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Systems and Engineering Ecology: Developing Formal Foundations for Ecological Engineering*

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Ecological engineering is an emerging field of study that lacks mature, unique engineering sciences, that typify traditional engineering disciplines developed from engineering physics, engineering chemistry, engineering biology and engineering mathematics. An academic programme in Systems and Engineering Ecology at the University of Georgia has been initiated that follows the model of established engineering disciplines and draws significantly from general systems science, systems ecology, engineering and the mathematics of network theory to:
(1) build insight into the behaviour and properties of ecosystems as holistic units;
(2) develop invariant properties of ecosystems as networks;
(3) establish science-based design processes for the practice of ecological engineering.

Keywords: ecological engineering; curriculum; systems; network

INTRODUCTION

ENGINEERING IS A DISCIPLINE of applied science and systems design founded on fundamental principles of physics, chemistry, biology and mathematics, with scales of application ranging from nano to landscape. Established disciplines of civil, mechanical, electrical, chemical and biological engineering, to name a few, have applied the basic sciences in designing systems to improve the quality of life for societies over many generations. New engineering disciplines emerge infrequently and then only after the underlying science has matured to a level for systems design and analysis to be formally established [1].

Ecological engineering is currently an emerging field of study that uses ecology as its foundational science; several major universities have established research programmes interfacing ecology with engineering. A professional society, the American Ecological Engineering Society, has been established through such activities, and a formal definition of the practice has been generally accepted as, 'the design of sustainable systems, consistent with self design and other ecological principles, which integrate human society with the natural environment for the benefit of both' [2–4]. While degree programmes remain a goal for colleges and universities with ecological engineering aspirations, the development and implementation of such programmes may prove difficult. Gattie *et al.* [1] outline key issues facing the development of academic programmes in ecological engineering and propose six criteria that must be met for ecological engineering to emerge from a field of study to an engineering discipline. A key outcome of Gattie *et al.* [1] is that all engineering disciplines have unique engineering sciences upon which the particular discipline has been established, and this engineering science criterion must be met for the field of ecological engineering to achieve discipline status. Therefore, research and other academic activities must collectively focus on the establishment of fundamental ecological engineering sciences and formal constructs for the design and analysis of ecological systems.

The University of Georgia, Athens, GA, USA, over the past five years, has attempted to develop an academic programme of study focused on the ecological engineering science criterion. At the core of the programme are:

(1) the proposition that general systems theory, systems ecology theory and engineering principles must be synthesized into novel, quantitative engineering sciences;
(2) these new engineering sciences should become the basic foundation for design activities in ecological engineering.

IDENTIFICATION OF CORE ISSUES IN DEVELOPMENT OF AN ECOLOGICAL ENGINEERING PROGRAMME OF STUDY

The University of Georgia academic unit, Faculty of Engineering, initiated efforts in the field of ecological engineering in 2000 by exploring possible collaborative relationships between the University's engineering programmes and the University's Institute of Ecology. Early goals

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focused on academic programmes of study, beginning with a rationale for developing an undergraduate degree. Discussion of an undergraduate programme for a fledgling engineering field of study sparked critical debate among the engineering faculty, as to the process by which engineering disciplines, in general, develop. Initial discussions focused on general academic concerns regarding the appropriate level of study for any emerging engineering field and the course content of such a curriculum. At the core of these general concerns were fundamental issues pertaining to basic engineering science principles, design theory, and standards (Table 1). The summary academic question was distilled as, 'Should a programme of study for ecological engineering be focused on graduate-level research or based on current knowledge from ecology and engineering at the undergraduate level'?

Principles, practice, and design

The **practice** of engineering is found in a creative profession that:

(1) requires specialized knowledge of the fundamental **principles** in the mathematical, natural and engineering sciences;
(2) applies that knowledge to **design** and optimize devices/processes/systems for the benefit of society's wellbeing.

Sometimes, engineering practice is mistakenly identified as the simple application of a technology to design a new product for society's consumption. This mistake typically evolves from misunderstanding engineering's definition of design.

From the fine arts to engineering, design is appreciated as an intellectual endeavour that produces a useful outcome. Webster's dictionary defines design as 'to conceive in mind; to invent'. In the practice of engineering, however, design takes on a more specific meaning where it must integrate basic principles of the natural sciences and of mathematics so the behaviour of the design solution can be predictive and, therefore, optimized. Unless this relationship between scientific principles and design is found, then the development of a new product/device/system cannot be considered an engineering practice.

The development of the modern steam engine is an excellent example of the design of a useful device without involving today's practice of engineering. Steam engines or devices that utilize steam have existed since 200 BC. However, full use of steam engines did not occur until the Industrial Revolution when society needed some form of technology to provide power. Several designs of a modern steam engine occurred in the 1700s with the Newcomes engine, invented by the English blacksmith Thomas Newcomes, becoming an accepted design. However, Newcomes and others could only develop new versions of a steam engine through the trial and error method. This became very unpleasant due to the potential for disasters with poor designs. Optimization of the steam engine design could not be accomplished on the drawing board until after the development of thermodynamics in the late 1800s.

Discovery of basic science principles is often accompanied by efforts to apply the principles in a way that could prove beneficial to society. Many pioneers of mechanical, electrical and civil engineering were engineering physicists who applied basic principles of physics to harness and control natural phenomena. Similar developments in engineering chemistry, engineering biology and engineering mathematics reflect the necessary relationship between principles, practice and design. It is proposed here that ecological engineering also follow this model.

In the field of ecology, concepts of organism, population, community, landscape and ecosystem ecology have been proposed over the past century. Population growth and distribution, predation, parasitism, competition, exploitation, mutualism, species diversity, disturbance, resilience, resistance, extinction, food webs, primary production, trophic chains, nutrient cycling, succession and conservation, to name a few, are often at the foundation of environmental laws and regulations worldwide, and are commonly applied in decision-making processes where the human footprint stands to impact negatively on environmental systems [5–9]. Pioneers in the field of ecological engineering have applied ecological concepts to remediate environmental pollution, manage environmental systems and treat human waste products [10–18].

Ecological engineering activities are currently based on ecological concepts such as these and on proposed principles for ecological engineering and ecological engineering design [2, 3]. The

Table 1. Considerations when developing ecological engineering curricula

Issues	Focal Question
General	
Appropriate Level of Study	Should curricula be developed and offered at the undergraduate or graduate level?
Course Content	What constitutes course content for an ecological engineering curriculum?
Core	
Basic Engineering Science Principles	Does the science of ecology offer quantitative principles upon which analytical methodologies can be developed?
Design	(How) Can ecological engineering be practiced without science-based design processes?

paucity of science-based design processes is not uncommon in the early stages of young engineering fields, where the design process is largely algorithmic, meaning, not necessarily transportable between applications [19]. While applications such as wetland restoration and the use of constructed wetlands for wastewater remediation are quite mature, there remains overall concern that ecological engineering not become a long-term practice where methodologies must be relearned with each application [3]. The need for invariant principles and science-based design processes remains a goal for the ecological engineering field, and academia's role in meeting this goal requires clear definition. The programme of study presented here represents the University of Georgia's research-based academic efforts to develop and mature principles for the field of ecological engineering through a novel programme of study in Systems and Engineering Ecology (Fig. 1).

Appropriate level for programme of study: undergraduate or graduate?

Undergraduate engineering programmes focus on preparing students to become practitioners capable of solving societal problems and meeting societal needs through the application of engineering sciences and the use of formal engineering design methodology. Since novel ecological engineering sciences and formal design processes have not been established for ecological engineering, an undergraduate curriculum would then by necessity be crafted from existing engineering science courses combined with existing ecology courses and from an apprenticeship approach to learned design. This is equivalent to developing a novel engineering academic programme on the current knowledge base in engineering science and ecology. During the process of developing the academic programme presented here, such an additive approach was considered fundamentally flawed because ecosystem scale properties of

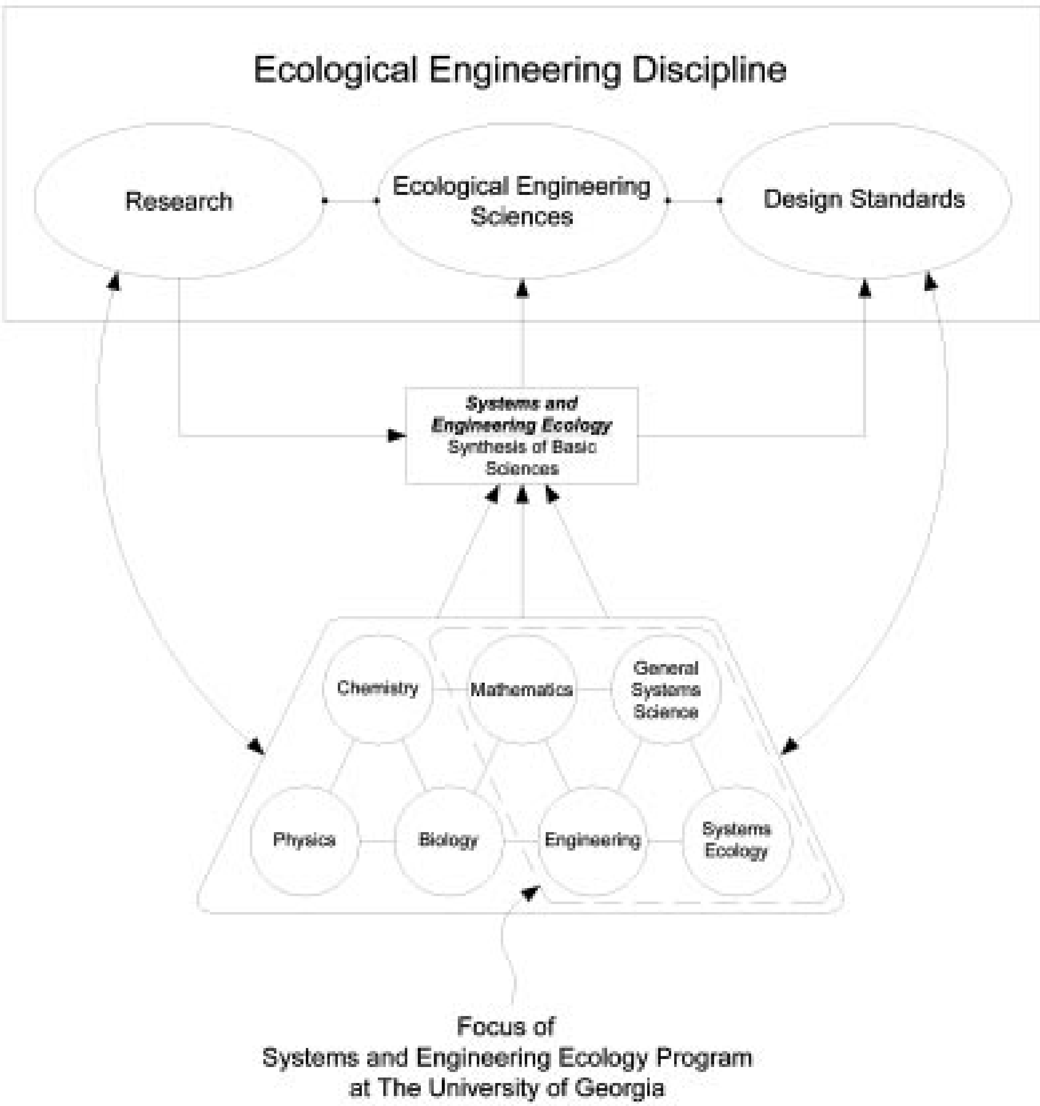

Fig. 1. General elements of ecological engineering as a discipline

energy, matter and biological life are not integral to current engineering sciences, and the student would be left to perform critical synthesis of knowledge from two traditionally disparate fields of study. As such, graduates would represent a body of engineers 'who have gained an appreciation of ecology by taking ecology courses', or 'who practice engineering with ecological considerations'. This reflects an inclusion of ecological thought into current engineering practice, but does not reflect a novel engineering discipline replete with the fundamental rigour associated with traditional engineering programmes of study. Programme development at the undergraduate level was assessed as a weak option for the fundamental reason that it would lack synthesis of knowledge with a novel engineering science base.

Graduate level was decided to be the appropriate placement, and three tenets for the research-focused programme of study were established early on:

- It will be a basic contribution to ecological engineering's long-term evolution from a field of study to an engineering discipline, in keeping with the course set in the development of traditional engineering disciplines;
- It will focus on ecosystem-scale, holistic properties of energy, matter and biological life in ecosystems, and the synthesis of knowledge from germane areas of ecology and engineering;
- It will motivate inquiry into ecosystem properties and lead to development of basic principles for ecological engineering and ecological engineering design.

SYSTEMS AND ENGINEERING ECOLOGY FRAMEWORK

Theoretical concepts are often proposed in physics, chemistry and biology, with some of them having withstood scientific scrutiny and accepted as basic, universal principles. The application of these principles in the design of engineered systems motivates the development of engineering sciences where invariant principles are critical for ensuring the safety and welfare of society. The atomic, molecular, cellular and macroscopic properties of energy and matter, the basis for these principles, have been the focus of the dominant Newtonian paradigm that has served society well, particularly through the engineering discipline (Table 2). These units of study are also tractable by nature and therefore can be empirically analysed.

Concepts of ecology range in scale from the organism to the ecosystem, with the ecosystem being the focal design unit for ecological engineering. Unlike the fundamental units of study in physics, chemistry and biology, ecosystems are proposed to function holistically, not reductively, as intractable units with properties that cannot be analysed part-by-part. Moreover, their properties are context dependent. For example, diverse ecosystems perform various functions. Lotic ecosystems comprised of fish, macroinvertebrates and aquatic microfauna process allochthonous detritus, while wetland ecosystems comprised of unique vegetation degrade various parent compounds to less toxic chemical constituents. However, highland and coastal lotic ecosystems

Table 2. Basic science aspects of engineering disciplines

Subject	Principles Relating To	
Engineering Physics	• Properties and behavior of material • Engineering mechanics • Statics • Dynamics • Fluid mechanics • Heat transfer • Buoyancy • Pressure • Motion	• Thermodynamics • Electromagnetism • Electrostatic energy/forces • Power dissipation • Electric flux • Magnetic energy • Force • Momentum • Gravitation • Light
Engineering Chemistry	• Chemical reactions • Bonding • Mass transfer • Kinetics • Catalysis • Molecular forces	• Multiphase flow • Absorption/adsorption • Solubility • Diffusion • Mixing • Equilibrium
Engineering Biology	• Cellular structure/function • Metabolism • Neuroscience	• Biotechnology • Bioseparation • Biomechanics
Engineering Mathematics	• Calculus • Vector calculus • Partial/ordinary differential equations	• Complex variables • Numerical methods • Laplace/Fourier transforms
Systems and Engineering Ecology	Principles Need to be Developed (Proposed Program of Study at UGA will focus on this area)	

differ markedly with regard to their biological constituents, as do freshwater and marine wetlands. There is, then, distinction within and across ecosystem types. Developing principles that are invariant and universal within and across diverse ecosystems is a fundamental challenge in the evolution of ecological engineering sciences. It is, however, a development that is needed in order to reflect a science base maturity similar to that in physics, chemistry and biology. Identifying and developing invariant principles was set as a major long-term research objective for the programme of study presented here, and selecting the research and academic framework within which this could be achieved was considered key.

The network construct

In a treatise on the state of ecosystem theory, Müller [20] identifies six theoretical approaches emanating from the system's analytical perspective of ecology. Of these approaches, network theory has been used over the past three decades to develop properties and behaviours of ecosystems as networks, resulting in a body of literature from which basic knowledge can be extended. In this regard, the network construct has much to contribute. A mature level of mathematics underpins network theory, contributing prolifically to the development of quantitative methodologies for analysing properties and behaviour of ecosystems as networks. Moreover, analysis of ecosystems as networks is conducive to meeting the objective of identifying invariant properties since network analysis can be based on the structure and function of a system of components linked by flows of thermodynamically conservative energy and material. Aquatic, terrestrial, marine, etc., ecosystem networks can be defined by, and analysed based on, their characteristic topology and associated flows along the network pathways, allowing comparative studies within and across various ecosystem models.

The network construct is the framework within which this programme is being developed as it facilitates insight into the possible invariant properties of ecosystems as networks. While other network theories for ecosystems have been proposed [21], *Environ Theory*, as developed by Patten [22–26], Patten and Auble [27] and Patten *et al*. [28] was selected as the initial construct because it stands alone as the single mathematical theory of environment. Moreover, its associated network environ analysis has been sufficiently developed for application to static, steady-state ecosystem network models [27].

Systems and engineering ecology

The programme of study has been entitled 'Systems and Engineering Ecology' and defined as 'development, synthesis and insight-building of theory and principles from the fields of General Systems Science, Systems Ecology, and Engineering, as they apply to making complex, holistic ecosystems, tractable study units of nature'. General academic objectives focus on synthesis of knowledge in the development of invariant principles of ecosystems as networks. Activities toward meeting these objectives include:

(1) follow the models of engineering physics, engineering chemistry, engineering biology and engineering mathematics to develop engineering ecology as a foundational science for ecological engineering;
(2) synthesize fundamental concepts from general systems science, systems ecology and engineering into novel bodies of knowledge, as opposed to offering individual courses from each field;
(3) emphasize understanding and development of theory and basic principles rather than application of proposed principles;
(4) focus on building insight into invariant network properties of ecosystem, the basic design unit of ecological engineering;
(5) integrate formal engineering design theory and principles with invariant properties of ecosystems to develop ecological engineering design processes;
(6) graduate students with a deep knowledge base in systems and engineering ecology (Table 2 above).

Seven hypotheses of ecosystem properties, as summarized from Patten [29], will serve as proposed network properties around which the academic programme will initially build (Table 3). While not comprehensive or exhaustive, these proposed properties represent the essence of ecosystem structure and function within the network construct and can be a springboard for exploring various ecosystem theories that have been developed over the past four decades.

Table 3. Principals for development of the systems and engineering ecology

Hypothesis	Reference
Ecosystems are networks of environments	[22, 30]
Ecosystem function is holistic and dominated by network indirect effects	[26, 31]
Ecosystems are structurally and functionally complex	[32]
Ecosystems cycle energy, material and non-conservative information along network pathways	[24, 25]
Autocatalysis is the key to the order-generating behavior of ecosystems	[21]
Ecosystems are self-organizing and adaptive	[16]
Ecosystems are hierarchical with emergent properties	[33]
Ecosystems are intractable and irreducible	[34]

PROPOSED CURRICULUM IN SYSTEMS AND ENGINEERING ECOLOGY

Nine upper graduate-level courses will be used as part of the above six activities as well as the integration of each student's individual research in systems and engineering ecology (Table 4). The general goal is to leverage the perspective of general systems thinking with the mathematical strength of network analysis and the insight-building capacity of modelling to establish design principles for human interface with ecosystems as complex network structures. It is expected that students will come primarily from the life sciences and engineering, as is currently the case with the University of Georgia's existing graduate degree in Biological Engineering. To build the necessary cross-disciplinary foundation in systems principles from ecology and engineering, students from both areas will take newly developed courses in Natural History and Principles of Engineered Systems. Control Theory and Graph Theory provide the theoretical background for constructing ecosystems as networks of biotic and abiotic compartments connected by flows of material and energy, while signal flow principles and state-space theory are integral for exploring the concepts of control, biological feedback and complexity in open systems.

Understanding the intractable nature and complex properties of ecosystems is a core value in the programme, therefore Open Systems Modelling, Ecological Energetics and Network Analysis provide the basis for building insight into ecosystem structure, function, behaviour and complexity. The final course, Interdisciplinary Experience in Complex Problem-solving, engages students from various backgrounds in the modelling, design and network analysis of an open system and its emergent properties, thus enhancing the insight-building objective.

CONCLUSIONS

Practitioners within established engineering disciplines graduate from academic programmes of study consisting of research, formal engineering sciences and design methodologies. Undergraduate engineering programmes of study are founded on engineering sciences that have withstood the scrutiny and rigour of scientific challenge and have been proved through testing and extended engineering practice. We assert that ecological engineering should be no different and must be underpinned with novel engineering sciences synthesized from basic sciences. The current body of ecological engineering science knowledge has

Table 4. Academic objectives of systems and engineering ecology

Academic Objective	Course	Course Description
Establish systems thinking as the foundational construct	General Systems Principles and Theory	General principles of complex, adaptive systems including concepts from cybernetics, networks and information theory
Develop concepts of natural history and engineering principles within the systems construct	Natural History	Development of populations, communities and environment as ecosystems. Major ecosystems of the world will be analyzed with regard to their development and function
	Principles of Engineered Systems	Basic principles and universal laws from physics, chemistry, biology and mathematics that have been applied within the systems design framework of engineering
Integrate fundamentals of control theory with graph theory structural and functional constructs of ecosystem networks	Control Theory	Principles of control, signal flow and state-space theories.
	Graph Theory	Principles and theory of the representation and construction of ecosystems as networks and directed graphs. Mathematical techniques for analyzing properties of networks will be emphasized
Identify principles for modeling and analyzing ecosystems as thermodynamically open networks	Open Systems Modeling	Principles and rules for identifying boundaries and components of hierarchical, complex systems. Modeling of the dynamics of systems thermodynamically open to their environment. Static, steady-state, dynamic and transient methods will be studied
	Ecological Energetics	Transport, flow and cycling of thermodynamically conservative energy and material within an ecosystem network
	Network Analysis	Methods for analyzing complex properties of ecosystems modeled as networks. Network environ analysis will serve as the foundation
Interdisciplinary experience in complex problem-solving	Modeling, Design and Analysis	Students from disparate backgrounds use knowledge from coursework to model, design and analyze an open system having complex properties

not matured to a level appropriate for an undergraduate programme of study, as engineering sciences unique to ecological engineering have not been formally established.

Existing ecological engineering education is predominantly focused on application and practice, with a significant bias toward aquatic systems. It is not argued here that these efforts should cease. Rather, the programme of study presented here, Systems and Engineering Ecology, relaxes the emphasis on application and practice of ecological engineering and stresses the development of holistic science concepts to underpin the practice and build insight into the structure and function of ecosystems and their complex behaviour and properties. Moreover, it endeavours to develop a strong element of formalism in the design and analysis of ecological systems by constructing complex, holistic ecosystems as tractable study units of nature.

While ecology should continue to be applied in decision-making processes and environmental problem-solving, we argue that robust development of an ecology-based engineering will find limitations without rigorous development of a systems and engineering ecology foundation. The research-based academic approach of the graduate programme in Systems and Engineering Ecology draws upon the mathematical foundations of network analysis to synthesize knowledge from general systems science, systems ecology and engineering in the development of invariant principles of ecosystems as networks. It represents a long-term approach toward developing ecological engineering sciences that will comprise ecological engineering when it eventually emerges as a discipline (Fig. 1 above). In our approach, we move deliberately away from the generic construct of ecological engineering described as, 'engineering with ecological considerations', which primarily focuses on the inclusion of ecological considerations within current engineering practice. Moreover, we contend that ecologists will not become ecological engineers by being exposed to engineering topics, and engineers will not become ecological engineers by gaining an appreciation for ecosystems and the environment. We offer a framework for students to focus on understanding the fundamental behaviour, properties and complexities of ecosystems, and developing methodologies for analysing these properties within the network construct. Graduates will have a sound knowledge base of systems and engineering ecology, which will complement other programmes that focus on graduating students prepared to be practitioners.

The Systems and Engineering Ecology programme at the University of Georgia, USA, is a unique academic effort to contribute toward the evolution of ecological engineering from a field of study based on proposed principles, to a discipline founded on engineering sciences. It is novel not only in title but also in objectives as it essays to follow the models of engineering physics, engineering chemistry, engineering biology and engineering mathematics that spawned the development of basic engineering sciences and produced traditional engineering disciplines.

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