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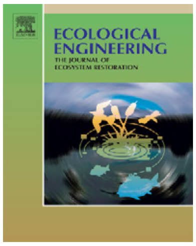

Analysis of microdynamic environ flows in an ecological network

David K. Gattie[a,b,*], *John R. Schramski*[c], *Seth A. Bata*[c]

[a] *Department of Biological and Agricultural Engineering, The University of Georgia, Athens, GA 30602-4435, USA*
[b] *Faculty of Engineering, The University of Georgia, Athens, GA 30605, USA*
[c] *Institute of Ecology, The University of Georgia, Athens, GA 30605, USA*

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ABSTRACT

Network environ analysis (NEA), an application of ecological network analysis (ENA), is presented as a mathematical basis for developing insight into ecosystem interconnectivity for ecological engineering design. Two seven-compartment models of nitrogen flow in the Neuse River Estuary (Summer 1988 and Winter 1989) are used in developing quantitative metrics of indirect ecosystem relationships that are not observable based on empirically determined flows of nitrogen alone. Network total system throughflow was mathematically decomposed into microdynamic environ flows, which are presented as the basis for understanding and developing insight into the indirect relationships that develop in ecosystems over network pathways. Mathematical derivations also indicate that empirically determined, intercompartmental flows are constituted by the smaller scale environ flows. Results indicate that 43.5 and 45.9%, respectively, of total system throughflow for the Summer and Winter networks are generated by nitrogen flow over indirect network pathways. Implications of these results are that indirect effects from non-adjacent network relationships are indeed necessary considerations for ecosystem design and management and they can be quantified using ecological network analysis. Mathematical derivations and their significance in ecological design are presented and discussed.

1. Introduction

Mitsch and Jørgensen (2004) propose the following principle of ecological engineering design:

> "The components of an ecosystem are interconnected, interrelated, and form a network, implying that direct as well as indirect effects of ecosystem development need to be considered".

Their proposition, from years of observation and experimentation with ecological systems, seems intuitive today. However, two centuries of a reductionist paradigm have been a barrier to the realization that living systems do not necessarily behave as do physical systems, and in fact require a science different than that built on Newton's principles (Ulanowicz, 1999, 2005). The linking of everything to everything else in ecological systems says much about the complexity of ecosystems and their highly coupled, interconnected nature. And intuitive as it may appear, this proposition establishes an analytical challenge for ecological engineers to quantitatively integrate interconnectivity into their designs. This stands to contrast with at least one design goal of traditionally engineered systems, that being to decouple system components. The concept of designing with complexity and emergence as system properties may not bode well within some traditional engineering design paradigms where functional inde-

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[*] *Corresponding author*. Tel.: +1 706 542 0880; fax: +1 706 542 8806.
E-mail address: dgattie@engr.uga.edu (D.K. Gattie).

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Nomenclature

f_{hi}	empirically determined flow from the focal compartment i to adjacent compartment h (mmol/m^2 season); using NEA, f_{hi} is shown to be constituted by the summation of output environ flows, $\varepsilon_{hi,k}$, over all network pathways of all path lengths from compartment i to compartment h, generated by boundary input at all compartments k)
f_{ij}	empirically determined flow from compartment j to the adjacent focal compartment i (mmol/m^2 season)
g_{hi}	dimensionless partitioning coefficient for distributing throughflow at i into environ flows from i to h
g_{ij}	dimensionless partitioning coefficient for distributing throughflow at j into environ flows from j to i
$\mathbf{G}$	$n \times n$ matrix of dimensionless throughflow partitioning coefficients
h	any compartment in the output environs of the focal compartment i, to which energy or material flows from i
i	the focal compartment
j	any compartment in the input environs of the focal compartment i, from which energy or material flows to i
k	compartment whose boundary input is to be traced along all possible network pathways of all path lengths, $m = 1{:}\infty$
n	number of network model compartments
n_{ik}	dimensionless partitioning coefficient for mapping boundary input at compartment, k, into throughflow at compartment, i
$\mathbf{N}$	matrix of dimensionless partitioning coefficients for mapping boundary input into compartmental throughflows
T_i	(compartmental throughflow in terms of observed flow) summation of inflows or outflows from compartment, i (mmol/m^2 season)
x_i	standing stock at the focal compartment i (mmol/m^2)
$\mathbf{X}$	$n \times 1$ vector of standing stocks for each compartment
y_i	boundary output from the focal compartment i (mmol/m^2 season)
$\hat{y}_{i,k}$	(output environ boundary flow) boundary output from compartment i generated by boundary input at a particular compartment k (mmol/m^2 season)
$\mathbf{Y}$	$1 \times n$ vector of boundary outputs at each compartment
z_i	boundary input at the focal compartment i (mmol/m^2 season)
$\mathbf{Z}$	$n \times 1$ vector of boundary inputs at each compartment

Greek letters

$\varepsilon_{hi,k}$	(microdynamic environ flow) flow over all network pathways of all path lengths m from the focal compartment i to a particular compartment h generated by boundary input at a particular compartment k (mmol/m^2 season)
$\varepsilon_{i,k}$	(environ flow) flow from the focal compartment i to all other compartments, h, within the network, generated by boundary input at a particular compartment, k (mmol/m^2 season)
$\theta_{i,k}$	(environ throughflow) partition of throughflow at compartment i generated by boundary input at a particular compartment k (mmol/m^2 season)
θ_i	(compartmental throughflow in terms of environ flow) the integrated output environ flow response over network pathways of a particular compartment, i, to boundary inputs at all compartments, k, in the system (mmol/m^2 season)
Θ_k	(total environ throughflow) the partition of total system throughflow, TST (Ω), derived from boundary input at a particular compartment, k (mmol/m^2 season)
Ω	(total system throughflow) a metric of ecosystem network response to material and energy exchange at the ecosystem boundary, as indicated by the cumulative network response of its individual compartments (mmol/m^2 season)

pendence is a dominant objective. Within the domain of ecological engineering, complexity is a desired property. While Mitsch and Jørgensen's proposed principle of interconnectivity may be easily acknowledged by ecologists and ecological engineers, ecological engineering design must develop rigorous mathematical methodology for analyzing this intuitive but complex interconnectivity. Mitsch and Jørgensen's principle of interconnectivity for ecological engineering design has been proposed from extensive and deep insight of two accomplished ecologists in spite of the dominant Newtonian paradigm. However, their proposed principle remains as a challenge to the ecological engineering community to develop quantitative analyses for the design and management of ecosystems as complex interconnected wholes.

A degree of difficulty is inherent due to the intangible nature of ecosystems as they have no actual boundaries. The physical, reductionist properties of ecological systems are empirical, detectable and measurable, and can be statistically analyzed for correlation among various parameters. However, complex holistic properties are not subject to technological probes. Rather, they are subject to the research question posed, and the method by which the ecosystem unit is abstracted, bounded and modeled. Ecosystems have been proposed as granular and mosaic in nature, with all the parts and connections not accountable (Allen and Starr, 1982; Ulanowicz, 2004). The compartments included within an ecosystem boundary then dictate much of what can be learned from any analysis. Moreover, because they are liv-