



The Heartbeat of Ecosystems

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ECOLOGY

The Heartbeat of Ecosystems

Margaret A. Palmer^{1,2,3} and Catherine M. Febría^{1,2}

People generally equate health with a long and active life, but when it comes to ecosystems there is no agreement on what it means to be healthy. On page 1438 of this issue, Woodward *et al.* (1) show that different conclusions on the health of stream ecosystems can be reached depending on which combinations of metrics are used to assess them. The work points to an urgent need for a general framework for assessing ecosystem health.

An increasingly popular way to assess ecosystems is to evaluate the level of goods and services they provide to humans, such as water for drinking or irrigation (2). However, using ecosystem services as an indicator of ecosystem health is an oversimplification of the ecosystems services concept (3) and does not provide sufficient information on the extent to which those services can be provided sustainably (4–6). A second, older approach bases ecosystem health on its similarity to a least-impacted, reference, or historical state. This is the main approach in use today by water resource managers and typically involves measurements of what ecologists call ecosystem structure (7).

Ecosystem structure refers to attributes that can be evaluated with point-in-time measurements and that are assumed to reflect the existing status or condition of an ecosystem. Structural attributes may be easy to measure, but they do not capture the dynamic properties of an ecosystem that represent its actual performance. Functional measurements, on the other hand, attempt to capture system dynamics through repeated measurements that quantify key biophysical processes (see the table).

Structure and function both contribute to ecosystem status and to the provision of goods and services, but what combination of measurements should be used to evaluate ecosystems is a matter of current scientific debate. Woodward *et al.* (1) evaluate river health on a continental scale using measurements or “health metrics”: the taxonomic composition of aquatic biota (structural), the

eutrophication status based on nitrogen concentration (structural), and the decomposition rate of organic material in the form of leaf litter (functional). Their work suggests that management efforts to reduce nitrogen pollution may not lead to recovery of desired species or efficient processing of organic matter. The data show that the functional metric of decomposition can be quite variable even at some fixed level of water quality. Other factors known to influence the measurements they used, such as river geomorphology and land use, were not reported.

On the surface, the results might seem unsatisfying, but in fact they clearly demonstrate why it is important to use multiple metrics. Ecosystem components interact in complex ways, and ecological processes are context dependent (8); interpretation of measurements thus requires multiple types of data. For example, the rate of organic matter decomposition in rivers and streams is well-known to be influenced by the species and size of aquatic insects that tear apart decomposing leaves while feeding. Other

Which indicators of ecosystem structure and function must be measured to assess ecosystem health?

key players that influence decomposition—microbes—increase their activity when nutrients are elevated and, like insects, also respond to other factors that typically change as rivers become eutrophic (9).

Recent studies have started to elucidate how these factors influence microbial production and community structure at large spatial and temporal scales (10). Such work is essential for understanding how to interpret and use metrics such as decomposition rate. Exploring patterns like those reported by Woodward *et al.* (1), coupled with clever natural and manipulative experiments (11, 12), is also an important step to take if ecologists hope to link suites of metrics to the desired future state of ecosystems. A review of more than 250 studies in the mid-Atlantic United States found that data are currently insufficient to identify which metrics will best reflect whether an ecosystem is on a clear trajectory toward improvement, because of the paucity of studies that couple functional measures with routine quantification of ecosystem structure (13).

METRICS FOR EVALUATING THE HEALTH OF RIVER AND STREAM ECOSYSTEMS	
Structural metrics	Functional metrics
Biological diversity or species of interest	Productivity/reproduction, migration, trophic status
Native riparian vegetation width	Pollutant removal rates
Floodplain presence/width	Hydraulic retention
Canopy cover	Photosynthetic active radiation
Oxygen level	Biochemical oxygen demand, whole stream metabolism
Nitrogen, phosphorus concentrations	Nutrient cycling or flux rates
Pollutant concentrations	Pollutant removal or sequestration
Organic matter	Decomposition rate
Temperature	Thermal regime (magnitude, duration and timing)
Mean annual flow and depth	Flow regime (magnitude, duration and timing)
Turbidity	Sediment flux
Channel morphology	Channel migration, erosion rate
Streambed substrate	Streambed mobility

Ecosystem structure and function. The components of an ecosystem (structure) interact with dynamic biophysical processes (functions) to produce goods and services that people rely on from rivers and streams (e.g., fisheries, drinking water, irrigation, flood mitigation, recreation). Structural measurements (left) may be easier to make but provide less information than related functional measurements (right). In practice, these metrics vary widely. For example, nitrogen processing, commonly measured as denitrification potential, varies with organic matter by several orders of magnitude (21). Metabolism varies by two to three orders of magnitude (15, 17), as does decomposition rate depending on leaf type (1, 14). As Woodward *et al.* show, combinations of structural and functional measurements may be required to predict the state of an ecosystem or availability of a good or service.

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Structural measures, such as the presence or absence of an iconic species like salmon, can indicate that something is wrong with an ecosystem, but typically not why. Thus, reliance on structure alone makes it difficult to prescribe ecosystem management or restoration actions. After all, doctors will routinely measure a sick patient's heart rate and blood pressure, rather than just their height, weight, and temperature. Human health metrics are based on long-term research that links metabolic processes to longevity and disease risk across highly diverse populations. Analogous studies for river and stream ecosystems are now accumulating (14–17).

To move river science into the realm of effective health diagnosis before ecosystems collapse, researchers must work with natural resource managers to compile regionally specific data on how functional metrics vary over time and space—particularly in rivers considered to be least impacted. Knowledge of the range of natural variability, the factors that drive changes in ecosystem functions, and how these functions respond to management actions will generate a framework for sound prescriptions to improving ecosystem health.

Such an understanding could help to address several pressing questions: Which ecosystem functions should be the target of management efforts, given desired outcomes? Is temporal variation in ecological processes itself an important driver of ecosystem states, much like annual cycles of high and low flows are thought to influence species composition in rivers (18)? Which metrics can be used as early indicators of degradation or recovery, and how do they vary with each stressor? Can we predict the ecological consequences of managing for a specific ecosystem service?

The recently launched Intergovernmental Platform on Biodiversity and Ecosystem Services (19) and other large-scale efforts will have these questions to address. Given worldwide declines in species, and growing evidence that biodiversity may control and not just respond to ecological processes (20), more data such as those provided by Woodward *et al.* (1) on how ecosystem structure and function vary across a large range of conditions are urgently needed. Only then will ecologists have enough information to determine which set of metrics, under which

contexts, best equates to the human heart-beat for ecosystems.

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CHEMISTRY

A Boron-Boron Triple Bond

Gernot Frenking and Nicole Holzmann

Although carbon readily forms double and even triple bonds, such bonds are much rarer between the heavier elements of the same group or between atoms of other main groups of the periodic system. Chemists have succeeded in creating some such molecules, such as double-bonded silicon compounds, although they are usually highly reactive. On page 1420 of this issue, Braunschweig *et al.* (1) report the synthesis of one such highly unusual chemical compound, which has a boron-boron triple bond.

In 2008, Robinson and co-workers reported the isolation of a compound with the formula $L \rightarrow Si=Si \leftarrow L$, where L is an N-heterocyclic carbene (NHC) that stabilizes diatomic silicon (Si_2) in an unprecedented way (2). Subsequent efforts to synthesize further members of this class of molecules, with the general formula $(NHC) \rightarrow E_2 \leftarrow (NHC)$,

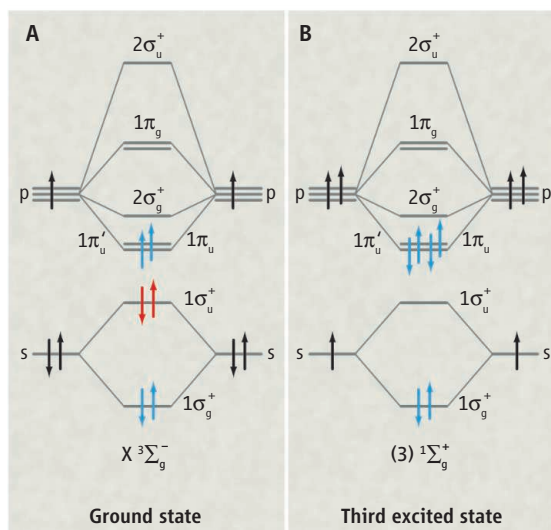
led to the synthesis of the group 14 species $(NHC) \rightarrow Ge_2 \leftarrow (NHC)$ (3) and the group 15 species $(NHC) \rightarrow P_2 \leftarrow (NHC)$ (4) and $(NHC) \rightarrow As_2 \leftarrow (NHC)$ (5). However, experimental attempts to isolate group 13 homologs, with $E = B, Al, Ga,$ and In , were not suc-

A complex with a boron-boron triple bond expands the range of genuine triple bonds known to chemists.

cessful. Quantum chemical calculations suggested that the complexes of the heavier group 13 atoms (Al, Ga, and In) have a double bond, $(NHC) \rightarrow E=E \leftarrow (NHC)$, and a trans-bent arrangement of the central atoms (6). For the boron homolog, the calculations predicted a

linear form with a boron-boron triple bond, $(NHC) \rightarrow B \equiv B \leftarrow (NHC)$. Braunschweig *et al.* now provide the experimental verification of this structure.

Toward explaining the triple bond. Schematic representation of (A) the ground state and (B) the third excited state of B_2 in the $(NHC) \rightarrow B \equiv B \leftarrow (NHC)$ molecule reported by Braunschweig *et al.* The ground state, seen in ligand-free B_2 , has two doubly occupied bonding orbitals (blue) but one doubly occupied antibonding orbital (red), giving a bond order of 1 and hence a single bond. In contrast, the third excited state observed in $(NHC) \rightarrow B \equiv B \leftarrow (NHC)$ has three doubly occupied bonding orbitals and hence a triple bond.



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