Funds, Flows and Natural Capital:
A Conceptual Reconstruction

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> What really is capital and what does it mean for value, growth, and distribution? Is it a pile of produced means of production? Is it dated labor? Is it waiting? Is it roundaboutness? Is it an accumulated pile of finance? Is it a social relation? Is it an independent source of value? The answers to these questions are probably matters of belief. (Rosser 1991:125)

With this agnostic set of questions, Rosser simultaneously summarized the history of capital theory and also alerted us to the danger of reducing the capital concept to a simple formula. As those familiar with the history of economics are aware, economists have faced a series of controversies concerning the definition and meaning of capital, disputes dating back at least to the era of Adam Smith.

Because the newly emerging field of ecological economics has focused its gaze on the conceptual gem of "natural capital" (Costanza and Daly 1992, Jannson et al. 1994, Prugh et al. 1995), it is imperative that we inspect this notion carefully in order to better appreciate its numerous facets as well as its possible flaws. In this paper, I first survey some of the definitions of "natural capital" that one can find in the recent literature. I then suggest how to put the natural capital concept in sharper theoretical focus. In light of this conceptual reconstruction, my paper discusses the problems associated with measuring natural capital; whether natural capital and human-made capital are likely to be complements or substitutes; and the degree to which natural capital is social, and not merely biophysical, in character.

Natural Capital: A Critical Survey

During recent years, ecological economists have cited numerous concrete examples of what they mean by "natural capital." Daly (1994:30) mentions fossil fuel reserves and populations of fish and trees. Cleveland (1994:181) points to climate, soil and mineral deposits. Ayres (1996:241), in turn, refers to such items as aquifers and stratospheric ozone.

Although these examples are apparently either "things" or "states of affairs," some authors also mention what seem to be "processes." Cleveland (1994:190), for instance, offers operation of the hydrologic cycle as an example of natural capital. Recycling of nutrients and pollination of crops have also been cited by Berkes and Folke (1994:129).

On a more macroscopic scale, Costanza and Daly (1992:38) have characterized ecosystems as natural capital.[1] Perhaps the most frequently cited example is biodiversity, a particular facet of ecosystems (Jannson and Jannson 1994, Ehrlich 1994, Cleveland 1994, Prugh et al. 1995).

All of these specific examples of natural capital are persuasive and instructive. At the same time, however, the sheer diversity of the examples to be found in the ecological economics literature is worrisome. Can the concept of natural capital cover simple objects or things, states of affairs, complex systems or structures, and dynamic processes all at the same time? Doesn't a concept of such broad scope tend to lose its analytical clarity?[2]

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[1] Soil, an apparently simple 'thing,' is actually a complex ecosystem. As Wild (1993:32) notes, a gram of soil contains millions of bacteria, fungi and other organisms.

[2] As Georgescu-Roegen remarked (1971:212) a quarter century ago, "[A]nalysis must … proceed by some heroic simplifications… The first step is to assume that actuality can be divided into … the partial process… [and] its environment… separated by an analytical boundary consisting of an arithmomophic void."

Instead of trying to derive a concept of natural capital inductively from a diversity of particular examples, one can, alternatively, offer a formal definition of its content. Several authors have followed this path. Natural capital, according to Daly (1994:30), is the stock that yields a flow of natural services and tangible natural resources.[3] Berkes and Folke (1994:129) go a step further. For them, natural capital consists of three major components:

(1) non-renewable resources extracted from ecosystems;
(2) renewable resources produced and maintained by ecosystems; and
(3) environmental services.

Although these definitions provide valuable guideposts as we explore the terrain of human society within nature's broader landscape, they are imperfect. How, exactly, can one tell whether a particular asset is "natural" or not? Is it proper to conceptualize services generated by ecosystems, materials extracted from those ecosystems and the ecosystems themselves as various forms of "natural capital"? Doesn't that formulation risk confusion between assets and income flows? Perhaps because of questions such as these, a few authors have concluded that the notion of natural capital is, at present, a rhetorical device intended to stimulate discourse, not yet a fully scientific concept (Harte 1995, Jacobs 1995). The next two sections explore a new route to the natural capital concept.

Funds, Flows and Stocks

One of the underappreciated classics of modern economics is the discussion of production theory by Georgescu-Roegen (1971:ch. IX). In that chapter, Roegen distinguished between two very different elements of the production process: "fund elements, which

[3] For similar formulations, see Costanza and Daly (1992:38) and Prugh et al. (1995:35).

represent the agents of the process, and the flow elements, which are used or acted upon by the agents" (p. 230). That is, there are the active subjects of production which physically shape and transport, chemically alter, and in various other ways transform materials and energy. These fund elements cannot play their transformative role, however, without access to the passive objects of production, input flows of low-entropy materials and energy.

During the course of production, fund elements maintain their physical identity and integrity while input flows are typically transformed into output flows of qualitatively different character. The fundamental distinction between fund and flow elements of production is suggested by their separate dimensionality. For instance, the operation of a dairy farm can be described by the input flows (kilograms of hay per day and liters of water per day), by the output flow (kilograms of manure per day and liters of milk per day), and by the size of the fund (number of cows). (See Figure 1.) Although occasionally the same physical item will appear as both fund and also flow within the same production process (e.g., the use of hammers to hammer hammers), that is typically not the case.

What about the connection between flows and stocks in the production process? The response of Georgescu-Roegen (1971:223-7) was both insightful and also emphatic:

1. A flow does not necessarily represent either a decrease or an increase in an actual stock of the same substance. E.g., the output flow of melted glass from a furnace does not diminish the stock of melted glass within the furnace, nor does that flow accumulate as a stock of molten glass in a warehouse.

Figure 1 Dimensionality of Funds and Flows		
measurement	input or output flow	services of fund element
amount	kilograms joules	machine-hours cattle-hours
rate	kilograms per hour joules per hour	machine cattle

2. There are occasional cases in which some sort of material flows from one stock to another. For most cases, however, the connection is between one stock and one flow. That is, a flow is an analytical or actual stock spread over some time interval. E.g., one can measure the notional stock of fossil fuels extracted from the Earth's crust since the Industrial Revolution or the actual stock of plutonium which has accumulated on Earth since the dawn of the nuclear age.
3. The provision of services by a fund requires a duration, and the quantity of service a fund can provide during a time period is rigidly determined by its structure. On the other hand, the decumulation of a stock is highly variable and constrained only by the availability of transformative funds. E.g., an oil refinery can process only so many barrels of oil daily whereas the flow of oil extracted from nature annually could triple if sufficient resources were invested in appropriate funds.

Nearly a quarter century after Roegen's pathbreaking contribution, Faber, Manstetten and Proops (1995) have offered us another valuable atlas with which to explore the terrain of flows, stocks, and funds. Whereas Roegen's theoretical map relied heavily on classical thermodynamic principles, Faber et al. emphasize ecological and genetic principles to a far greater degree. They also rely heavily on Prigogine's notion of dissipative structures.[4]

According to Faber et al., the concepts of fund and organism are logically equivalent to one another. On the one hand,

> [O]rganisms… interact with each other as part of their mutual maintenance… We term these interactions as services, and the organisms as funds… [A]ll organisms are funds, necessarily rendering services to other organisms (pp. 44, 48).

On the other hand, a fund "gives services to one or several other organisms… [and] reproduces itself" (pp. 48-49).[5] In order to produce these services, organisms require a material intake of low-entropy drawn from accessible stocks (pp. 47-8).

This recent proposal to revise the concepts of fund, flow and stock displays both strengths and weaknesses. Perhaps it greatest strength is an ecological focus on interactions among populations of organisms, not the provision of a particular service by a single organism.[6] As Faber, Manstetten and Proops (1995:48) express the matter,

> [A]ll organisms are funds, necessarily rendering services to other organisms… On the other hand,… each organism/species also needs services… Thus organisms/species can be viewed, as well as being funds, also as being users of funds… [I]t is [usually] convenient to employ the corresponding species as the elementary unit of a fund. This is so because a fund continues over time, which does not hold for an organism.…

The discussion by Faber et al. is worrisome in several other respects, however. Can we afford to restrict the concept of fund to biological agents alone, as they propose?

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[4]For another appreciation of Prigogine and his work's relevance for ecological economics, see England (1994).

[5]Faber et al. (1995:51) characterize machines as being part of the fund of humans, by association, or as partial funds like human organs. The inability of machines to reproduce themselves without human assistance, it is argued, denies them full status as funds.

[6]For similar treatments, see Jannson and Jannson (1994) and Boulding (1978: ch. 4).

Georgescu-Roegen (1971:232) insisted that the Earth's surface, i.e., Ricardian land, is an active agent in the production process since it captures rainfall and sunlight and also because it provides a platform for other funds on which to operate. Was he wrong? Are dachshunds better able to reproduce without human assistance than hammers are? Possibly not.

Another claim of Faber et al. (1995:49) which warrants critical inspection is that the services of a fund/biological population may include individual organisms harvested from that population. This claim leads them to conclude that such a fund has the characteristic of also being a stock. Is it not essential, however, to distinguish populations of living organisms which are actively processing materials and energy from stocks of dead organisms which are being acted upon by other agents?[7] If one accepts this distinction, then the stock and fund, although perhaps intimately related, are qualitatively different.

After meandering along this critical path, my conclusion is that we can still learn a great deal from Georgescu-Roegen's discussion of funds, stocks, and flows. His insistence that land, humans, horses and machines all qualify as fund elements is compelling. We should thank Faber et al., however, for proposing that the transformative activity of funds be analyzed at the scale of interacting populations, not at the scale of the individual entity.[8]

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[7]Using the example of Faber et al., the fund of living rabbits processes flows of grass, water, and oxygen whereas the stock of dead rabbits provides organic materials which can be eaten or decomposed by predator and decomposer funds.

[8]This approach reminds one of Clark and Munro (1994:360), who argue that ecological interactions require us to think about the economic return on a portfolio of natural assets rather than on individual resources. At the same time, however, we need to keep in mind the comments of Boulding (1978:87) and Harte (1995:162) that there is differentiation within the population of any species and that empirical evidence does not suggest an equilibrium vector of population sizes within any particular ecosystem.

A Reconstruction of the Natural Capital Concept

How shall we proceed, then, in order to sharpen our conceptual image of natural capital? I would like to propose the following methodological strategy:

1. Stress proper classification of entities as funds, flows, or stocks and acknowledge the actual diversity which exists within each of these three categories.[9]
2. Specify the analytical boundary between the economic and environmental subsystems of the global system properly while simultaneously admitting that this boundary falls within a dialectical penumbra (Georgescu-Roegen 1971:45) of conceptual ambiguity.

Putting this pair of methodological dicta to work, let us first identify the fund elements of the global system:

1. $(B_1, \ldots, B_m)$ the populations of nonproduced organisms, each population representing a particular biological species;
2. $(K_1, \ldots, K_n)$ the populations of durable, produced means of production ("capital goods");
3. L the population of human producers and their dependents; and
4. A the Earth's surface area, which serves as a site for other funds' activity and as a solar energy collector.

What distinguishes the produced capital goods (the K_j) from the nonproduced biological populations (the B_i)? One might be tempted to say that the capital goods are nonliving machines whereas the nonproduced funds are living populations. That notion is incorrect,

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[9]For any particular fund, flow or stock, however, we normally have to abstract from its own internal diversity or differentiation, e.g., the various models of computers. The human mind can consider only so many distinctions at once.

however, and reflects a narrowly industrial point of view. In fact, produced capital goods include domesticated plants and animals as well as various types of tools, equipment and structures.[10] As Perrings (1987:ch. 6) has implied, the crucial distinction is whether humans exercise a substantial degree of control over another fund or not. Capital goods, then, are the mechanical or biological slaves of humanity.[11] Nonproduced organisms, on the other hand, reproduce, develop and evolve without a significant degree of conscious human intervention.

It is commonly argued that humans and their slaves, both biological and mechanical, occupy "developed" land areas (A_H) whereas nonproduced species live on "undeveloped" land (A_B). This distinction has a great deal of merit, but, once again, analysis encounters a dialectical penumbra. Rats and viruses largely outside human control thrive in New York and New Delhi, whereas indigenous peoples inhabit the "wilderness" of the Brazilian Amazon. Let us assume, however, that particular parcels of land can be classified as either "settled" or "wild," but not both, so that $A = A_B + A_H$ (Schröder 1995).

Upon what does the activity of the various funds depend? Each, in its own distinctive way, requires input flows of energy and of appropriate materials at the appropriate moments.[12] As Georgescu-Roegen (1971:303) insisted, there are two and only two sources of these input flows:

[M]ankind disposes of two sources of wealth: first, the finite stocks of mineral

[10]A recent proposal to reform the U.S. national income accounts incorporates this assumption. See Bureau of Economic Analysis (1994:Table 1).

[11]Note, however, that domesticated plants cast seeds outside the farmer's field, and tame horses sometimes escape to the wild. Hence, the boundary between produced and nonproduced biological populations is somewhat ambiguous: It falls within a "dialectical penumbra."

[12]On the crucial importance of the timing of the inputs to funds, see Georgescu Roegen (1971:ch. IX). Note the similarities to Faber and Proops (1990:ch. 8).

> resources in the earth's crust which within certain limits we can decumulate into a flow almost at will, and second, a flow of solar radiation the rate of which is not subject to our control.

Each fund also requires information and purpose, as recorded in its genetic code, consciousness and memory, or engineering design (Boulding 1978:12, Georgescu-Roegen 1971:282, Faber et al. 1995).

Let us denote the solar energy flow by ϕ and the input flows from inert terrestrial stocks as $x_k \geq 0$, $k = 1, 2, \ldots, p$. Since the activity of funds does not physically consume or annihilate matter or energy, we must expect output flows as well, call them $w_k \geq 0$, $k = 1, 2, \ldots, p$. The nonliving stocks from which flows are extracted and into which materials get emitted are denoted by $S_k > 0$, $k = 1, 2, \ldots, p$. For some purposes, e.g., tracking entropic dissipation of materials, it would be desirable to disaggregate each global stock into a matrix of physically homogeneous, but spatially-specific, stocks.[13] That refinement is not pursued here.

Thermodynamic principles teach us that these connections among funds, flows, and stocks are both cyclic and also entropic. With minor exceptions, the physical masses of particular chemical elements remain unchanged as these substances change location, combine chemically with other substances, and migrate between inert stocks and active funds. This conservation of physical masses gives rise to the carbon cycle (Munasinghe and McNeely 1995:123) and a variety of similar cycles within the global system. Energy flows, on the other hand, are linear and irreversible – from a state of low to high entropy. Hence, we need to take account of an outflow of degraded energy into outer space (Smil 1991:291), denoted here

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[13]Hence, there is a stock of ozone at ground level in Manhattan and a stock of ozone over Antarctica at

by e. These considerations lead us to the picture of our global system presented in Figure 2. This depiction is similar to earlier “preanalytic visions” (Binswanger 1993:225, Daly 1994:24), but differs from those sketches of the global system in its (i) focus on funds, flows and stocks, and (ii) emphasis on biological and physical diversity.

A variety of trends during the modern era can be displayed within this simple framework. These trends include:

1. human population growth ($\Delta L > 0$)
2. human settlement of new territories ($\Delta A_H > 0$)
3. loss of habitats for nondomesticated species ($\Delta A_B < 0$)
4. loss of biodiversity ($\Delta m < 0$)
5. increased specialization within the economic subsystem ($\Delta n > 0$)
6. technological innovation and obsolescence ($\Delta K_j < 0$ for some j, $\Delta K_j > 0$ for other j)
7. human synthesis of new materials ($\Delta p > 0$)
8. combustion of fossil fuels ($\Delta e > 0$).

A list of this length and importance suggests that Figure 2 provides an effective conceptual framework for thinking about economy-environment interactions.[14]

What, then, are the components of natural capital? Our analytical map of the global system (Figure 2) suggests an amazingly diverse list of candidates: (i) the earth’s nondepreciating surface; (ii) the solar flux, or perhaps the sun itself; (iii) the interacting set of

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tropospheric altitudes. Same substance, different consequences.

[14]For an interesting discussion of the relationship between items (3) and (4), see Baskin (1994).

nonproduced, but biologically reproducible, populations in various ecosystems; and (4) the physically diverse set of material stocks in the earth's crust and atmosphere. (See Figure 3.)

By "amazingly diverse," I mean two very different things. First, the sheer number of nonproduced biological populations and inert physical stocks is immense. Millions of species have evolved biologically on this planet, and only a few have been domesticated. There are hundreds of thousands of chemical compounds, many the products of biological evolution but an increasing number the creation of industrial society.

Our list of candidates for inclusion as natural capital is also incredibly diverse for another, more subtle reason: the dimensionality of the candidates. The rate of solar flux is measured in joules per second. The rate of services by natural funds is measured simply by km^2, bees, trees, etc. The rate of input flow from geochemical stocks is measured in kgs. per second. The stocks themselves are measured in kilograms. Hence, issues of both physical diversity and also temporality arise as one seeks to define and measure natural capital.[15]

It seems, therefore, that ecological economists face several options as we negotiate a shared meaning for natural capital, call it N:

Definition 1 (**D1**): $(A, B_1, \ldots, B_m)$, or

Definition 2 (**D2**): **D1** + $(S_1, \ldots, S_p)$, or

Definition 3 (**D3**): **D2** + the capitalized value of ϕ.

[15] This complexity of the natural capital concept has been acknowledged by several authors (Berkes and Folke 1994:130, Harte 1995:158, Victor 1991:203). For a valuable discussion of the heterogeneity of a system's elements and the implications for aggregation, see Martel (1996).

Figure 2

Figure 3

The first definition accepts only nonproduced funds as natural capital. Although still physically and biologically diverse, this narrow version avoids the dimensionality issue and focuses attention on the active agency of nature. **D1** also focuses attention on durable "fixed assets" in both economic and also environmental subsystems and reflects an ecological perspective.

The second and third definitions, on the other hand, acknowledge that funds cannot play their productive roles without access to inventories of "working capital," i.e., low-entropy materials and energy. These broader, thermodynamically-informed conceptions of natural capital carry a significant methodological price, however: dimensional as well as numerical complexity. How are we to choose among these three definitions? I would propose a pragmatic approach: We should adopt that specification of "natural capital" which helps us to explore the theoretical and practical issues that we care about.

Arguably the most important issue faced by ecological economists is whether produced means of production (the K_j) can substitute for natural capital (N) in production or not. Daly (1994:25) has forcefully claimed that "[m]an-made and natural capital are fundamentally complements and only marginally substitutes."[16] His hypothesis is of paramount importance in light of this observation by Victor (1991:195):

> [Many neoclassical economists] believe that concern with the sustainability of development in a finite world is misplaced since through substitution (and technological progress) the output of the economy can be expanded without limit even when the stock of natural resources is being depleted.

Why do Daly and others hypothesize that human-made capital (L and the K_j) are

[16]For other examples of this claim, see Daly (1990:2-3), Costanza and Daly (1992:41), Prugh et al. (1995:35), and Ayres (1996:241).

complementary to natural capital in production? The supporting argument is that human labor and produced capital goods are transformers of flows of matter and energy into finished products and that the stock of natural capital is the source of these essential input flows (Daly 1990:3, Costanza and Daly 1992:41, Daly 1994:25).[17]

This line of argument, which is thermodynamic in perspective, emphasizes the physical input flows (the x_k) derived from terrestrial stocks (the S_k). Hence, it favors adoption of **D3** as our natural capital concept. In Aristotelian language, the input flow from the natural capital stock is the material cause of production whereas the humans and their enslaved funds (either mechanical or biological) are the efficient cause (Daly 1994:26).

There is another argument for the complementarity of natural capital and human-made capital, an argument rooted in ecological research. According to de Groot (1994), ecosystems perform a wide variety of regulation, carrier, production and information functions. (See Appendix.) If we denote the services provided by ecosystems as σ_h,
$h = 1, \ldots, s$, then

$$(B_1, \ldots, B_m) \Rightarrow (\sigma_1, \ldots, \sigma_s).$$

That is, it is the ecological interaction of many nonproduced funds which generates an extensive ensemble of services useful to the economy.

If every one of these services could also be provided by a specialized human artifact, i.e.,

$$K_j \Rightarrow \sigma_j, \ j = 1, \ldots, s \leq n,$$

then humanity could destroy all nonproduced biological funds (the B_i) and enjoy the entire

[17]Examples of complementarity cited by Daly (1994:26) include saw-mills and forests, oil refineries and

ensemble of natural services (the σ_j) by accumulating the appropriate mix of produced means of production (the K_j).

If, on the other hand, specialized capital goods cannot produce each and every service needed by human society, then preservation of complex ecosystems is essential for sustainability. Ecological economists hypothesize that the latter case is true. If this hypothesis is correct, then one could adopt the **D1** definition of natural capital and still maintain that natural and human-made assets are complementary in production.

It seems, then, that ecological economists need to discuss at greater length which definition of natural capital to adopt. That choice might be influenced by empirical evidence on the relative importance of low-entropy stocks of materials and energy and of those ecosystem services which cannot be replicated by capital goods. Even if professional consensus cannot be reached, however, each ecological economist should specify clearly his or her personal choice of definition.

On the Social Character of Natural Capital

By this point, it should be clear that, regardless of how one defines the "stock of natural capital," it is a very heterogeneous notion from a biophysical point of view. (Recall Figure 3.) Hence, measurement of the aggregate stock of natural capital requires valuation of its various biophysical components.

This process of valuation is problematic, however, as Victor (1991:203-4) has warned us:

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petroleum reserves, and irrigated farmland and aquifers.

> Measurements of natural capital stock made exclusively in physical terms are problematic because of the difficulty of adding up… quantities expressed in different units…. By valuing each resource stock in money terms, the total value of natural capital can be measured… but there are several problems with this approach.

Facing problems squarely is of fundamental importance if ecological economics is to stand on a secure theoretical foundation.

In my opinion, the most serious of these problems is that valuation of natural capital is a social, and not merely a technocratic, process. That is, placing values on tropical ecosystems, natural gas reserves and the stratospheric ozone layer requires assessments by the whole of human society, not just calculations by scientific experts. Those assessments, in turn, will depend upon the exact pattern of social stratification among the members of humanity.[18] If one disagrees with society's current valuation of natural capital, then one must face the possibility that one is implicitly questioning the existing pattern of stratification within society.

Using current market prices to value the components of natural capital is, then, a dubious practice -- unless one acknowledges that these market prices reflect the present distribution of wealth and power among the members of humanity.[19] As Harris (1978:239) argued nearly two decades ago, the "quantity of capital… as a sum of exchange value obtained by valuing the [physically] different capital goods at the ruling prices, depends on the rate of profit." Thus, defining and measuring natural capital cannot avoid an exploration of the

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[18]This point was recognized two centuries ago by Smith, Malthus, and Ricardo. For the classical economists, "Labor, Land, and Capital were… social categories corresponding to the prevailing class relationships among individuals in contemporary society… Accumulation [of capital] and distribution [of income] were seen to be interconnected through the use that was made by different social classes of their share in the [aggregate] product" (Harris 1978:6-7).

[19]For more on this point, see Nell (1980) and Kurz and Salvadori (1995:ch. 14).

origins of profit.

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Appendix on Ecosystem Functions

Regulation Functions

1. Protection against harmful cosmic influences
2. Regulation of the local and global energy balance
3. Regulation of the chemical composition of the atmosphere
4. Regulation of the chemical composition of the oceans
5. Regulation of the local and global climate
6. Regulation of runoff and flood-prevention (watershed protection)
7. Watercatchment and groundwater-recharge
8. Prevention of soil erosion and sediment control
9. Formation of topsoil and maintenance of soil-fertility
10. Fixation of solar energy and biomass production
11. Storage and recycling of organic matter
12. Storage and recycling of nutrients
13. Storage and recycling of human waste
14. Regulation of biological control mechanisms
15. Maintenance of migration and nursery habitats
16. Maintenance of biological (and genetic) diversity

Carrier Functions

Providing space and a suitable substrate for:

1. Human habitation and (indigenous) settlements
2. Cultivation (crop growing, animal husbandry, aquaculture)
3. Energy conversion
4. Recreation and tourism
5. Nature protection

Production Functions

1. Oxygen
2. Water (for drinking, irrigation, industry, etc.)
3. Food and nutritious drinks
4. Genetic resources
5. Medicinal resources
6. Raw materials for clothing and household fabrics
7. Raw materials for building, construction and industrial use
8. Biochemicals (other than fuel and medicines)
9. Fuel and energy
10. Fodder and fertilizer

Information Functions

1. Aesthetic information
2. Spiritual and religious information
3. Historic information (heritage value)
4. Cultural and artistic inspiration
5. Scientific and educational information

Source: de Groot (1994:154).