January 2017
No. 2017-001-e

*Journal of Integrated Creative Studies*

# Ecological Integrative Systems in Linking Sciences and Societies

# - Social Consilience Based on Information Provision and Ecological Efficiency Appreciation

**Tae-Soo Chon**[1, 2]
[1]Pusan National University (Prof. Emer.)
[2]Ecology and Future Research Association
E-mail: tschon.chon@gmail.com

**Abstract.** Due to unprecedented economic growth and human aggregation, disturbances are ubiquitous across life system hierarchy from genes to ecosystem including living modified organisms, for instance, tolerance to extreme environment, pest/disease eruption, biodiversity loss, stability/safety problems at the levels of genes, individuals, populations, communities, and ecosystems, respectively. Ecological sciences enter a new phase due to urgency of ecosystem stability in parallel with rapid development of information and communication techniques at the same time. A key concept for solving complex ecological problems is "integration" by utilizing four components that have been already ready for establishing the system: gene information, mathematical biology, mobile sensor networks, and modelling techniques. All components of systems could be combined in a most optimal way to achieve the unified goal, sustainability (e.g., safety, stability, efficiency) of ecosystems. Multi-disciplines are involved in pursuing ecological projects and could be divided into ecological contents (ecosystems, taxa, and size) and connection to humans (academic fields and human involvements). In acquiring information on ecological contents effectively, surveys/experiments could be conducted by utilizing mesocosms and mobile sensor networks. A structure property residing in interplay between social pressure and disturbance in ecosystems could be a basis for social concerns caring more about the public property than private property. Based on suitable information provision and appreciating ecological efficiency, altruistic feedbacks by humans could be arisen to resolve the tragedy of the common consequently in human societies.

**Keywords:** Ecosystem sustainability, Multi-disciplines, Mesocosm mobile sensor networks, Virtual ecosystems, Socio-economic models

# 1. Introduction

## 1.1. Disturbances and disasters

Due to unprecedented economic growth and human aggregation, disturbances (and stressors) are ubiquitous; examples are numerous across life system hierarchy from small (e.g., gene) to large (e.g., ecosystem) units (Table 1). Starting from living modified organisms (LMOs) at the gene level, critical issues are lined up, tolerance to extreme environment, pest/disease eruptions, biodiversity maintenance, and stability/safety problems at individual, population, community, and ecosystem level, respectively, for instance. Living organisms and substrate environments (e.g., water, air) are prone to damages in exposure to disturbing agents locally and globally. Accumulation of instabilities may cause disasters in large scales (e.g., severe drought/storm, pollution, epidemics/epizootics). It would be a critical issue, whether a gradual change may eventually cause a sudden shift in ecosystem stability systematically (Folke, 2004).

However, numerous biological and environmental factors are involved in ecosystem problems in a complex manner. Understanding the causality relationships in ecosystem disturbances is not an easy task. Moreover, egocentric human attitude is involved: people tend to concern their own properties more than public properties. This makes it difficult for humans to sufficiently care about substrate environments they share (i.e., the tragedy of the common). New paradigm is needed to solve this contradictory problem in achieving safety and stability in ecosystems.

**Table 1.** Example cases of stress and disturbance across life system hierarchy from genes to ecosystems.

| Unit | Issues |
|---|---|
| Ecosystem | Global warming, Biogeochemical cycle abnormality, Energy efficiency problem |
| Community | Biodiversity maintenance, Food web stability |
| Population | Species invasion/extinction, Epidemics, Pests, Food crisis |
| Individual | Tolerance to extreme environment/pollution, Behavioral abnormality/adaptation |
| Cell and Gene | Living modified organisms, Pesticide resistance, Toxicological response |

A key concept that may be considered for solving complex ecological problems would be "integration": all components of systems are combined in a most optimal way to achieve the unified goal, sustainability of ecosystems. The goal would be to integrate the system components in such a way that safety (e.g., dealing with toxic residues) and stability (e.g., population/community dynamics, nutrient cycling) are achieved along with efficiency in ecosystem functioning concurrently. Humans should most suitably care about environment and natural resources to make our ecosystems survivable for living organisms in the long-term aspect. Synthetic as well as analytic views are both needed in dealing with complex problems in an integrative scheme in pursuing the objectives of ecological projects (Jørgensen, 1997).

**1.2. Two views on science contribution**

Regarding the application side of science in contributing to humans, there would be two views. The first view would be to put an emphasis on production; enhancement of technology is emphasized to achieve maximum production by continuous positive feedbacks for innovation. Due to unlimited development human societies may experience unprecedented industrial development and economic growth. Consequently, however, energy would be dissipated in a great amount due to unbalanced consumption of natural resources (e.g., deprivation, waste, pollution). Since production is emphasized rather than conservation in this view, the developments require environmental sacrifice. Once damaged it is very hard to recover ecosystems. Most scientific and engineering fields, however, are in fact based on this view, which may be called a pink design.

The second view would concern more about conservation, rather than production. Although maximum production may not be achieved, efficiency is more emphasized in dealing with ecosystem management in this view (e.g., Odum, 2005). Minimization of environmental damages along with maximization of energy efficiency and ecosystem recovery are main concerns, and this view may be called a blue design, being prudential not to make irreversible mistakes of damaging ecosystems further. The blue design would consider more about overcoming the tragedy of the common naturally, encouraging humans to have altruistic attitudes for conserving ecosystems instead of egocentric attitudes.

In order to link ecological sciences with human concerns more effectively, I would like to present an integrative ecological system to be feasible in achieving objectives in the blue design. Ecology is the science of studying the totality of relations among biological and environmental factors in determining abundance and distribution of life organisms by considering ecosystem functioning (e.g., biodiversity, energy circuit, biogeochemical cycling) (e.g., Krebs, 2001; Odum, 2005). The integrative approach would be a characteristic of ecological projects to achieve the unified goal of ecosystem sustainability in a comprehensive manner by combining all the components effectively.

Although the components may have existed already, integration proposed in this article could be considered new in the sense that all necessary components are effectively integrated into a system to achieve ecosystem sustainability. Regarding integrative achievements in human history, we may have similar examples, cars and computers. With cars, the components such as engines and the parts for locomotion (e.g., tires, brakes) have been already developed. Subsequently, however, all the components had to be integrated newly in order for them to become a most convenient transportation tool for humans. Similarly for computers, components such as semi-conductors, digitization techniques, and algorithms have been already introduced to human societies. However, a versatile computation tool that is convenient for calculations for human lives was possible only after all the components were integrated to be a universal computation tool, called a computer. In ecology, by the same token, components are ready to be integrated to a system that could make our ecosystems more survivable with safety, stability, and efficiency. In line with recent developments in sciences and engineering, four components are ready in a broad scope for establishing an integrative ecological system: gene information, mathematical biology, mobile sensor networks, and virtual ecosystems.

As is well known, the issue of ecosystem sustainability was raised along with ecosystem stability/services since the 1990s. Study on ecosystem sustainability was initiated by regarding importance of interactive controls between key variables within stable bounds in the system (e.g., negative feedbacks in food availability) (e.g., Chapin, 1996; Christensen, 1996). Costanza (1997) reported the value of the world's ecosystem services critical to the functioning of the Earth's life-support system. Regime shifts were recognized in relation to resilience of complex adaptive ecosystems (e.g., functional roles of biological diversity) (Folke, 2004). Numerous accounts of methodological studies were subsequently followed, for instance, quantification and valuation (e.g., emergy, exergy) (Rapport, 1998; Zhang, 2010; de Groot, 2002), harvesting strategy with refugia (Gadgil, 2000), and evaluation based on fuzzy logic (Prato, 2005). Ecological issues in ecosystem management were also dealt with in a broad scope, including biodiversity (Tilman, 1996, 2006), conservation (Egoh, 2007), climate effects (e.g., Walker, 2008), and policy interface (Perrings, 2011). Principles of ecosystem sustainability were further applied to target ecosystems specifically such as agro-ecosystems (Tilman, 2002), landscape (Fischer, 2006), water management and aquatic ecosystems (Grant, 2012; Glibert, 2012), and human ecosystem and health (Stephens, 2007; Waltner-Toews, 2005). However, the integrative system that consider extensively the overall contemporary scientific achievements as stated above and address both information availability and ecological efficiency appreciation by humans as well has not been reported specifically.

## 2. Components of integrative approach and technical readiness

### 2.1. Gene information

Since the double helices of nucleic acids were introduced as genes of life organisms in 1953 (See Watson, 1968), molecular biology has been developed exceedingly and currently leads contemporary biological sciences in almost all aspects of applied fields including health, conservation, agriculture/fishery, industry, etc. Further development in molecular ecology (e.g., Zane, 2002) is foreseen in the future along with next generation sequencing, for instance, gene-based disease diagnosis, systematic medical care, genomics-based breeding in agriculture and fishery, revealing genetic functioning, systematic biodiversity management for conservation, etc.

Along with development of whole genomics sequencing, evolutionary processes would be also closely adopted in genetics in addressing survival and adaptability of organisms to environmental disturbance and stress. The principles in evolution would be addressed in revealing adaptive mechanisms and provision of information for ecosystem management in response to natural and anthropogenic selection pressures along with development of population/quantitative genetics and molecular ecology/evolution.

### 2.2. Mathematical biology/ecology

Mathematical biology unravels structure properties residing in life events: theoretical approach would be effective in addressing complex life phenomena interplaying between living organisms and environmental factors in a more objective manner. Mathematical biology has been introduced in ecological sciences in various fields including population/quantitative genetics, population dynamics (e.g., pest/disease dispersal), biodiversity maintenance, and ecosystem stability. Moreover, mathematical biology has been broadly applied to the whole scope in biological sciences such as morphology (e.g., pattern formation in embryonic development), physiology (e.g., cell growth, disease development, polyphenism), behavior (e.g., optimal foraging theory), and strategy/game theory (Iwasa, 1998, 2008; Murray 2003a,b).

In relation with gene information as stated above, research on evolution would be also extensively dealt with in mathematical biology. Genetic diversity and gene functioning should be addressed in association with computational analyses of eco-evolutionary processes (e.g., adapting to extreme environment, sexual evolution, life history schedule). Molecular ecology and evolution would be a step stone to reveal life system dynamics in responding to anthropogenic and natural variability through generations. Since evolution theory was proposed by Darwin (1859) computational approaches were introduced early in the 20$^{th}$ century regarding gene dispersal in time and space, including neutral theory (e.g., Wright, 1931; Kimura, 1968). Further developments in mathematical approaches are broadly foreseen along with adaptive dynamics, fitness landscape, evolutionary game theory, replicator dynamics, and individual based models in eco-evolutionary processes (Dercole and Rinaldi, 2008).

**2.3. Mobile sensor networks and mesocosms**

It is timely that information and communications technology (ICT) has been expanded to measurements of ecological responses in both laboratory experiments and field surveys in real time in a broad scope. As stated above prompt and objective information provision on ecological responses is a key element for humans to understand ecological phenomena closely and deeply: humans could be more familiar with importance of conservation and recovery of ecosystems. A notable achievement has been made in interfacing and real-time measurements in ecosystems *in situ*. Sensor network is an outcome of ICT that could be effectively implemented in ecological sciences especially in field conditions in real time. Sensor networks are spatially distributed autonomous sensors to monitor physical or environmental conditions and to cooperatively pass their data through the network to a main location (January 1, 2017; available from URL https://en.wikipedia.org/wiki/Wireless_sensor_network).

Missing some sensors would not be a serious problem for operation in field conditions: other systems could substitute the missing ones. Multitude of sensors is an extra advantage to be helpful for sensing ecological responses in difficult situations of measurements (e.g., disasters) *in situ* effectively. The sensor networks would make the monitoring system more robust in real conditions. In addition robots could be installed on the sensor networks further. The mobile components (e.g., robot arms) could assist for the sensor networks to automatically and continuously measure behavioural/ecological responses in behalf of humans especially in the situations where experimentations would be difficult or not possible. If the sensor network components are connected over a space spanning the target ecosystems, spatial conformations of species dispersal could be provided regarding how species would either invade, establish, or extinct dynamically. Information on decision making could be also available from the data obtained by the sensor networks regarding numerous issues of disasters and disturbances (e.g., pest/disease, natural disaster, radioactive accidents).

It is noteworthy that mesocosms could be additionally utilized along with sensor networks in field conditions *in situ*. A mesocosm (*meso*- or 'medium' and *-cosm* 'world') could be defined as any outdoor experimental system that examines the natural environment under controlled conditions (Janurary 1, 2017; available from URL https://en.wikipedia.org/wiki/Mesocosm) in an intermediate scale comparing to either micro- or macro-cosms. Open types of mesocosms could be designed in such a way that target organisms may visit or stay inside mesocosms for a substantial period of time. Resources for organisms such as food, water, and resting place could be provided in sensor networks. Behaviour of organisms staying in the mesocosms could be recorded continuously and automatically with the sensor networks. The accumulated information would be useful in close-to-nature conditions for understanding life events of the organisms more precisely. In the long term behaviour profiles of individuals and populations could be revealed to provide key information on life cycle schedules (e.g., adult age for reproduction) and strategies (e.g., *r* strategy, *K* strategy).

### 2.4. Modelling and virtual ecosystems

Modelling and systems approach are a useful methodology to open a new door in delivering ecological information to human societies more effectively. Ecological modelling can be used for numerous purposes in ecological sciences, objective description of life events, identifying important variables, causality relationships, prediction, and provision of information on policies for ecosystem management (e.g., Odum, 1993; Jørgenesen, 2008).

It is also noteworthy that modelling could be extended to virtual ecosystems according to individual (or agent) based models (DeAngelis, 1992; Grimm, 2005). Virtual ecosystems have the advantage of studying disasters (e.g., earthquakes, severe droughts, radioactive accidents) that cannot be experimented readily in real world. The course of disasters could be visualized through simulation in virtual ecosystems. Consequently scenarios could be provided according to disturbing agents or other constraints (e.g., physiological/genetic adaptability to new environmental conditions). Spatio-temporal development of disasters will be projected in the system along with ecosystem responses. Various management plans could be also tested according to urgency and severity of disasters and disturbances. Manuals for provision of management policies could be further provided according to scenarios for keeping safety and stability in ecosystem functioning in disastrous situations.

## 3. Development of integrative systems

### 3.1. Multi-disciplines

Ecology deals with complex phenomena in multi-disciplines. There would be five main disciplines that should be dealt with in pursuing ecological projects concurrently: ecosystems, taxa, scales, academic fields, and social involvements (Figure 1). Subtopics could be further defined at lower levels in each discipline. Three disciplines, ecosystems, taxa, and scales, could represent ecological contents. Different kinds in ecosystems could be considered as the focal objects for ecological projects, for instance, forest ecosystem, agroecosystem, aquatic ecosystem, etc. Taxa could represent the target biological organisms that would take a main role in ecosystem functioning, including the kingdoms of animals, plants, and microorganisms, and could be further divided into smaller scales, phylum, class, order, family, genus, species, etc. Subsequently units from genes to ecosystems could be presented in different scales in hierarchical life systems (Figure 1).

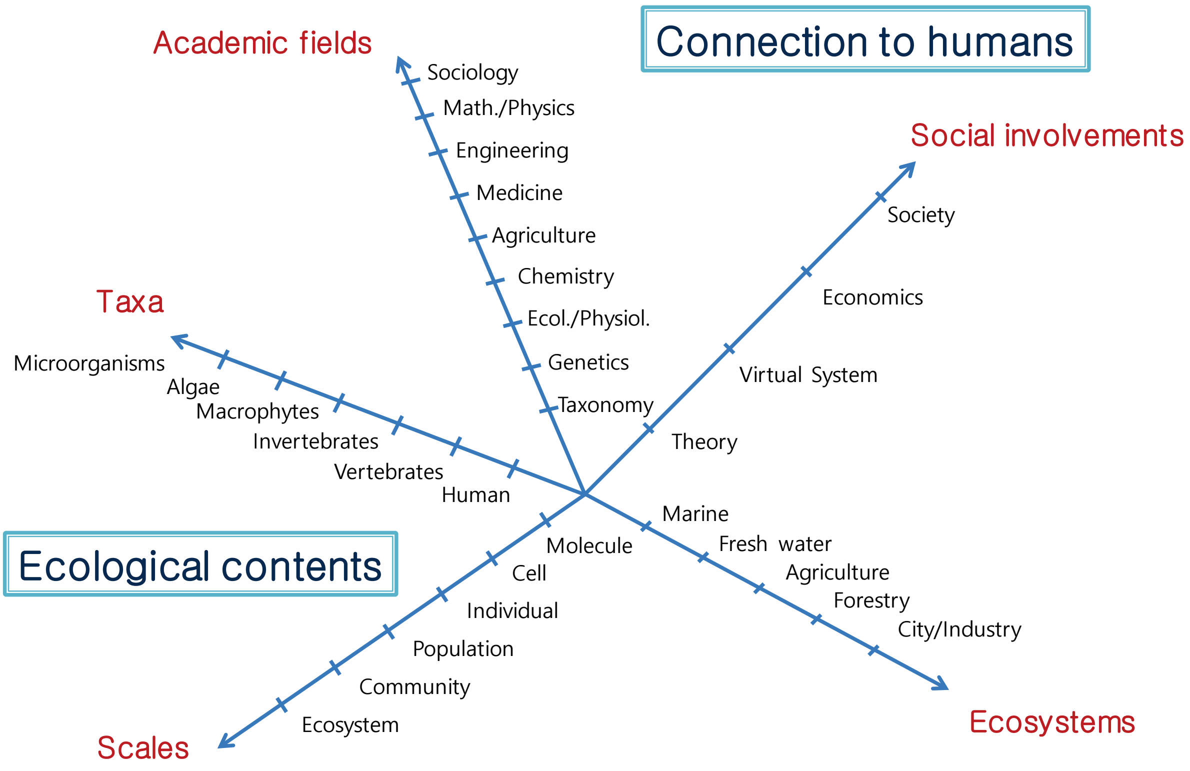


**Figure 1.** Multi-disciplines for pursuing ecosystem sustainability in ecological projects.

The other two disciplines, academic fields and social involvements, would serve to link the ecological contents with human societies (Figure 1). Academic fields include all subjects across sciences, engineering, and sociology in relation with ecological sciences. According to the scale from genes to ecosystems biological sciences could be listed along the horizontal axis and interlinked with other sciences as illustrated in Figure 2. Physiology and ecology would address phenomenological life events, addressing associations and causality relationships for survival in adapting to environmental conditions. Ecology may be viewed as "from outside to inside approach": life phenomena are observed from surrounding environments outside and the mechanisms are addressed to reveal functioning in smaller scales by physiological processes at molecule and cell levels inside the body. In contrast, physiology would reveal live events "from inside to outside": the life mechanisms at fine scale could be linked to larger scales, individuals, populations, communities, and eventually ecosystems in adapting to environmental conditions totally.

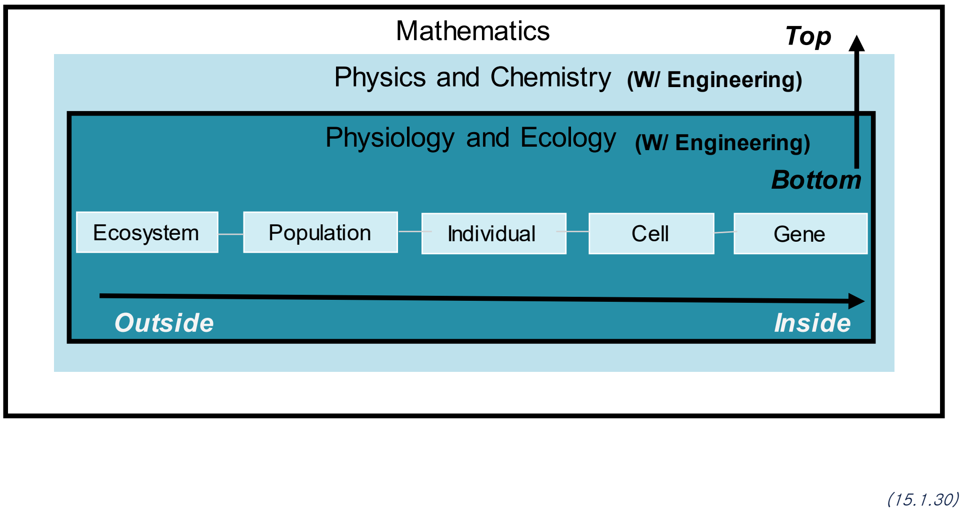


**Figure 2.** Academics fields in association with life system hierarchy: "bottom-up" and "inside-outside" approaches.

Natural sciences and mathematics could be additionally listed along the vertical axis in Figure 2 in presenting the relationships between different academic fields. A high level of variability is observed in complex ecological phenomena. Physics and chemistry unravel complexity in life events to address structure properties and functional processes residing in biological systems and are helpful in inferring living mechanisms observed in ecological phenomena at low, phenomenological level. Various fields in engineering would be helpful for measurements and realizing experimental/model results. Knowledge in life events could be further abstracted in a high level to reveal regularities in life processes with mathematics and computational approaches eventually (Figure 2). Overall, mathematics would have a top-down approach to provide regularities (top) that could be useful for addressing complex life events more objectively at the phenomenological level of physiology and ecology (bottom). Biological sciences, in contrast, considered to have a bottom-up approach by examining phenomenological events (bottom) first to provide information that could be extracted to find regularities in life events through formal, theoretical approaches (top) (Figure 2). Both top-down and bottom-up approaches would be needed concurrently in exploring biological/ecological events effectively.

Finally the fifth discipline, social involvements concern realization of ecological contents in human societies (Figure 1). Initially academic knowledge accumulated in life phenomena could be useful for interfacing with human perceptions. Subsequently the knowledge could be further used for life event description/prediction and provision of management policies through modelling and virtual ecosystems. It is noteworthy that virtual ecosystems would be useful for dealing with the situations that may not be possible to experiment directly in real world by generating augmented reality such as natural (e.g., earth quakes) and anthropogenic (e.g., pollution) disasters as stated above.

### 3.2. System description

An integrative ecological system could be developed to achieve the unified objective in ecosystem management by utilizing the components in multi-disciplines. The overall framework of the integrative system could be presented as Figure 3. Since the integrative system in Figure 3 is complex, an outline is presented in Figure 4 separately. The five disciplines (Figure 2, and the left hand side of Figures 3 and 4) stated above would be linked with human activities and could be divided into ecological contents (bottom left, Figure 4) and connection to humans (top left, Figure 4) as stated above. In acquiring ecological information in an integrative manner, *in situ* measurements could be additionally conducted in surveys/experiments, utilizing mobile sensor networks and mesocosms (bottom right, Figure 4). Connection to humans will be further integrated with human involvements and social consilience would be arisen through human networks and modelling (including virtual ecosystems) (top right, Figure 4).

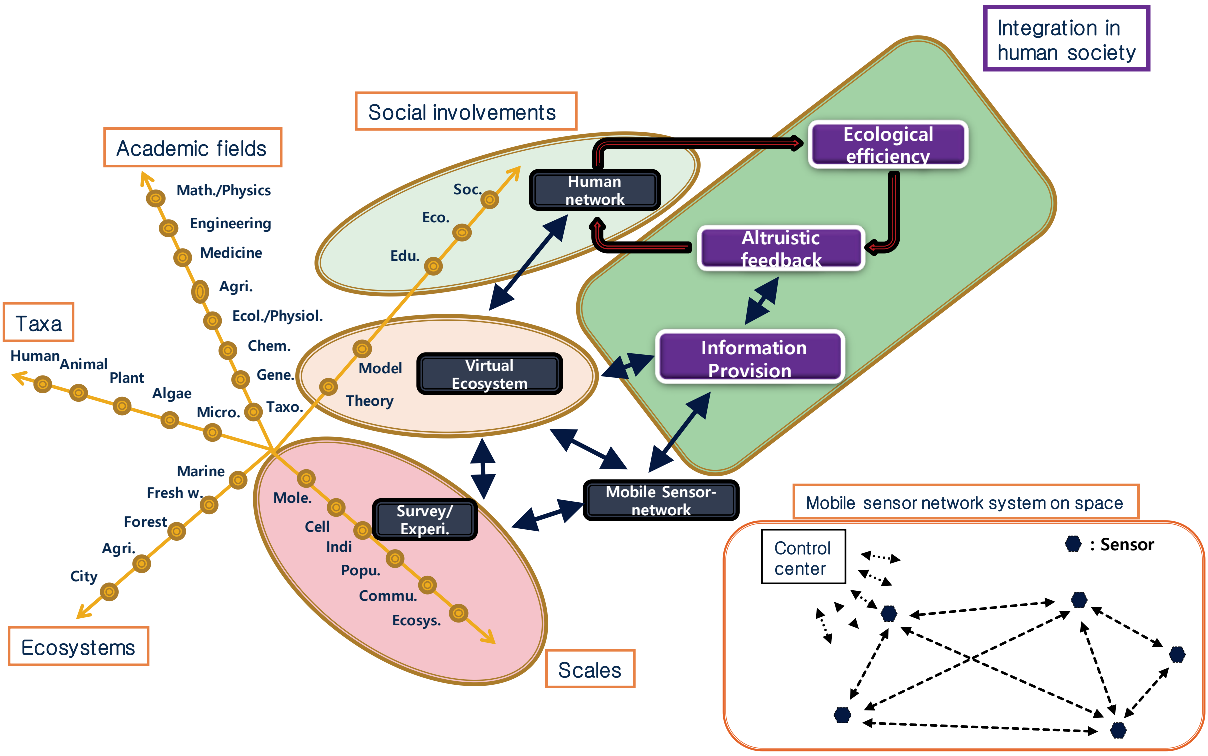


**Figure 3.** An integrative ecological system based on multi-disciplines linked with information provision and ecological efficiency appreciation in human societies to enhance altruistic feedbacks for achieving ecosystem sustainability.

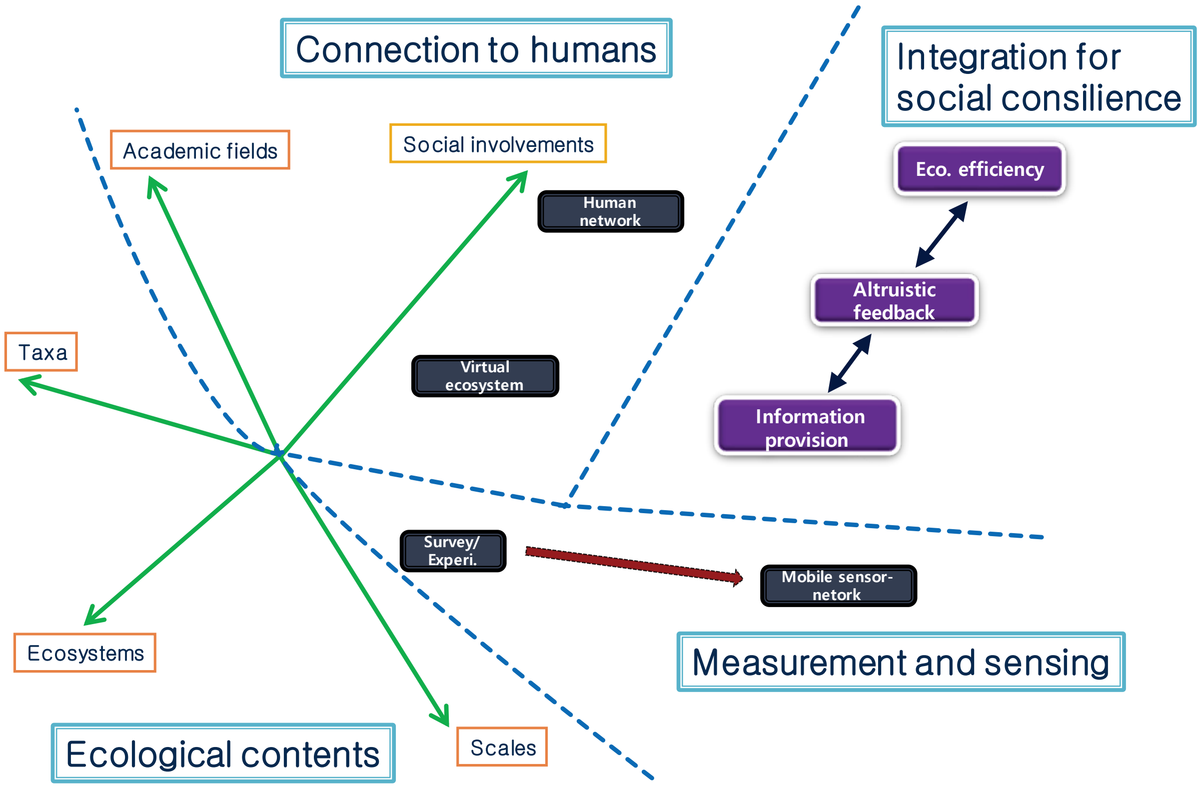


**Figure 4.** Outline of integrative processes: ecological contents measured by sensing systems are connected to human societies to achieve social consilience by acquiring altruistic feedbacks based on information provision and ecological efficiency appreciation.

In practical aspect operation of the system could be considered as shown in Figure 5. Initially a steering committee consisting of specialists in various fields including ecologists, computation specialists, and engineers could be organized to define the system in the initial stage. The committee would also establish a means of public relationships (Figure 5). Based on the system definition researchers in various fields could be organized in groups with multi-disciplines (Figures 1 and 3). The groups of specialists would further refine the system (e.g., variables, boundary) more precisely and set up research plans based on integrated system diagrams.

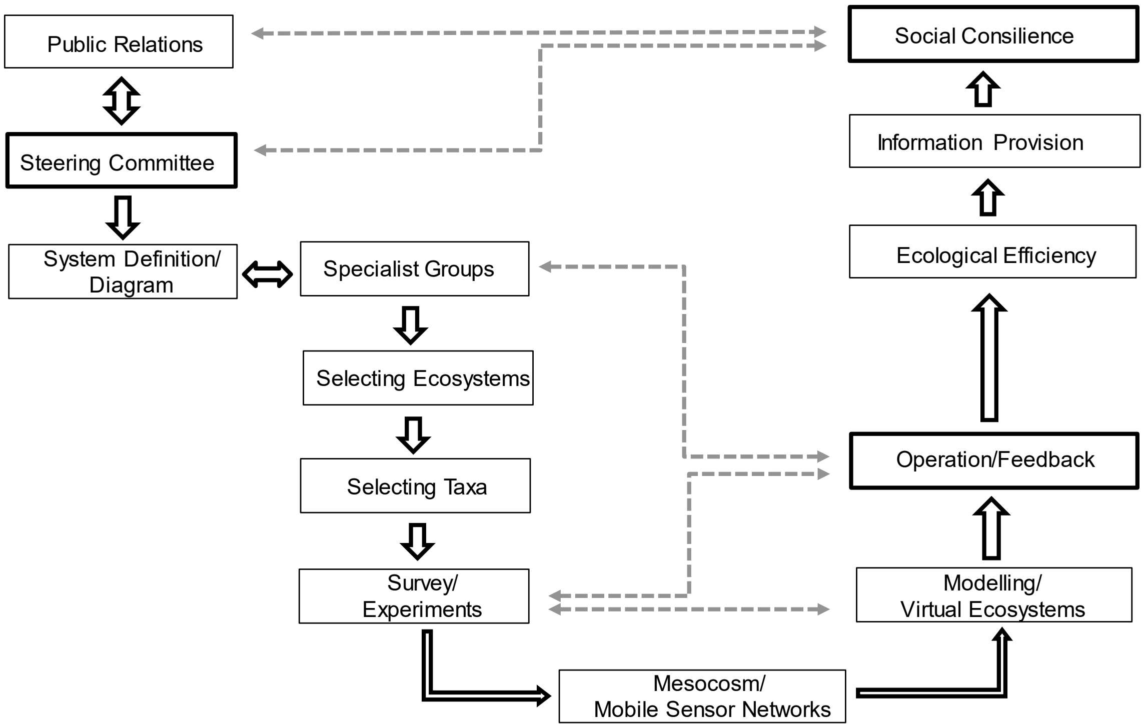


**Figure 5.** Operation processes for an integrative ecological system consisting of system definition, operation, and feedback flows in order to achieve social consilience for ecosystem sustainability based on information provision and ecological efficiency appreciation by humans.

After the planning step, ecosystems and target taxa are selected for the projects (Figure 5). Surveys and experiments could be conducted by utilizing mesocosms and mobile sensor networks as stated above (Figures 3 and 4). Models including virtual ecosystems could be further developed for revealing causality relationships and prediction. Based on results from surveys/experiments and modelling the system could be operated to achieve the system objectives by dealing with the controllable variables through flow interactions and feedbacks, ensuring robustness and precision for modelling output. Efficiency achieved in ecosystem functioning (e.g., energy circuit, recycling index) through system operation would be conveyed to human societies efficiently by using information provision methods (e.g., social networking service (SNS)). By appreciating ecological efficiency social consilience would be achieved for ecosystem sustainability in an objective manner (Figures 3 - 5).

### 3.3. Integration and social consilience

Regarding social consilience, the key issue would be how individuals/groups in societies will cooperate and are willing to yield individual benefits (e.g., time, money) to achieve sustainable ecosystems for public. The attitude concerning more about public property could be arisen on the ground of two components: information provision and appreciating ecological efficiency by humans as stated above (Figures 3 and 4).

However, raising altruistic attitudes among humans would be a difficult issue because people would naturally more care about their own properties. One possible entering wedge would be utilizing the mechanism of social cooperation that could be naturally arisen in conflict situations, for instance, disturbance severity in public property versus individual interest. A pioneering study was a socio-economic feedback model in handling a pollution case of lake eutrophication. Suppose cooperative (*B*) and non-cooperative (*A*) players pay the cost $C_B$ and $C_A$, respectively, social pressure, *S*, could be expressed with cooperator frequency and environmental concern (Iwasa, 2007) (Figure 6):

$$S = \alpha(1 + \xi F_t)\phi(Q) \quad (1)$$

where $\alpha$ is a constant for the basic strength of social power, $F_t$ is the fraction of cooperative players adopting *B* at time *t*, $\xi$ is a positive constant for the strength of frequency dependence, and $\phi(Q)$ indicates the society's concern on the water pollution according to pollution level, *Q*. The total cost for non-cooperative (*CostA*) and cooperative (*CostB*) could be expressed as:

$$CostA = C_A + \alpha\emptyset_0 q_0(1 + \xi F_t)[p_A(1 - F_t) + p_B F_t] \quad (2)$$

$$CostB = C_B \quad (3)$$

where $p_A$ and $p_B$ are pollution release by the non-cooperator and cooperator, respectively, and $\emptyset_0$ and $q_0$ are some constants representing the degree of environmental concern and pollution input, respectively (Iwasa, 2007).

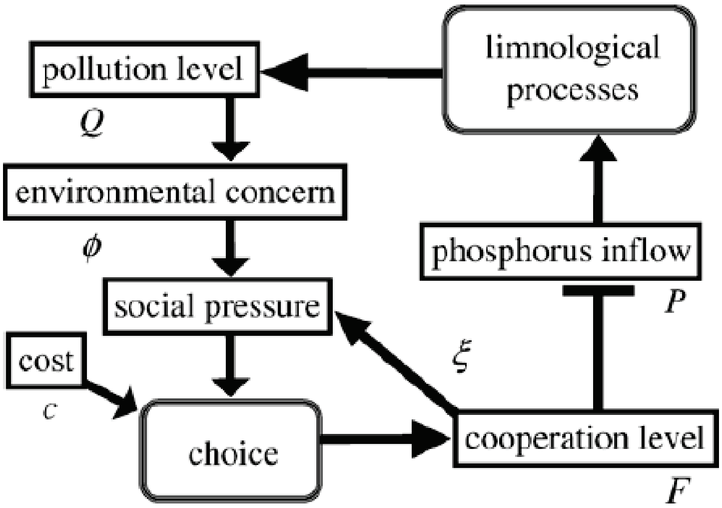


**Figure 6.** Flow chart for demonstrating social collaboration based on both negative and positive feedbacks regarding pollution source reduction and frequency dependence of social pressure (Iwasa, 2007; Quotation of the figure permitted by the Publisher).

With inclusion of positive (frequency dependence of social pressure) and negative (pollution source reduction) feedbacks in interrelationships among pollution, social concern, and cooperation levels, diverse dynamical behaviors were created (Figure 6). The model often showed bistability. In addition to low cooperation resulting in polluted water, a high level of cooperation among people was obtained to have clean water as a solution as well, indicating that social concerns could be inherently arisen through the feedbacks in dealing with pollution severity and public concerns on pollution (Iwasa, 2007). Suzuki (2009) further reported that social pressure regards a psychological factor in promoting cooperation. The pressure would become stronger when more players in the society are cooperative, and enhancement of the cross-group conformist tendency was effective in minimizing differences in cooperation levels and to mitigate conflict between groups. This type of social concerns indicates that altruistic feedbacks for collaborations by humans could be naturally arisen in the societies due to the structure property residing in social concerns by the humans.

**3.4. Subsystem objectives**

Since the system components are numerous in ecological projects the integrative ecological system could be considered as a meta-system (Figures 3 and 4). There would be a chance that the system functioning would diverge if the objectives are not well focused on within the overall framework of the grand system. In this regard subsystem objectives need to be well defined in line with the global objective of the system: subsystem objectives could be narrowed down in such a way that the locally addressed objectives could fit to the total system to achieve the global goal in harmony. In this regard, the subsystems could be viewed from ecological, ecology-relevant, and social aspects (Figure 7). Each subsystem may have sub-sub systems with focal points of their own.

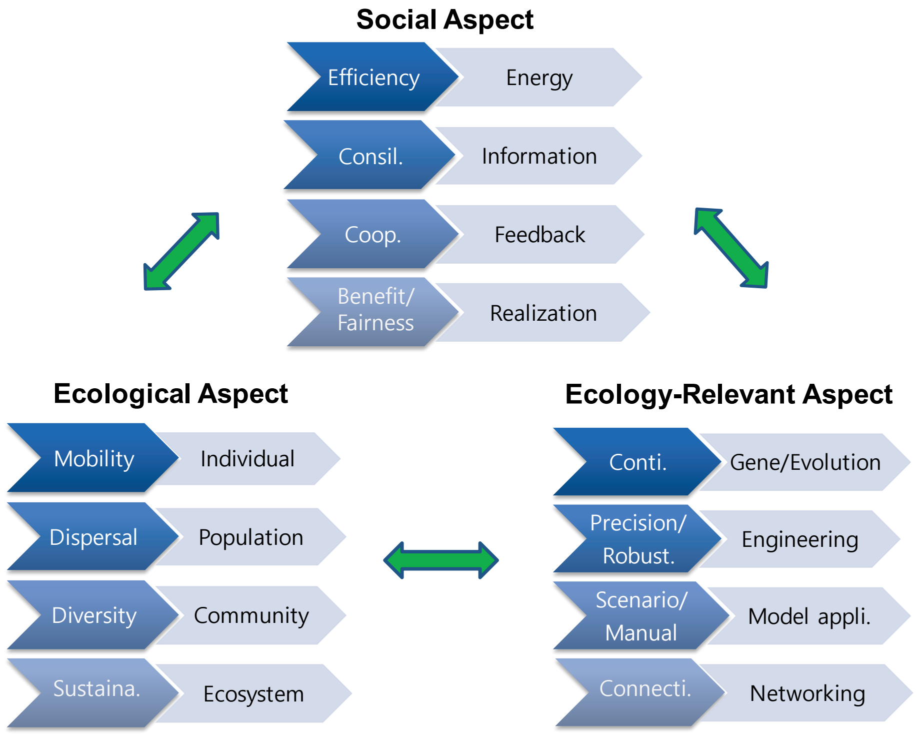


**Figure 7.** Key evaluation points and subsystem objectives in realizing the global objective of the ecological integrative system from the scientific (ecology and ecology-relevant) and human aspects. (See full characters for abbreviations in the text.)

Ecological aspect could be presented by the unit size of life from individuals to ecosystems (bottom left, Figure 7). The key goal could be defined for each subsystem as mobility, expansion, diversity, and sustainability at individual, population, community and ecosystem level, respectively. Mobility, for instance, would be a fundamental character to represent universal activity of living organisms for almost all basic life events such as food finding, escaping from predators, and approaching to mates. Similarly dispersal (e.g., species extinction/invasion) and diversity (e.g., biodiversity maintenance, food web) are key issues at population and community levels, respectively. Naturally sustainability that includes safety, stability, and energy efficiency in ecosystems would be the essential, global concern at the ecosystem level.

The ecology-relevant aspect should be considered in associated fields of science and engineering in order for the ecological contents to be efficiently realized through the integrative system. The components in the ecology-relevant aspect would consist of gene/evolution, engineering, model application, and networking (Figure 7). Continuity (e.g., population growth, inheritance) could be the fundamental issue with gene/evolution in presenting species survival according to fitness optimization in eco-evolutionary processes. Precision and robustness should be considered in developing hard- and soft-ware in engineering aspect (e.g., mobile sensor networks). Model application is also important in applying ecological contents to societies in presenting causality relationships, prediction, and provision of information for decision making. Development of scenarios and manuals according to virtual ecosystems could be considered also as a key objective regarding visualizing various cases of disturbances and disasters. Networking among the components (both biological and abiological factors) is also important in realizing ecological contents in human societies. Naturally connectivity would be a fundamental issue in networking.

Finally the integrative ecological system should be viewed from the aspect of linking human societies in achieving the unified goal of ecosystem sustainability. The aspects include energy, information, feedback, and realization (Figure 7). Efficiency should be regarded as the essential concern in energy and related ecological parameters (e.g., net productivity rate, recycle rate). Consilience should be considered in information distribution in human societies (e.g., information sharing). Enhancing cooperation among citizens would be the objective through feedback mechanisms based on information supply and appreciating ecological efficiency. Once the cooperation is settled through altruistic feedbacks among humans, benefit and fairness (e.g., considering equality and equity) should be the objective in realization so that citizens would have eco-friendly minds, "Sustainability in ecosystem eventually makes our town, country, and broadly the earth, survivable for humans and other life organisms in the long term."

## 4. Discussion and conclusion

Although numerous accounts of studies have been reported on ecosystem sustainability regarding measurement and methodology (e.g., Costanza, 1997), ecological issues (e.g., biodiversity maintenance (e.g., Tilman, 2006)), and target ecosystems (e.g., Fischer, 2006; Grant, 2012) as stated above, a universal system, interlinking measurement methodology on the one hand and human involvements for social consilience on the other hand, has not been discussed extensively in association with trans-disciplines across different regimes in ecological projects (Figures 2, 4 and 5). An entering wedge is needed in resolving complex ecological problems. In this study the process of integration is *de novo* in the sense that the system interweaves the four components of scientific developments, gene information, mathematical biology, mobile sensor networks, and virtual ecosystems, subsequently further interlinking two key points, provision of ecological information to humans and appreciating ecological efficiency in the societies as stated above (Figures 4 and 5).

A fundamental issue raised in this study would be how individuals in societies are willing to optimally sacrifice individual resources (e.g., time, money) to achieve sustainability in ecosystems under the constraints of various selection pressures (Figure 5). Consequently the origin of altruistic behavior mechanism should be more carefully studied from the aspect of evolution and behavior ecology. Altruistic behaviors are observed in animals to sustain their populations with the benefit from sacrificing some individuals for other individuals in behavioral ecology (Alcock, 2009). It is noteworthy that the altruistic behavior would be structurally inherent and could be more effectively addressed if the ecological systems, including human ecosystems, are set up in such a way that the group survival could be effectively traded off with individual survival for keeping population stability through evolution. Although human behaviors are more complex than animal behavior, the key principles should be still addressed at the fundamental level, being interfaced with adaptability of natural life systems. Precise examinations, however, will be further needed in dealing with more delicate and complex situations in human behavior such as conflict (Matsuo, 2014) and corruption (Lee, 2015), for instance.

Care, however, should be given cautiously, regarding application of principles obtained in behavior ecology to human activities; the principles of animal evolution could not be the grand rule in governing human behavior totally, since the humans have their own ethics and judgment rules based on culture beyond the ecological aspect. An extra space should be reserved for addressing humans' own characteristics (e.g., morals, culture) in interpreting human activities in dealing with ecosystem management.

Methods for developing meta-models should be also taken into consideration in managing integrative models (France, 2003; Messac, 2008; Lean, 2009). Since numerous subsystems are involved in the global system, the subsystems should be well coordinated to achieve the global goal. Precision, feasibility, and robustness should be carefully checked in the total execution of model performance. Determination of variable importance and evaluating model feasibility should be also carefully examined. These fields would belong to computational modelling and development of algorithms, and are out of scope for the current study. Meta-model development and evaluation in ecological sciences with big data warrant further studies in the future.

In conclusion ecological sciences enter a new phase due to urgency of keeping our ecosystems survivable in parallel with rapid development of ICT concurrently. A key concept for solving complex ecological problems is "integration": all components of systems are combined in a most optimal way to achieve the unified goal, sustainability (e.g., safety, stability, efficiency) of ecosystems. An integrative ecological system could be developed in line with recent developments in sciences including engineering and computation. Multi-disciplines are involved in pursuing ecological projects and could be divided into ecological contents (ecosystems, taxa, and size) and connection to humans (academic fields and human involvements). In acquiring information on ecological contents effectively, surveys/experiments could be conducted by utilizing mesocosms and mobile sensor networks. Connection to humans could be realized through modelling and virtual ecosystems, and social involvements. Based on suitable information supply and appreciating ecological efficiency as well, altruistic feedbacks in human societies would be arisen to resolve the tragedy of the common.

## Acknowledgment

This research was financially supported by the International Research Unit of Advanced Future Studies at Kyoto University.

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## Figure Legends

**Figure 1.** Multi-disciplines for pursuing ecosystem sustainability in ecological projects.

**Figure 2.** Academics fields in association with life system hierarchy: "bottom-up" and "inside-outside" approaches

**Figure 3.** An integrative ecological system based on multi-disciplines linked with information provision and ecological efficiency appreciation in human societies to enhance altruistic feedbacks for achieving ecosystem sustainability.

**Figure 4.** Outline of integrative processes: ecological contents measured by sensing systems are connected to human societies to achieve social consilience by acquiring altruistic feedbacks based on information provision and ecological efficiency appreciation.

**Figure 5.** Operation processes for an integrative ecological system consisting of system definition, operation, and feedback flows in order to achieve social consilience for ecosystem sustainability based on information provision and ecological efficiency appreciation by humans.

**Figure 6.** Flow chart for demonstrating social collaboration based on both negative and positive feedbacks regarding pollution source reduction and frequency dependence of social pressure (Iwasa et al, 2007; Quotation of the figure permitted by the Publisher).

**Figure 7.** Key evaluation points and subsystem objectives in realizing the global objective of the ecological integrative system from the scientific (ecology and ecology-relevant) and human aspects. (See full characters for abbreviations in the text.)