Ecosystem Design Methodology

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Awareness of declining resource availability, climate change and other forms of environmental degradation is generating demand for sustainable production in all sectors. Meanwhile, increasing interest in urban agriculture, horticulture and gardening is stimulating interest in container-based cultivation, especially where sites have limited growing space or severely compromised field soils and in operations growing high-value crops. At the intersection of these trends, demand is growing for a sustainable, intensive container-based horticulture for gardening, subsistence farming and small-scale commercial farming.

The mission of building a sustainable, intensive horticulture strongly suggests an ecological model of production, wherein productive processes and corresponding energy and resource flows mimic natural biological systems. Because ecological horticulture andpermaculture align with the same natural processes present in all well-functioning ecosystems, understanding ecosystem function and ecology is key to designing productive ecosystems.

The Ecological Model

In the most general terms, an *ecosystem* is “the environment” – the physical, chemical and biological world around us, and *ecology* is the study of an ecosystem. In more scientific terms, the ecosystem is defined as:

> “Any unit that includes all the organisms (ie., the “community”) in a given area interacting with the physical environment so that a flow of energy leads to clearly defined trophic structure, biotic diversity, and material cycles (ie., exchange of materials between living and nonliving parts) within the system.”

In this context, ecology is the study of ecosystem components and how they function and interrelate through time, with special emphasis on energy flows. In regard to energy flows, ecology is “fundamentally concerned with the manner in which light is related to ecological systems, and with the manner in which energy is transformed within the system.

Energy is the fundamental ability to do work. The primary unit of energy in living systems is the electron, the unit of energy that drives all metabolic and biological processes. Electrons even drive photosynthesis, which uses photons to obtain electrons from water in the first of a long sequence of energy transactions that fuels biology. *Metabolism* is the process of obtaining, transporting, storing and expending electrons, which organisms use to create *energy-potential gradients*, from which they generate work. Metabolism involves the dual processes of *catabolism*, the process of gaining energy (as electrons) by decomposing a molecule and *anabolism*, the process of building a molecule using the electron gained through catabolism. As organisms use electrons to grow and function, energy is expended into heat, thereby dissipating the energy into the atmosphere. Each metabolic process creates a molecule by-product with less energy, less ability to do work and more entropy.

In the most general terms, this energy transformation begins with organisms that use light to obtain electrons from water and store them in sugars. Ecologists call these organisms *primary producers* because they produce the energy-rich sugars that other organisms consume to live. These primary producers are *autotrophic*, because they gain energy and carbon independently of other organisms. The organisms that consume primary producers are called *primary consumers*. These organisms are *heterotrophic*; they depend upon other organisms for their energy sources and carbon.

Ecologists refer to these levels of energy transformation as *trophic levels*. Primary producers occupy the first tropic level, and the primary consumers that consume them function at the second tropic level. As primary consumers consume primary producers, they transform sugars and other energy-rich compounds into energy for their own growth and function. These second-trope, heterotrophic organisms are generally referred to as *herbivores*. Organisms in the third trope that consume organisms in the second trope and are called *carnivores.* Third-trope organisms that also consume first trope organisms are called *omnivores*. Fourth level tropes can often emerge, as well, including yet more carnivores and omnivores consuming organisms in the lower tropes. Often, organisms will occupy different tropes at different stages of their lives.

Within this *trophic web* are heterotrophic organisms that form *symbiotic* relationships with hosts. Symbiotic organisms, usually fungi or bacteria, simultaneously consume energy and mineral resources obtained from hosts while providing them with energy, water and protection from pathogens. Finally, organisms that consume dead tissue for energy are called *saprophytes.* These organisms generally live in the soil, decompose organic materials, consume and incorporate carbon and dissipate the remaining energy that has flowed through the trophic web, releasing most of it as the low-energy chemical bonds forming CO2. The entire assemblage of tropic levels constitutes the *food web*.

Within the food web, more energy and carbon flow through a relatively lower trope than a higher trope, with the autotropes transforming the most energy and determining the total energy budget. Plants, the most important autotropes for agriculture, fix massive quantities of energy into plant tissue and fluids (metabolic compounds in water solution). As they expend energy to grow and function, they dissipate energy through respiration, releasing the low-energy carbon compounds CO2. Organisms at the second trophic level derive energy from plant tissue and fluids, dissipating it into heat as they grow and function. This chain of energy transformations continues until energy is expended by the highest trophic-level organisms and the saprophytes.

As a whole, energy flow quantitatively decreases between lower and higher tropic levels, due to energy dissipation at each level. The energy efficiency at a tropic level is equivalent to the ratio of energy fixed in ecosystem production to the energy dissipated. Ecosystem production, or *net production*, is the increase in biomass within a given area over a defined time period, which equals total production minus respiration losses as CO2 and H2O. *Biomass* is the total weight of organic material in an ecosystem, which is the sum of living organisms and decomposing tissue of dead organisms. The quantity of energy a trope contributes to net production compared to the total quantity of energy available to it from the next lowest trope or tropes defines its efficiency.

Each of these organisms is able to maintain a high-degree of chemical and physical order and stability and a low state of entropy by constantly gaining and expending energy through the metabolic process of respiration, in which the organism frees energy from high-energy compounds and expends it to do work, simultaneously dissipating it as heat. Thus, organisms are dissipative systems, as is the trophic web as a whole. Defined as the trophic web in a physical-chemical environment, an ecosystem is also an energy-dissipative system.

> Organisms, ecosystems and the entire biosphere possess the essential thermodynamic characteristic of being able to create and maintain a high state of internal order, or a condition of low entropy (a measure of disorder or the amount of unavailable energy in a system). Low entropy is achieved by a continual dissipation of energy of high utility (light or food, for example) to energy of low utility (heat, for example). In the ecosystem, "order" in terms of a complex biomass structure is maintained by the total community respiration which continually 'pumps out disorder'."

As ecosystems mature, in a process called *ecological succession*, they increase in biological complexity and diversity, or *biodiversity*, the diversity of biological composition, structure and function in an ecosystem. *Composition*, which describes the species and taxa and their proportional representation in an ecosystem, expands and likewise increases the magnitude and diversity of ecosystem *functions*, the energy-transforming, contingent processes that drive an ecosystem. Composition and function shape *structure*, the shape, volume, weight and appearance of ecosystem components, which in turn shapes composition and function. As plant cover increases to ecosystem's maximum ability to transform light into electro-chemical energy and the higher tropes retain more energy and carbon, marking an increase in overall energy and carbon efficiency. As ecosystems continue to mature, they approach a *climax stage*, wherein biodiversity and carbon pools remain stable. Plants expend more energy and carbon for maintenance respiration, available soil nutrients become more scarce (immobilized into living and dead biomass) and soil microbes expand the volume of nutrient exchange networks between different plant and microbe species. As the trophic web becomes more dense and and networks stabilize, resource networks between organisms, primary productivity and energy and carbon efficiency increase and net primary production decreases. In the absence of catastrophic disturbance, a stable balance emerges between plant litter-fall, decomposition, labile carbon and soil organism biodiversity.

Robust, sustained systems exhibit high biodiversity with relatively high energy and carbon use efficiency. In these systems, many functions are redundant, meaning that more than one species can complete the necessary processes to complete the function. Because of this redundancy, late-succession ecosystems are more resilient to ecosystem stresses, which means that they can return to full function following a minor disturbance. The outcome for agricultural systems includes a vast array of *ecological services* (or *ecosystem services*), such soil fertilization, plant pollination, water retention and other processes that aid net production.

In contrast to ecological succession, *ecological disturbance*, in its many forms, reduces complexity and increases entropy in an ecosystem in an on-going relationship with succession. Disturbance takes many forms but always involves a significant and punctuated release of energy, as in a fire or a significant wind storm, flood, land-clearing or timber harvest. Disturbances can affect ecosystems at all geographical scales depending upon a complex of factors relative to the specific event, from a fallen tree or wind-blown forest patch or a lightning strike to a catastrophic forest wildfire. These sudden interactions transform mass and energy, shaping the following succession with a complex mosaic of resource reservoirs and sinks.

The mutually-determining processes of ecological succession and disturbance shape an ecosystem through time, maintaining a dynamic relationship through which species and clades evolve. In this dynamic suspension, ecosystems transform slowly from high-entropy ecosystems to complex, productive ecosystems and then suddenly transform into simplified ecosystems. In the absence of systematic human disturbance, complex ecosystems predominate on a landscape.

Soil Food Web

In the soil food web, which includes the *detrital food web*, energy flows through plants (first-trope), then through second-trope herbivores and saprophytes (decomposers) as well as multi-trope omnivores, then through third- and fourth trope, predators and omnivores. Plants, the primary autotrophs, fuel soil food webs by providing carbon, energy, nutrients, water and ecological resources, concentrated in living tissue, root exudates and dead tissue, to a wide variety of organisms. Plants are active feeders that obtain nutrients by growing roots towards nutrient sources and by hosting and regulating a system of soil microbes in the *rhizosphere* (root zone) that in turn provide nutrients, water and protection for pests and pathogens to the plants.

Plants regulate this system by secreting *root exudates.* These complex solutions contain mostly low molecular-weight (low-Mr) compounds like amino acids, organic acids, sugars, phenolics, and various secondary metabolites in addition to some high-Mr compounds including mucilage (high-Mr polysaccharides) and proteins. Plants exudates have a number of roles, ranging from soil aggregation to communication with other organisms. For example, with exudates, plants can alter the physical rhizosphere to hold water and promote soil aggregation or regulate rhizosphere chemistry, raising or lowering pH to increase nutrient solubility. Likewise, plants use exudates to signal and attract symbiotic bacteria and fungi and provide them with nutrients and carbohydrates in exchange for increased water availability, nutrients in plant-available form (N, P, K, S, Ca, Mg, Cu, Co, Ni, Cl, Zn, and others), plant growth hormones and other resources. Exudates can also repel and confuse signaling by pathogens and repel plant roots from other species (allelopathy). Bacteria and fungi induce changes in the chemical composition of exudates, as well, and plant roots produce different exudates at different times and on regions of the root.

A wide range of organisms feed off root exudates and tissue, including symbiotic partners as well as pests and pathogens. Fungi play many important roles, including important functions in the nutrient cycle. The symbiotic fungi that exchange nutrients with plant roots (and confer resistance to pathogens) are called *mycorrhizal* fungi (MR fungi). MR fungi exchange minerals (including nitrogen and phosphorous), water, and plant growth promoting hormones for carbohydrates, sugars and amino acids. Some MR fungi can transfer sugars from one plant to other plants in the mycorrhizal network – and to other plant species. These *mycelial* networks grow throughout the soil, intensively and extensively; their complex form creates large surface-area per soil-volume, and mycelium can grow over a large area. (*Mycelium* is the living mass of a fungus, made up of networks of *hyphae*, the fungal growing points.) Thus, mycorrhizal mycelium vastly increases the effective surface-area of plant roots, while effectively connecting plants with neighboring plants in a large, mycelial network. This increased surface-area proportionately increases the plant's ability to obtain nutrients and water from its environment, effectively expanding the plant's rhizosphere and growing space. Many MR fungi can obtain nutrients such as phosphorous (anion) and potassium (cation) from organic sources like decaying plant or animal material, or inorganic sources like clay, sand or even bare rock in a process called *weathering*. Mycelia apply bending-force to the rock, creating stress on the crystal-structure, while secreting acids at the stress point in a sophisticated, gradual system. Most MR fungi seem to weather rock symbiotically with bacteria; however, because the biofilms within rhizospheres are difficult to observe and are amazingly complex, definitive scientific conclusions are yet elusive on this mechanism.

Mycologists have named seven MR fungal types, of which ectomycorrhizal and endomycorrhizal fungi are predominant. *Ectomycorrhizal* fungi, which form relationships with woody perennials, form mycelium sheathes around the root cortical cells, just inside the epidermis. *Endomycorrhizal* fungi, specifically the *vesicular-arbuscular mycorrhizal fungi* (VAM, Glomeromycota phylum), form relationships with annual plants. VAM hyphae form arbuscular structures (vein-like branched hyphae) within the host cortical cells. This phylum is the most widespread of the seven mycorrhizal types, benefits most annual-cycle plants, and promotes plant aggregation through secretion of glomalin.

Bacteria also have important roles in the soil food web, as symbiotic partners with plants and fungi and as decomposers. Bacteria commonly form symbiotic relationships with mycorrhizal fungi and both have roles in regulating rhizosphere chemistry and nutrient cycling. As with fungi, bacteria also play key roles in nutrient-cycling, interacting directly with the root or, more commonly, in association with MR fungi to decompose rocks, obtain nutrients (minerals in soluble form) and deliver them to roots. Often bacteria will provide the acids for rock weathering, yielding minerals that fungi metabolize and transport to fine root-hairs. Bacteria create *biofilms*, which are cohesive communities of bacteria living in an adhesive matrix of carbohydrates and sugars – *exopolysacchrides*. Biofilms can provide enhanced protection from pathogens, drought, and nutrient depletion while creating channels for efficiently transporting nutrients. These biofilms generally cover the entire surface of a plant. Though usually transparent, they are visible with a electron-scanning microscope.

Another important type of symbiotic bacteria transforms atmospheric nitrogen (N2) into plant soluble form (ammonia, or NH3 or its conjugate acid, NH4); these *nitrogen-fixing bacteria* are the main source of nitrogen available to the living world. Nitrogen-fixers form nodules within plant-roots to create the anaerobic conditions necessary for the transformation. In exchange for ammonia, plant roots feed and regulate the bacteria through root exudates.

Decomposing bacteria also have have an important role in the nitrogen cycle by concentrating nitrogen from organic materials with relatively low N-content, which they obtain from woody debris and leaf litter, dead root tissues, exudates, animal excrement and all dead organisms, below- and aboveground. Bacteria cells have the lowest C: N ratio of all organic material, living or dead, at 4-6, so to obtain adequate N, they must consume foods with more carbon than they can use. They release this extra carbon to the atmosphere as CO2 and transform the nitrogen and remaining carbon into cell mass. When third-trope bacteria consumers, protozoa (especially amoeba) and bacteria-feeding nematodes, consume the high-N bacteria, they obtain more nitrogen than they require in addition to the carbon and energy that they do require. These organisms release the extra nitrogen to the rhizosphere in soluble form as ammonium, NH4. This ammonium is immediately available to plant roots and other organisms. Many organisms in the rhizosphere (in addition to plants) consume NH4 from nitrogen fixers and other ammonium sources. The ubiquitous *nitrifying bacteria* transform NH4 to NO2 (nitrite) and then to NO3 (nitrate), another plant-available form of nitrogen. Further, under anaerobic conditions (which we seek to avoid), *denitrifying bacteria* complete the cycle, converting nitrates to N2 or N2O, both gaseous forms that enter the atmosphere. In addition to roles in the nitrogen cycle, bacteria and biofilms can block pathogenic and parasitic colonization. Further, cell-walls fragments from decomposed bacteria are a significant source of soil organic matter (SOM) once known as humus.

In turn, protozoa consume bacteria, thereby releasing nitrogen, phosphorous, and other nutrients. Protozoa feed mostly on bacteria, though some species feed on fungi, other protozoa, and even nematodes (microscopic worms), thereby releasing nutrients. However, more often, nematodes prey upon protozoa, as well as on bacteria, fungi, and other nematodes – and on weakened plant roots under anaerobic conditions. In turn, a variety of organisms prey upon the nematodes, including collembola (six-legged micro-arthropods, also known as spring-tails), tardigrades (eight-legged micro-arthropods), turbellarians (flat worms) and mites (arthropods), as well as predatory nematodes, large protozoa, obligate bacterial parasites, rhizobacteria, earthworms and several types of fungi. In natural settings, short of severe mechanical, temperature or chemical disturbance, these organisms are generally ubiquitous within mineral soil profiles. In container ecosystems, they must be introduced via composts.

Aerial Ecology

Herbivorous pests are second-trope organisms that feed on managed plants, introducing economic costs to an enterprise. *Pest enemies* include the third-trope organisms that feed on these second-trope organisms and many of the fourth-trope organisms that feed off pest and pest enemies as well. Third-trope pest enemies can be host-specific consumers (*monophagous*) or generalist consumers (*polyphagous*). Both monophagous and polyphagous organisms consume plant nectar, pollen and sometime plant tissue, especially fruit, in addition to prey. Further, pest-enemies often depend upon as honeydew, the modified phloem sap that homopteran pests (aphids) exude. Fourth-trope organisms, which are more likely to be polyphagous (generalists), consume second- and third-trope organisms, other fourth-trope organisms, and nectar, pollen, other tissue (like fruit) and honeydew at various developmental stages.

According to the *Resource Concentration Hypothesis*, pests favor areas with intense concentration of food supply, such as found with monoculture crops, which grow only one plant variety over large areas, providing a vast target of pests. Diverse plant composition (*species richness*), structure and function interrupts resource concentrations, confusing and distracting pests with terpenes (aromatic compounds exuded by plants as secondary metabolites produced for plant defense), visual blocking, masking and shading, and physically blocking and diverting pests from their target plants.

According to the *Natural Enemies Hypothesis*, pest enemies have a primary role in suppressing pest populations, especially in agricultural contexts. Pest enemies, especially insects, require several resources to survive and reproduce, many of them provided by plants. Flowering plants are highly important to pest enemies, providing them with nectar, pollen, alternative prey and hosts and shelter. Researchers sometimes refer to these resources as *floral benefits* or *SNAP benefits*, in reference to the acronym SNAP, for shelter, nectar, alternative prey/hosts and pollen. Plants that provide these benefits are *insectary plants*.

Ecological Agriculture

Human agriculture, with few exceptions, substantially disturbs and simplifies ecosystems and reduces biodiversity without the corresponding succession. Agriculture substitutes existing energy flows with mechanical activities like plowing, spreading fertilizers, planting seed or spraying chemical solutions on weeds, disturbing existing energy pathways and re-arranging energy and mass reserves (by thousands of miles). Unlike complex ecosystems, agriculture concentrates biomass production, reorganizing energy and resource flows from an extensive area to an intensive area and then harvests that production. This function primarily involves mechanical energy; chemical energy contributions are minimal – excrement, sweat, other gases and toxic liquids.

As such, human enterprises, which intervene and supplant native dissipative systems, generally increase entropy and decrease complexity in the ecosystem. These enterprises vastly reduce or eliminate diverse biological communities, which are highly important dissipative structures for long-term ecosystem production. Degrading these ecosystems results in substantial resource loss, physical degradation, decreased biological capacity and severely diminished natural productivity (productivity without human inputs from the larger area).

Biodiversity, even at a small scale, is necessary for establishing naturally productive ecosystems. Even with arthropods and microbes, wide species representation is better than narrow representation. The most robust, sustained systems exhibit high trophic, functional, and taxonomic diversity, and the vast majority of the smaller organisms are beneficial.

Though the vast majority of human enterprise is ecologically disruptive, agriculture can and should contribute to complexity. Preserving and contributing to ecosystem complexity, in turn, increases native productivity, decreasing the need for inputs from outlying areas. As the human role in ecosystems is to contribute work (through mechanical energy), increasing natural productivity with the aid of abstract reasoning is *smart work* – for example, careful seed selection and placement (genetic distribution) and efficient movement and transformation of resources (water, biomass, soil). Smart work obtains a much higher yield for the effort than ordinary mechanical work.

The emerging professional fields that embody smart work are *ecological engineering* and *permaculture*. H.T. Odum, a pioneer in modern ecological theory, viewed described the smart work of ecological engineering as " environmental manipulation by man using small amounts of supplementary energy to control systems in which the main energy drives are still coming from natural sources."

Ecological design is the process of embodying the smart work of ecological engineering into workable, implementable and practical designs to create productive, designed ecosystems. These systems typically use relatively low energy and material inputs, rely on natural processes, align with ecological principles and evolve with lessons learned by personal observation (including failure) and applied experimentation. Ecological agriculture involves applying ecological design and engineering to agricultural production.

Ecosystem Design, Ecological Horticulture and Permaculture

Ecosystem Design is about applying ecological engineering and permaculture design to intensive horticulture in an urban or suburban setting. It is about creating basic, practical horticultural ecosystems that align with ecological patterns and processes and increase productivity in these systems, decreasing inputs from outlying areas and optimizing labor and work.

This type of smart work focuses on a) closing loops, b) increasing biodiversity, c) maximizing the productivity of ecosystem inputs on-site, and d) making work and operations efficient. Each of these management goals will markedly improve the productive capacity of a site.

Closing loops is a term for substituting site and local resources and energy for those imported from off-site or from non-local sources. For example, making fertilizers from on-site plant and animal resources can substitute for buying fertilizers, and using sunlight instead of electric lights substitutes and on-site energy resource for buying electricity or extra photo-voltaic capacity to power lights.

Increasing biodiversity in container horticulture involves growing and preserving plants that provide benefits to arthropods and other small organisms that suppress pest populations. For example, planting permanent perennial flowering plants on the site and growing annual flowering plants amid the horticultural target species increases plant and animal biodiversity. Biodiversity, even at a small scale, is necessary for establishing naturally productive ecosystems. Even with arthropods and microbes, wide species representation is better than narrow representation. The most robust, sustained systems exhibit high trophic, functional, and taxonomic diversity, and the vast majority of the smaller organisms are beneficial.

Adopting systems to conserve and reuse water and energy, minimize fertilizer loss, and reduce the waste of horticultural resources reduces costs, increases benefits and increases short-term and long-term productivity by optimizing resource availability. For example, catching fertigation solution leachates to re-use for feeding pest-suppressing plants increases overall productivity and minimizes loss to pests.

Thus, sustainable horticulture operating with an ecological perspective will necessarily focus attention on closing loops, maximizing biodiversity and conserving and recycling resources.