6. Ecology and Thermodynamics

6.1 Ecosystems and Ecosystem Components as Thermodynamic Systems

Ecology is the study of interactions of organisms and their biotic and abiotic environments. These interactions can be analyzed in terms of material cycles and energy flow. Thermodynamics is the study of conservation of the quantity and quality of energy, and thus, describes the physical realm in which interactions of organisms and their environment take place.

Typically, thermodynamic implications for material cycles and energy flow in ecosystems are in the form of two types of restrictions. One type of restriction is imposed by the first law of thermodynamics which constrains output and storage of materials and energy to be equal to material and energy inputs into the processes. The second restriction is caused by the law of increasing entropy; the second law of thermodynamics limits the efficiency at which materials and energy are used. Both types of constraints on the performance of ecosystems and ecosystem components are discussed subsequently in this section.

The application of thermodynamic laws to ecosystems makes one aware not only of the thermodynamic limits imposed on material and energy use in ecosystems but also the necessity for a clear definition of the systems to which the laws of thermodynamics apply. Analogously to engineering systems, ecosystems can be defined by boundaries in space and time. Since ecosystem boundaries are defined often arbitrarily for the purpose at hand (Golley 1984), recognition of well-defined boundaries and material and energy flows across these boundaries enhances analyses of organism-environment interactions in terms of these flows.

Thermodynamic restrictions on material cycles and energy flow in ecosystems are well recognized in the literature (Lotka 1924, Lindeman 1942, Ulanowicz 1986, Wicken 1987). These restrictions can be applied, for example, in analyses of the utilization of materials and energy in living cells and organisms, or at a community or ecosystem level. Based on thermodynamic analyses it can be shown that the efficiency of organisms to bind the energy of solar radiation in biomass is typically very low, and energy efficiencies on a community level are even lower when transfer inefficiencies among trophic levels are included (E.P. Odum 1983). However, the concept of efficiency is an anthropocentric one, defining the capability to do work, not the ability for survival and maintenance.

For an ecosystem-wide level H.T. Odum (1971, 1982) develops methods to describe material cycles and energy flow and their influence on the
structure and function of ecosystems. Ulanowicz (1972) and Hannon (1973b, 1979) provide models that trace energy flow among ecosystem components based on the first law of thermodynamics. Similar models that include material and service flows are offered by Costanza and Hannon (1989) and Hannon (1991), and are discussed in more detail in the following chapter.

Reference to the second law of thermodynamics is made frequently with regard to the structure and function of ecosystems and ecosystem components. Ecosystems use energy from outside systems to support their highly ordered states of organization (Morowitz 1968, Prigogine 1980). For example, Schneider (1988, pp. 116, 122) emphasizes that

"biology and ecology are replete with evidence of compliance with the expanded principles of thermodynamics. The living cell is an expression of lower entropy and higher order than the nonliving components of nature. [...] Life itself is a product of the thermodynamic histories of the global ecosystem as it evolved from chemical elements and, through energy flux transformations, developed useful genetic materials that reproduce and metabolize into highly organized systems through stepwise energy transformations."

Organisms are systems that require continuous input of available energy to maintain themselves, grow and reproduce. As working systems, organisms are subject to the second law of thermodynamics in a way

"that is not fundamentally different from that of nonliving systems of a similar (if far simpler) kind. For example, steam engines and organisms function only because they are provided with (or acquire) a continuous supply of free energy." (Brooks and Wiley 1988, p. 33)

With the acquisition of free or available energy and the creation of high entropy, second law analyses can be conducted in the same way for ecosystems and ecosystem components, as for the economic system and its components (see Chapter 5). In particular, the use of renewable resources by the economic system can be interpreted analogously to employing "machines", i.e. organisms, to transform materials and energy into desired products (see Chapter 2). Such a treatment of renewable resources leads explicitly to an analysis of second law implications of harvesting natural resources.