A PRIMER ON ECOLOGICAL SYSTEMS

Ivan M. Johnstone BSc (Physics), BArch (Hons), PhD

Former Senior Lecturer, Department of Property, The University of Auckland

Nature never breaks her own laws - Leonardo da Vinci

INTRODUCTION

Ecology can be defined as that branch of science which studies the relationship of living organisms with each other within their physical environment. Organisms and their physical environment form ecosystems. Human settlements also form ecosystems within larger ecosystems. At any point in time, ecosystems can be new or old, changing their boundaries and growing or declining, or in a form of climax or steady state. This section uses energy diagrams developed by Howard Odum (1976) to help compare ecosystems and recognise equivalent roles in different systems, including that of human settlements.

ENERGETIC SYMBOLS

The following symbols and diagrams used by Odum (1976) help us to visualise the laws and flows of energy within ecosystems by introducing the idea of an ecosystem as a combination of interacting parts. The symbols might be familiar to those who have studied electronics or dynamic systems analysis.

The *Energy Circuit* symbol shows the direction and flow of energy from a *Source* of energy or a unit such as a *Storage Tank*.

Figure 1: Energy Circuit Symbol

The *Source* symbol is used for sources of energy that are external to the system under examination.

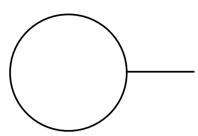

Figure 2: Source Symbol

The *Storage Tank* symbol represents a stock of energy such water, and minerals in the ground.

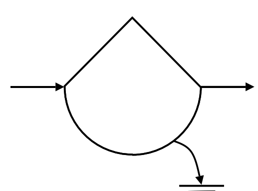

Figure 3: Storage Tank Symbol

The *Heat Sink* symbol, an arrow pointing down into the ground, represents the loss of degraded energy from a system and the depreciation and degradation of that system as the material of the system becomes dispersed. All *Storage Tanks* have a *Heat Sink* as a result of the Second Law of Thermodynamics.

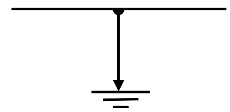

Figure 4: Heat Sink Symbol

The *Interaction* symbol*:* All processes involve the interaction of two or more types of energy and matter. All *Interactions* also have a *Heat Sink* as a result of the Second Law of Thermodynamics.

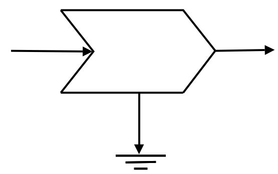

Figure 5: Interaction Symbol

The *Producer* symbol represents the processes, interactions, and storages that collects and transform low-quality energy into high-quality energy flows. An example is the process of photosynthesis where biomass is produced from diffuse solar energy.

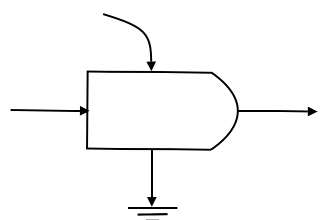

Figure 6: Producer Symbol

The *Self-Interaction* symbol represents processes where self-interaction results in a faster action that would otherwise take place.

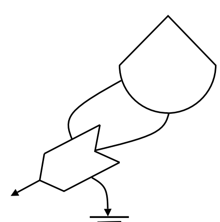

Figure 7: Self-interaction symbol

The *Consumer* symbol represents a system that maintains itself by using *Storage Tanks* and *Interactions* to make use of inflowing energy and materials. Examples include organisms.

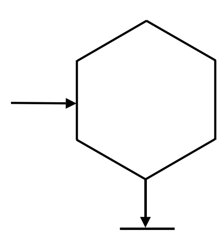

Figure 8: Consumer Symbol

The *Miscellaneous* symbol is used for subsystems as labelled.

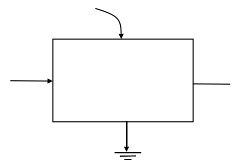

Figure 9: Miscellaneous Symbol for sub-systems

PRODUCERS AND CONSUMERS

All ecosystems are solar based and have some common characteristics that abide by the Laws of Thermodynamics. Within an ecosystem there are food producers in the form of plants which use sunlight to produce food and food consumers in the form of animals which use this food. Both producers and consumers maintain an ecosystem by recycling the by-products given off by each other. Figure 10 shows a balanced ecosystem.

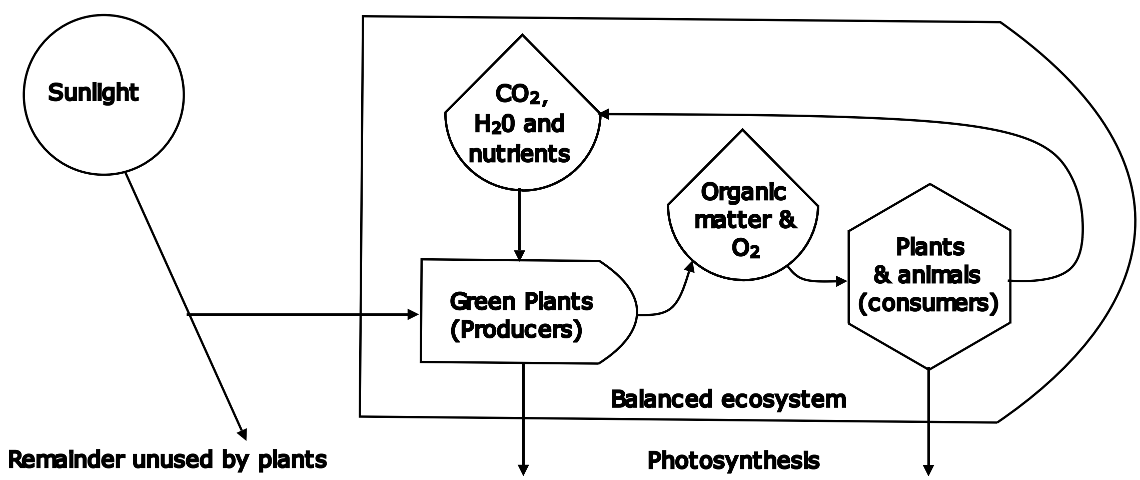

Figure 10: Balanced Ecosystem (Odum & Odum, 1976, p95)

Sunlight supports the photosynthetic process used by producers whereby heat disperses into the atmosphere and oxygen is produced. Consumers use this oxygen and feed on the food provided by producers and give off heat and carbon-dioxide as they do so. Carbon dioxide plus sunlight forms the food of the producers. The producer-consumer interaction of the two processes of photosynthesis and respiration are complementary - one provides what the other needs. This complementary interaction is called symbiosis.

Figure 11 shows this producer-consumer (P-R) symbiosis. Chemical components are isolated to show how they cycle in the P-R process. Each component contributes part of the energy requirement. The nutrients are shown coming out with the heat, but going on separately to be cycled and reused.

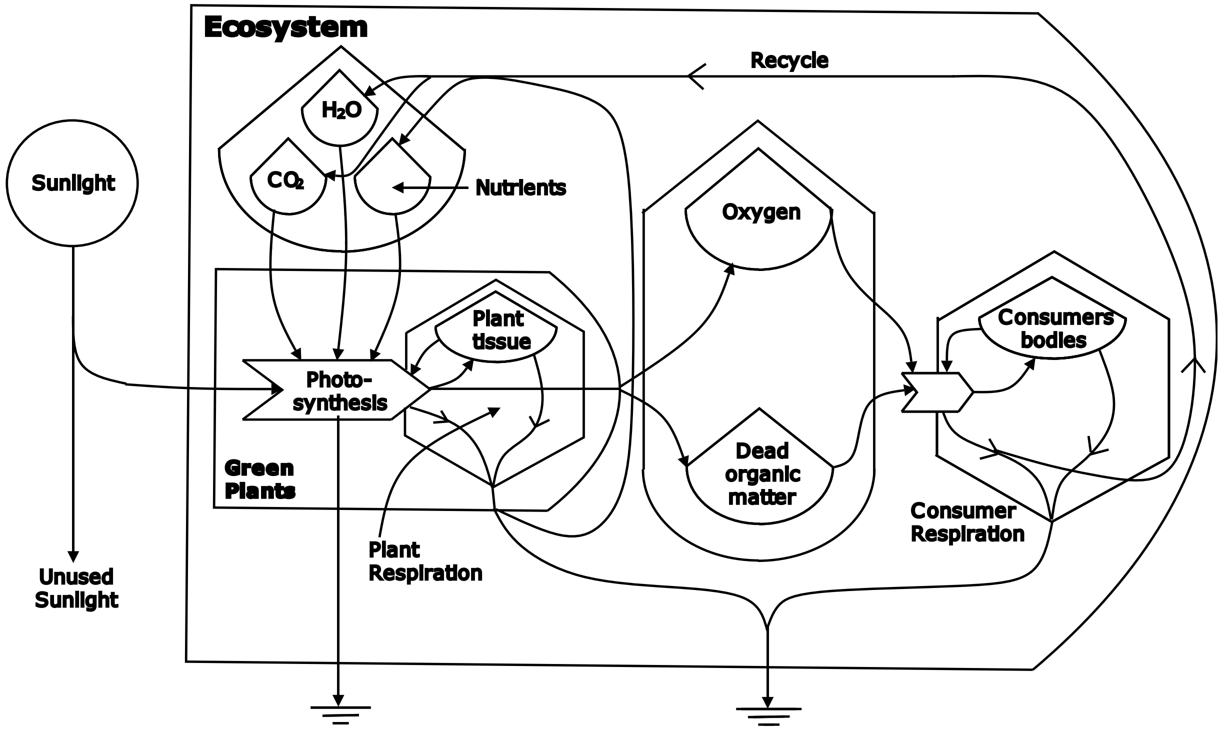

Figure 11: Producer-consumer symbiosis (Odum & Odum, 1976, p100)

Plants develop living biomass from the process of photosynthesis. Upon dying, this biomass falls to the ground as wood and forest litter. Some of this biomass is eaten by consumers before dying, or is consumed by insects and microbes after dying. These processes form a food chain. A plant eaten by one animal might in turn be eaten by another animal, and so on. Most ecological systems develop food chains with at least five stages. A food chain is linear and follows the generalized form of Plant - Herbivore – Carnivore. The quality of energy is upgraded at each step of the chain, but with an inevitable accompanying loss of energy to heat due to the Second Law of Thermodynamics.

In nature, the food and feeding relationships of plants and animals are rarely in the form of a simple linear food chain, but instead interconnects with a large number of other food chains to form a food web. This web can become extremely complex, and the discovery and description of a food web in any given habitat is an enormous task. Tampering with a food web can have some unexpected and undesirable effects.

Animals at the base of a food chain are relatively abundant, while those at the other end are relatively few in numbers. There is a progressive decrease between the two extremes. When comparing the population of other carnivores and herbivores with that of humankind, humankind does not have the same symbiotic relationship within the ecosystem. The reason why is because humankind has been able to tap resources of energy which other parts of the ecosystem cannot use. By utilising this energy, humankind has been able to sustain a larger population than that of other similar sized animals.

All members of an ecosystem have inflows and outflows of mineral nutrients. Figure 12 is representative of a typical ecosystem with inflows of both organic matter and mineral nutrients. Both photosynthesis and respiration are stimulated to higher levels than they would reach without the inflows.

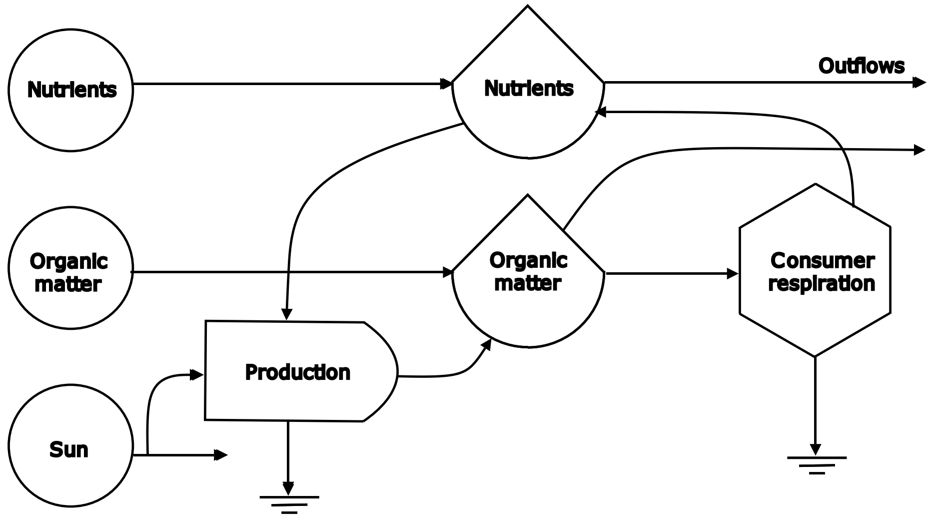

Figure 12: Steady state inflow and outflow of nutrients (Odum & Odum, 1976, p104)

MAXIMUM POWER PRINCIPLE

The Maximum-Power Principle first formulated by Lokta (1925) explains why some ecological systems survive others. This principle can be stated as follows:

> *The systems that survive in competition are those that develop more power inflow and use it best to meet the needs of survival.*

According to Odum (1976, pp40-1), ecological systems which use the Maximum-Power Principle develop storages of high-quality energy which are used to increase inflows, recycle materials as needed, organise control mechanisms that keep the system adapted and stable, and set up exchanges with other systems to supply special energy needs. Figure 14 demonstrates these ideas.

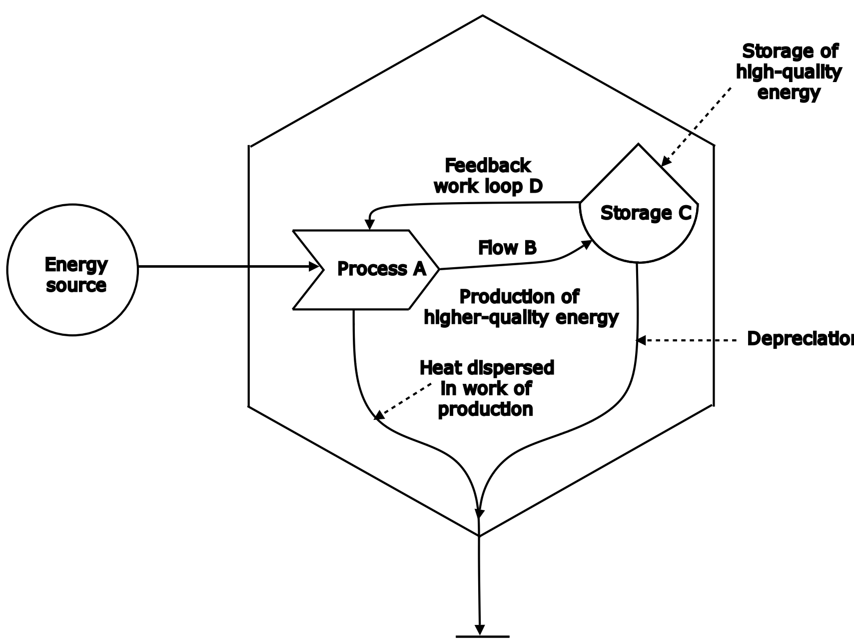

Figure 13: Energy feedback loop (Odum & Odum, 1976, p41)

The more energy that is pumped into the storage C, the more is fed back to process A. This energy-pumping feedback stimulates inflow from the source of energy, E. The steeply rising graph of growth produced by this feedback acceleration with a large source of energy is sometimes called 'Malthusian growth". As long as the source is larger enough to maintain a constant force in spite of a greater drain of energy, the pumping will increase faster and faster until natural limits are reached.

SUPER - ACCELERATED GROWTH

Over the past 100 years, economic growth as measured by GDP in the developed countries has grown at a faster rate than growth in population. The growth in GDP per capita has been due to a universal conviction that growth and expansion has a positive value. The profit motive, the protestant work ethic, and a capitalist system has enabled a unified effort in bringing together resources for a maximum rate of economic growth. Mutual co-operation, a self-interaction process, has enabled super-accelerated growth.

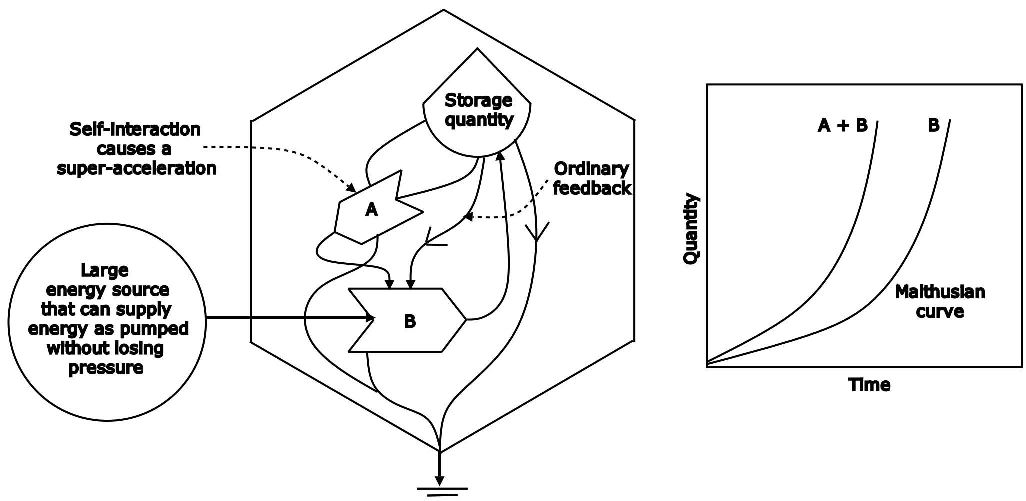

Figure 14: Super-accelerated growth. (Odum & Odum, 1976, p69)

Growth is faster with self-interaction pumping than with ordinary Malthusian feedback pumping. The A+B curve is the super-accelerated growth that has been made possible. A system that is able to accelerate its growth faster than another system is able to capture the energy source flows from other systems. A system with super-accelerated growth survives at the expense of another system.

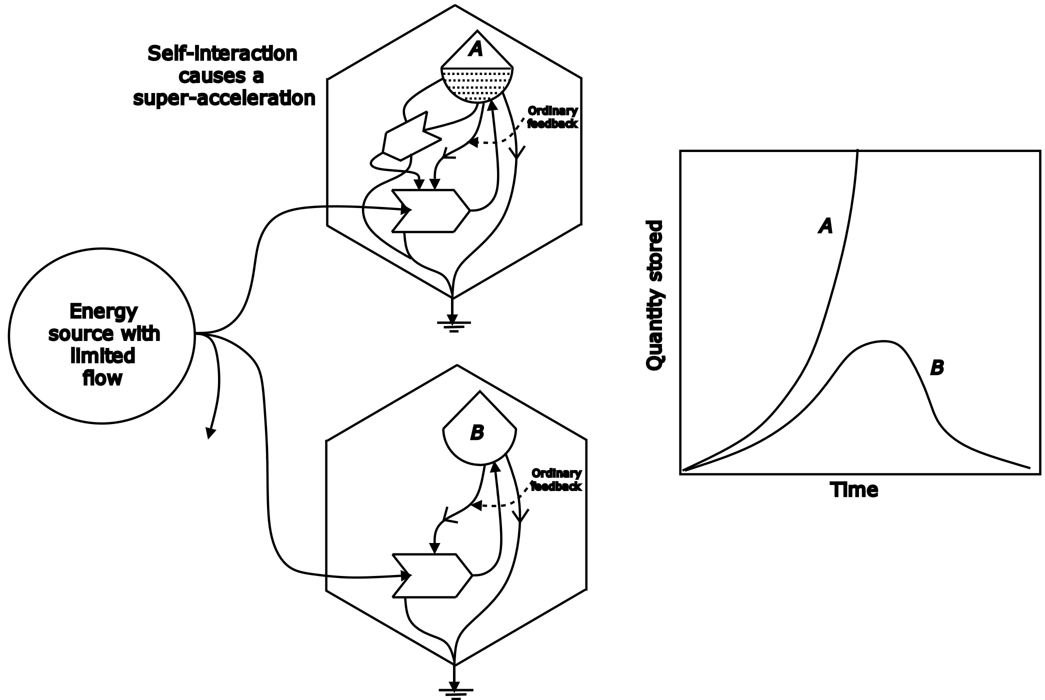

Figure 15: Competitive exclusion. (Odum & Odum, 1976, p71)

GROWTH AND LIMITED ENERGY SOURCE

A limited energy source is where the source itself controls the energy flow. An example is sunlight falling upon Earth. Photosynthesis depends on this incoming flow of energy. Once this incoming energy has been used to the fullest, growth either declines - a situation in which outflows exceeds inflows and storages are decreasing - or the system maintains a steady state where the inflows of energy just keep up with depreciation and losses as shown in Figure 16.

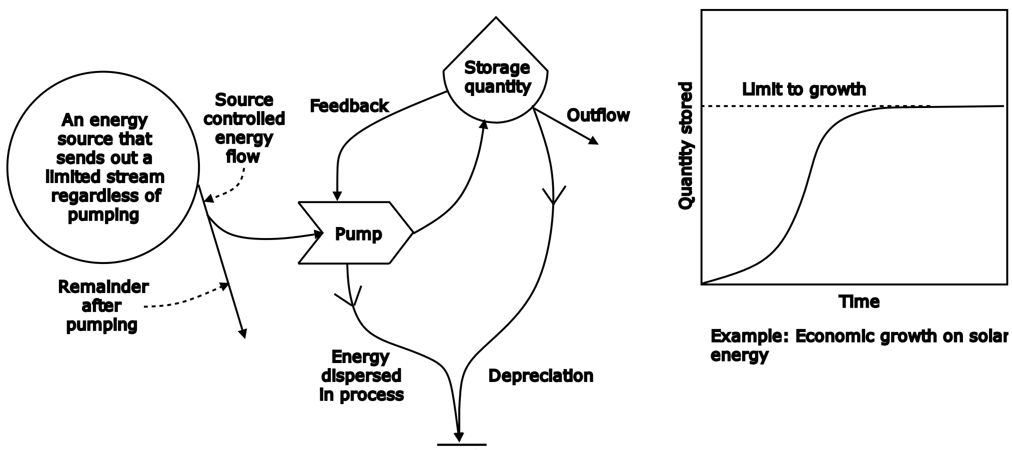

Figure 16: Growth to steady state using solar energy.

Figure 17 shows the process of decline. An example would be termites feeding off a log until the energy source is completely eaten away.

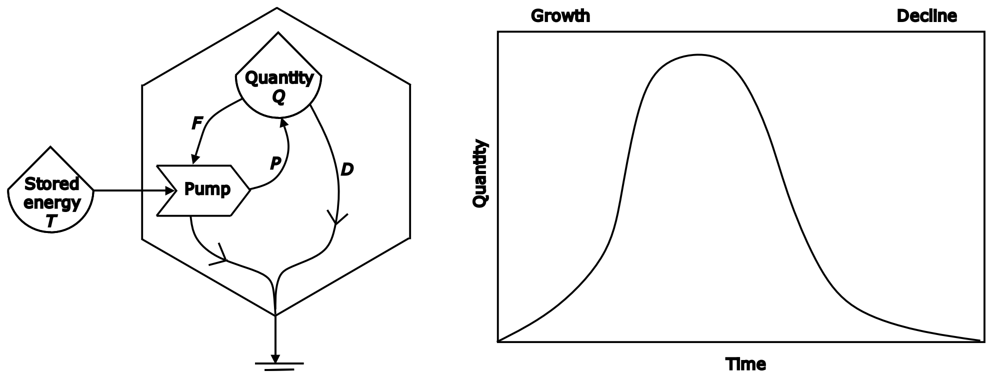

Figure 17: Process of decline. (Odum & Odum, 1976, p72)

Growth of quantity (*Q*) accelerates at first until the source (*T*) begins to run out. The quantity of stored order (*Q*) then gradually declines as depreciation (D) and outflow of feedback (F) exceed production (*P*).

Most systems are able to tap into a steady source of energy and during their period of rapid growth they have been able to tap into a temporary energy source as well. Figure 19 shows a surge of growth and then a return to steady state.

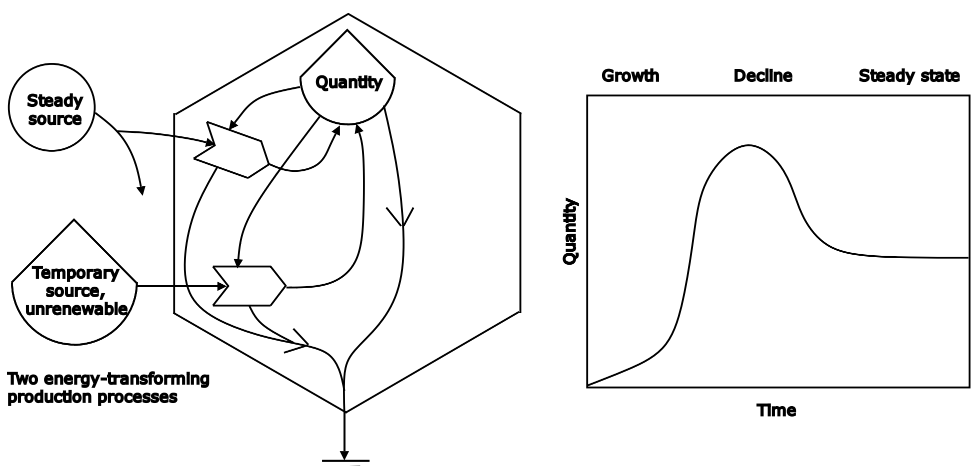

Figure 18: Surge growth to steady state (Odum & Odum, 1976, p73)

HOMOEOSTASIS

All ecosystems have developmental stages corresponding to that of a single organism - birth, early rapid growth, followed by maturity. Each developmental stage brings and ecosystem closer to steady state, a state of homeostasis in which there is a dynamic equilibrium interaction between the ecosystem and its physical environment.

Succession is a natural process where organisms within the same ecosystem succeed one another by maximising their energy inflow until a highly stable climax ecosystem develops. During this succession stage, energy and nutrients are added to the ecosystem with the result that the net ecosystem production is high. The ratio of gross production *P* to respiration *R* is greater than 1 and the food chains of the ecosystem are linear.

As an ecosystem approaches climax, the *P*/*R* ratio approaches 1, the net ecosystem production approaches 0, and the food chains of the ecosystem tend to be woven into food webs. A climax ecosystem is stable and in a condition of internal self-regulation where feed-back mechanisms enables the ecosystem to return to equilibrium following any stress of change in climate, energy, and nutrient resources.

There is a relationship between diversity or complexity and the stability of an ecosystem. Increasing the complexity of an ecosystem may or may not increase the stability of the system. The development of a high degree of diversity can favour the collection of energy and provides flexibility in cases where there are changes in the relative availability of energy resources. On the other hand, the energy required for organising diversity is large and can be either an aid or a drain on energy. During the succession stage there is a low diversity of species, but a high level of diversity of special adaptations within the species. At climax there tends to be a high level of species diversity. A careful evaluation of an ecosystem should be made before any change in diversity is considered and implemented.

Humans are omnivores who can eat both plants and meat. We are now no longer hunters and gatherers. Instead, we are now essentially grazers who either feed off grain directly or indirectly through the breeding of animals which we eat. Agriculture is an attempt to increase the *P*/*R* ratio for human consumption by preventing the natural process of succession and decreasing diversity. Humankind has been able to crop a high yield from an unstable agricultural ecosystem by feeding in energy in the form of fertilizers and insecticides. Monoculture systems of growing crops, building dams and roads, and pollution threaten the homeostasis of ecosystems. Environmental impact assessments of proposed developments should use an eco-energetic approach to establish whether proposed development will result in runaway instabilities in the surrounding ecosystem.

CARRYING CAPACITY

The carrying capacity of an environment is the maximum population of a species that can be supported in that environment. Both Individual organisms and ecosystems have developmental stages where there is initially a period of slow growth and a period of rapid growth followed by a stable period of non-growth where there is a steady state climax. This also applies to the growth of the population of an organism within an ecosystem as shown in Figure 19.

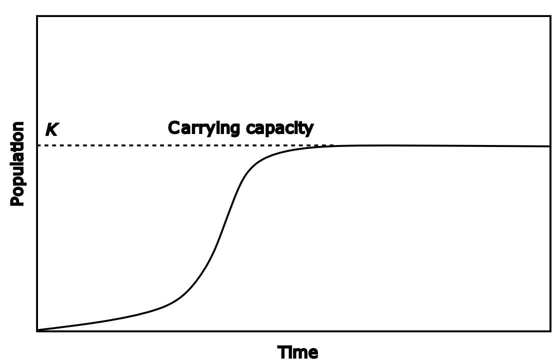

Figure 19: Carrying capacity

The limiting factor that prevents further population growth is the availability of nutrients. In climax ecosystems there are complex food webs where the cycles of nutrients are tightly interlinked. The carrying capacity of each organism in a given environment is limited by the stock of any indispensable necessity of life that is in shortest supply. The following simplified diagram shows the interdependence of the nutrient cycles.

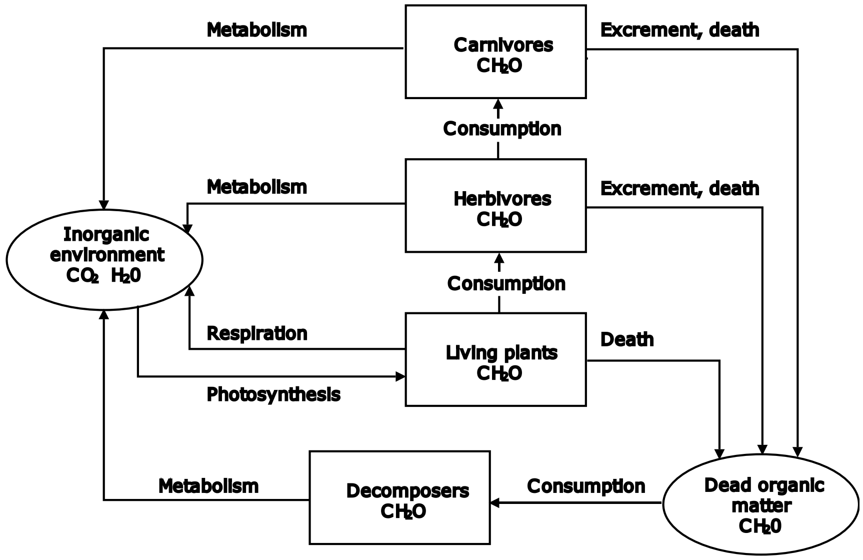

Figure 20: Interdependence of Nutrient cycles. (Ehrlich et al., 1977, p77)

Herbivores feed on plants, and carnivores feed on herbivores and fellow carnivores. As can be seen, the ultimate limiting factor of total biomass (combined carrying capacities of all organisms) in an ecosystem is the process of photosynthesis carried out by plants, algae, and certain bacteria.

GROSS PRIMARY PRODUCTION (GPP)

The total quantity of solar energy entering the Earth's atmosphere is in the order of 15.3 x 108 calories/m2/year. Much of this energy is absorbed by the atmosphere, or reflected back to space by clouds. The actual quantity of solar energy available to plants ranges from 2.5 - 6.0 x 108 calories/m2/year depending upon the geographic location. However, much of this available energy is not used in the process of photosynthesis. As much as 95% to 99% of this available energy is lost from the plants in the form of sensible heat and heat of evaporation. The remaining 1% to 5% of energy is used in photosynthesis and is transformed into the chemical energy of plant tissues (phytomass). Even then, not all this energy is continuously available to herbivores as this energy represents the Gross Primary Production (GPP) of the plant.

NET PRIMARY PRODUCTION (NPP)

The Net Primary production (NPP) which is continuously available to herbivores is the sum of the Gross Primary Production less the respiration (R) of the plant. The ratio of respiration to gross production can range from 0.20 to 0.75, depending upon the type of plant. Figure 14 shows an example of the available Net Primary Production available to herbivores.

The photosynthetic efficiency of plants which is the ratio of Net Primary Production to the amount of solar energy received while the plant is in leaf ranges from 1% to 5%. A plant with high photosynthetic efficiency may not necessarily produce more phytomass per unit time than a plant with a low photosynthetic efficiency. The latter plant may have a higher productivity factor as plants have a different ground coverage percentage and not all plants carry out photosynthesis during the entire year. Over one year an average Net Primary Production is approximately 0.25% of the incident solar energy for land plants. Under favourable conditions this may reach 2% over the growing season. Because of these intervening complexities, it is more useful to consider productivity rather than photosynthetic efficiency as a comparison indicator of different plants.

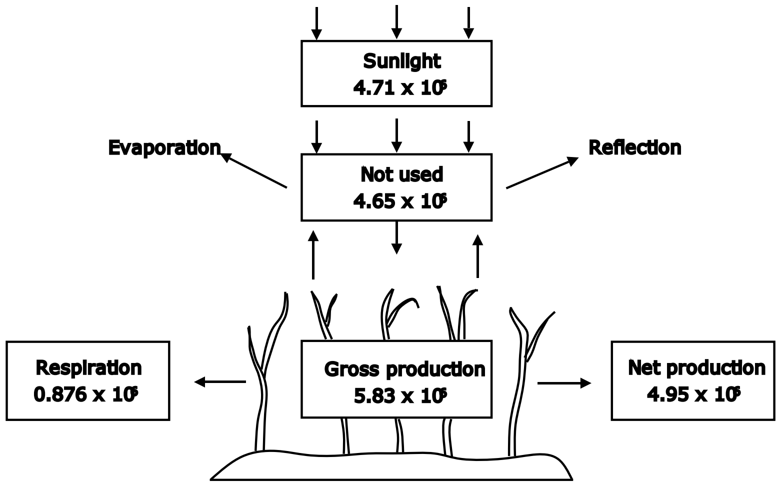

Figure 21: Net production (Phillipson, 1966, p6)

Herbivores feed on the available Net Primary Production. On average they convert approximately 10% of their food intake to growth. The individual Gross Growth Efficiency – (Calories of Growth)/(Calories Consumed) - varies from 6% to 37% among the species. A high Gross Growth Efficiency indicates an efficient assimilation of food energy for growth with little being voided as faeces or used in respiration.

The Gross Growth Efficiency of an organism reduces as the organism grows larger. Another growth factor is the Net Growth Efficiency - (Calories of Growth)/(Calories Assimilated) - where a high Net Growth Efficiency indicates that a relatively small amount of the assimilated energy is lost as heat of respiration and that the remainder is used for growth. Tissue growth efficiencies tend to decrease as one goes up the trophic level food chain. Herbivores, in building up their body tissues, dissipate a large proportion of the phytomass energy they consume. The efficiency of energy transfer between trophic levels – (Calories Consumed by Predator)/(Calories Consumed by Prey) - known as Linderman's Efficiency is approximately 10%. This efficiency ratio accounts for why the total phytomass of plants is greater than the biomass of herbivores which is greater than the biomass of carnivores. The biomass pyramid in Figure 22 shows this relationship.

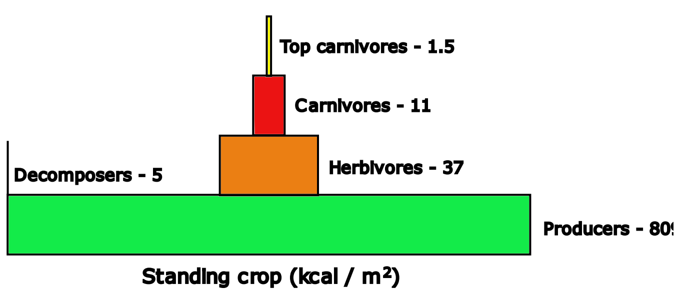

Figure 22: Biomass pyramid (Ehrlich et al, 1977, p134)

Although the biomass of bacteria and fungi accounts for only 0.58% of the community biomass, the following energy flow pyramid in Figure 23 shows that they account for approximately 17% of the energy flow because smaller organisms have a higher metabolic rate in general and reproduce more rapidly than larger ones.

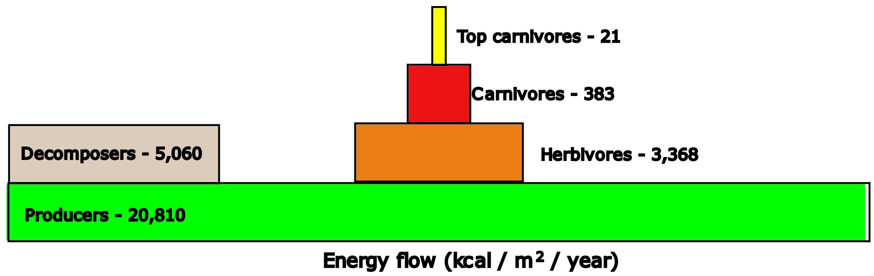

Figure 23: Energy flow pyramid (Ehrlich et al, 1977, p134)

NET COMMUNITY PRODUCTION (NCP)

The Net Community Production (NCP) available to humankind as a food and energy source is that share of the Net Primary Production or net phytomass which humankind shares alongside with other herbivores. Humankind is concerned with maximising food and energy resources by maximising the NPP/GPP and the NCP/GPP ratios.

If humans wish to maximise food and energy resources, then humans should remain exclusively herbivores and feed directly off plants and use sustainable phytomass as fuel alongside with hydro-electricity and other solar based energy sources. In doing so, humankind would be sharing the available net phytomass alongside other herbivores.

A question arises as to whether humankind should attempt to succeed other herbivores. It is improbable that humankind will ever succeed bacteria and insects by taking over their share of the net phytomass which is available. However, humankind has caused birds and animals to become extinct at a faster rate than normally occurs within nature. Assume that humankind does monopolise a larger share of the available phytomass. Would humankind be able to return all necessary nutrients back to the soil? For humankind to attempt its own monoculture of species would be to upset the balance of nutrient and energy cycles resulting in succession of humankind by lower order species. Humankind needs to live in harmony with plants, animals, insects, birds, fish, and bacteria in order to survive. In striking a balance between food consumption and energy consumption from phytomass together with other forms of solar energy collection, we need to understand more fully the patterns of energy flows within ecosystems and, in particular, our own energy flows and their impact on the environment.

SUMMARY TABLE

	ECOSYSTEM ATTRIBUTE	GROWTH STAGE	CLIMAX
Energetics			
1	Gross production/respiration (P/R) ratio	Greater than 1	Approaches 1
2	Net production (yield)	High	Low
4	Biomass supported/unit energy flow (B/E ratio)	Low	High
4	Food chains	Linear	Weblike
Structure			
5	Species diversity	Low	High
6	Stratification and spatial heterogeneity (pattern diversity)	Poorly organised	Well organised
Life History			
7	Life cycles	Short and simple	Long and complex
Nutrient and Energy Cycling			
8	Mineral and energy cycles	Open	Closed
9	Nutrient and energy exchange rate	Rapid	Slow
Selection Pressure			
10	Growth form	For rapid growth	For feedback control
11	Production	Quantity	Quality
Overall Homeostasis			
12	Internal symbiosis	Underdeveloped	Developed
13	Recycling	Unimportant	Important
14	Stability (resistance to external stress)	Poor	Good
15	Entropy	High	Low
16	Information	Low	High

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