework.

pursue systems integrity, civility, and governance. The integration of ecological and societal integrity into scenarios would require 'normative competence' − the ability to collectively map, specify, apply, reconcile, and negotiate values, principles, goals and targets. This value-focused competence enables to assess the sustainability trajectory of ESS and to craft communal vision, which must precede the construction of direction and orientation about transformation toward sustainability (Wiek *et al*., 2011; Cote and Nightingale, 2011).

Envisioning a sustainable ESS is an important step. Without engineering it, however, the vision will not stick and remain as daydream. Other key (inter personal, strategic, and anticipatory) competences would enable a triad of adaptive activities (i.e., governance, management, and monitoring) to be carried out in concert toward sustainability (Kay and Boyle, 2009; Wiek *et al*., 2011). Fig. 3 represents the combined SOHOs-Visioneering (SOHOs-V) frame work. Sustainability is all about maintaining the integrity of the combined ESS. Integrity is preserved when the system's self-organizing processes are preserved, something that happens naturally if we maintain the context for self-organization in ecological systems, which, in turn, will maintain the context for the continued well-being of the societal systems (e.g., Jørgensen, 2006; Kay and Boyle, 2008; Ash *et al*., 2010). It is worth noting in Fig. 3 that there are feedback/feedforward loops connecting ESS with visioneering through 'nudged self-organization' that is guided by both the entropy principle (as the most probable state) and the action principle (as the most probable path/trajectory) toward sustainability.

IV. Application of SOHO-V to Sustainable Development Golas (SDG) Lab

In order to have a major breakthrough in the realization of 17 Sustainable Development Goals (SDG), Future Earth recently has called and endorsed 20 SDG Labs with high degree of innovation, transformative potential and scaling potential (http://www2.ir3s.u-tokyo.ac.jp/icss2017/). 'Rural Systems Visioneering (RSV)' is one of those SDG Labs, which is now underway in rural villages in Tanzania. RSV SDG Lab focuses on rural areas and engages in multiple SDG (i.e., no poverty, quaity education, clean water and sanitation, affordable and clean energy, sustainable cities and communities, responsible consumption and production, climate action, and life on land). What are the essential challenges? Tanzania still remains poor and non-industrialized, heavily relying on very underdeveloped agriculture. Despite isolated good cases, the science and technology system as a whole is not influencing innovativeness in farms and firms. Rural villages in Tanzania still lack (1) resources (electrical power, storage for food and vaccine), (2) infrastructure (for management and monitoring), (3) quality education (training and mentoring), and most of all (4) communal vision and its engineering (i.e., visioneering).

RSV SDG Lab employs the SOHOs-V framework in collaboration with the 'Tanzania-Korea Innovative Technology and Energy Center (iTEC)' in the 'Nelson-Mandela African Institution of Science and Technology (NM-AIST) to (1) co-create innovative sustainability science and appropriate technology necessary for the renewable energy-based electrical, climate-smart agricultural, and resilience-based educational fields and (2) co-grow with rural villages through visioneering processes.

To mobilize rural people and villages, the following applications are in progress: (1) sustainability education with focuses on nurturing the basic (inter-personal) and key (e.g., systems thinking, normative, strategic, and anticipatory) competences, (2) climate-smart agriculture and its quantitative assessment based on biotic/network/thermodynamic indicators by monitoring and modeling energy-matter-information flows in and out of rural systems using (eventually inexpensive) flux measurement, computer modeling and remote sensing, (3) multiagent-based systems analysis for emergent solutions for better productivity and profit for heterogeneous smallholder farmers, and (4) linking the above-mentioned efforts to the rural communities with feedback loops (i.e., guided self-organization process) to create profit, to promote micro-enterprise, and to nurture servanthood entrepreneurship that ensures sustainability (e.g., Lee, 2015). The follow-up African counterpart SDG Lab, i.e. 'BaobabTalker' will be launched during the upcoming Sustainability Science conference 'Seedbeds of Transformation: The Role of Science with Society and the SDGs in Africa' in May 2018 in Port Elizabeth, South Africa (http://seedbeds.futureearth.org).

V. Concluding Remarks

There is a growing recognition that the human society must be viewed and studied as an integral part of ecological systems. Various conceptual frameworks have been proposed to characterize the dynamics of ecological systems and societal systems apart, yet out-of-the-box thinking is needed to bridge ecological and societal systems. The framing of SOHOs-V is built upon the first principles, i.e. the principle of entropy and the principle of least action. Such a conceptual framework encourages us to think about the relationships between the natural and human-constructed world and challenges us to develop science that allows studying their co-evolution. It also inspires us to educate students with particular key competences that will prepare them to engage in sustainability challenges by envisioning and implementing sustainable options to the current and anticipated concerns in complex ESS (Brundiers and Wiek, 2010; Wiek *et al*., 2011; Lang *et al*., 2012). Ruth *et al*. (2011) emphasized that three kinds of institutional innovations must take place: (1) the academic world where sciences are integrated to advance understanding of coupled ESS dynamics; (2) the ways in which sciences and modeling mutually inform and are informed by social needs; and (3) institutions guide investment and policy making on the basis of sustaining the integrity of the combined ESS rather than with a myopic view towards direct, desired impacts. As Kay and Boyle (2009) asserted, new scientific inquiry and endeavor must be an act of collaborative learning and knowledge integration with expert's role shifting from giving correct answers to sharing information about options and trade-offs.

In looking beyond our diverse fields, we, the authors, are delightfully reminded of a story of a scientist who traded rigor for speculation (Gleick, 2011). About 75 years ago, Erwin Schrödinger, the pioneer of quantum physics, stood on the podium to give the Statutory Public Lecture at Trinity College, decided the time had come to answer one question: What is life? He began by apologizing, "S*ome of us should venture to embark on a synthesis of facts and theories, albeit with second-hand and incomplete knowledge of some of them and at the risk of making fools of ourselves*." Later, as Gleick (2011) pointed out, a little book he made from these lectures revolutionized the science community and laid a foundation for a new science - molecular biology. Schrödinger provided two important insights in his explanation of life: (1) formulation of life as a thermodynamic process and (2) observation of appearance of global order from local fluctuations, i.e. self-organization (Chatterjee, 2016a). Likewise, we hope that this letter helps bring more transdisciplinary sciences to the podium!

적 요

지속가능성과학은 다양한 학문 배경과 관심을 가진 과학자, 전문직 종사자 및 이해당사자들 간의 소통과 협력뿐 아니라 결정론적 환원주의적 접근에서 오래전 기본으로의 패러다임 전환이 요구되는 떠오르는 초학문적 연구다. 생태-사회시스템은 많은 구성성분(또는 행위자)들로 이루어져 이들의 국지 규모의 무작위 상호작용이 자연스럽게 시스템 전체 규모의 질서를 만들어내는 공진화하는 복잡계다. 여기서, 시스템과 주변 환경 간의 에너지와 물질과 정보의 흐름이 중요한 역할을 한다. 본 통신에서는 이렇게 계속 변화하는 역동

적 시스템, 즉 '자기-조직화하는 계층구조의 열린 시스템(SOHOs)'의 개념적 틀을 소개한다. 먼저 SOHOs의 구조와 기능성을 이해하기 위해 물리학의 두 기본 법칙을 다시 논의한다. 두 법칙의 재해석을 통해 시스템의 운명과 지속가능성을 향한 보다 나은 경로, 또한 생태계의 온전함과 사회의 비전/가치 추구를 어떻게 조화시킬 것인가에 대한 이해를 돕고자한다. 그 다음에 소위 '비저니어링(V)'이라는 틀을 되먹임/전방급전(feedback/feedforward) 루프로 SOHOs 틀에 통합시켜서, '슬쩍 찌르는(nudged) 자기-조직화'가 시스템을 구성하는 행위자들이 합력하여 지속가능한 생태-사회 시스템을 이루어 가도록 유도한다. 마지막으로, SOHOs-V의 적용사례로서, 현재 탄자니아의 농촌마을에서 진행되고 있는 미래지구의 지속가능발전목표 연구실(SDG Lab)인 '농촌시스템 비저니어링(Rural Systems Visioneering)'을 예로 제시하였다.

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