The Leaf as a Sustainable and Renewable System

S. Krupanidhi[1*], N. Madhan Sai[1], Homan Leung[2], J. Kineman[3,]

[1]Department of Biotechnology, Vignan's University (VFSTRU), Vadlamudi 522213 AP, India.

[2]Department of Biology, Hong Kong Baptist University, Hong Kong SAR.

[3] CIRES & ENVS, University of Colorado, Boulder, USA.

[*]Corresponding author: Email: krupanidhi.srirama@gmail.com

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Abstract

Leaves play a critical role in the Earth's biosphere, regulating weather, renewing mineral nutrients, and maintaining biotic processes to support both flora and fauna. Leaves also form an important resource for consumers. Together, plant hosts and consumers represent complex adaptive selection. We used systems dynamic and holon models to understand the ability of the leaf to meet both host-plant and host-consumer criteria resulting in socio-ecological system sustainability. We first identified dynamic cycles facilitated by the leaf as a component of both plant and consumer systems. Each of the variables in these loops serves a critical role in the production and function of the leaf, recycling energy and matter through plant and consumer systems. Control feedback balances the system, optimizing opposing selective forces to meet criteria for viability of host-plants and usability by consumers, which return benefits through various services. We then examine the organization of the leaf-host system, revealing mutually closed sub-systems corresponding to a definition of "component life". We thus show the leaf-host relation to be a theoretically 'whole' system having positive, sustainable impacts on biomass, food, energy, etc.. These results may inform more general sustainability assessments by offering a mathematical definition of sustainability as emergent, cyclical organization in ecosystems.

Keywords: Leaf, Causal loop model, Vensim, R-Theory, Life, System Sustainability

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Introduction

The existence of life on Earth is significantly entailed with wonderfully complex relations associated with the leaf of plants, enabling both nature and much of human ecology, from food and industrial uses to ancient traditional medicine that allows us to remain healthy (Panda 2002). Leaves are considered here as life-supporting biological systems that evolved within the vascular plants (Krieger et al., 2017) during the mid-Silurian period, about 410 million years ago.

"The Leaf" is one of the three organs of vascular seed plants, taxonomically classified under angiosperms. The remaining two, namely root and stem of a vascular plant, facilitate sprouting, support and the function of a leaf to assimilate solar energy through photosynthesis and generate biochemical energy through respiration (Rossatto & Franco, 2017; de la Riva et al., 2016; Tanaka et al., 2015). Hence, leaves though looking flexible, feeble, thin and vulnerable, provide innumerable cubic meters surface area in the canopy for the absorption of blue and red wavelengths from sunlight and therefore contribute to the enhancement of biomass (Tanaka et al,. 2015). The role of the stem of a plant is to provide only skeletal support with vascular channels, whereas the root provides both gravitropism and assimilation of minerals and nutrients from soil. Thus, the leaf is a raised, inclined and suspended metabolic surface of a plant receiving ingredients such as minerals and water through roots and sunlight from the atmosphere.

The importance of the leaf is revealed by extremely subtle optimizations across most biota, which are the result of complex selection and adaptation processes that are only partially understood. Leaves are powerful systems in the functioning and regulation of biota. They provide goods and services that aid life through various pathways supporting the requirements of a vast majority of biota (Botkin 1993), for example providing molecular energy, medicinal properties, cultural uses, nutritious food, soil fertility via compost, protection, shade and shelter, and other innovations throughout the biological world. Their ecology is also highly optimized for this purpose. The area and spacing of leaves at different vertical strata, and leaf-inclination angles (which increase with the height of plants in the forest), have adaptive significance in relation to exchange of energy and transpiration necessary to maintain plant and leaf function. Relative leaf and wood areas are adaptive characteristics of a forest canopy, of which the former is always greater in the overstory canopy (Hutchison et al., 1986).

Furthermore, leaves are subject to predation and use by consumers; pressures that the leaf and its host plant must also adapt to as such consumers also adapt to the quality of goods and services provided by leaves. Some plants have evolved complex defenses, while for the most part their leaves serve beneficial uses to many other species. Consumers, which gain huge ecological benefits from leaves, have in turn evolved many services that benefit leafy plants, such as seed dispersal, plant protection, and in the human case even agriculture and genetic improvement.

While we assume complex selection is involved in the co-evolution of such intense mutualism, we wish, in this study, to explore how such selection is related to sustainability. All questions of sustainability encounter limits due to time and circumstance, thus sustainability is considered here as an 'ability', not a realized end. We also adopt the rather obvious hypothesis that plant-hosts and consumer-hosts of various leaf producing processes establish selection criteria that confer sustainability as part of an optimizing and stabilizing feedback loop. We were thus motivated to probe the dynamical and relational systems behind such loops, which may contribute to overall sustainability of leaves, host plants, and host consumers. We also wanted to know if sustainability involves principles of 'wholeness' that are evident in organisms, and if so might ecological systems share that property through similar systemic organization. We presume that organisms have the essential quality of sustainability because they adapt and evolve to survive.

Figure 1 shows varieties of leaves (A-D), the biochemical structure of chlorophyll (E), morphology of stomata (F), biomass production (G), and power generation (H), the later shown to illustrate the adaptability of leaves and their contribution to human ecology. Leaves vary by habitat; such as, desert, tropical, temperate, deciduous and aquatic environments, and there is a vast diversity with regards to the morphology, thickness, color (affording camouflage), spines (affording protection), and presence or absence of stomata to protect leaf plants from water loss through evapotranspiration (Rossatto & Franco, 2017). We give these examples to emphasize that leaves play a very complex critical role in both natural and human systems, and are thus subject to adaptive and evolutionary pressures from both. Any analysis of leaf sustainability thus needs to consider how these systems interface.

<insert Figure 1>

Figure 1: The Importance of Leaves[1]

A. Reduced leaf in Xerophyte plants seen in dry environment as an adaptation to prevent transpirational water loss
B. Small and multiple leaves of an early evolved and a low-raised Pteridophyte plant.
C. Wider leaves of advanced trees adapt to several niches and constitute a rich wealth of the flora of Angiosperms.
D. Aquatic succulent leaves developed a floating mechanism to face direct sunlight.

[1]Figures collected from a Google search and their web links are shown along with each figure:

E. Biochemical structure of a chlorophyll molecule in a leaf that absorbs blue and red wavelengths of sunlight and manufactures complex carbohydrates.
F. The minute openings predominantly found on the lower surface of a leaf are called stomata that facilitate gases (oxygen and carbondioxide) and water vapor to exchange between plants and their environments.
G. The growth of cultivated Indian green bazra plants reflecting biomass.
H. Green Industry dedicated to generate power from biomass.

Methods

We chose a dynamic biological system, the leaf of a plant, as an example to conceptualize efficient causal loop models, and then to examine the contextual organization of causal loops to explore sustainability by analogy to other living system types (organisms) known to be self-sustaining through ecological adaptation and evolution. We used two methods of systems analysis: (a) *Vensim*™, a graphical interface tool[2] that we used to analyze feedback dynamics (efficient loops), and (b) R-theory, a holistic framework that we used to identify contextual dependencies (functional loops).

Vensim software is a modeling platform designed for economic systems (Jetha et al., 2015), climate simulation for decision-makers (Maani, 2013), and simulation models in growing organizations (Laura & Farzana, 1998) among many other uses. *Vensim* also has the capability of simulating dynamics, and indeed one can explore how variables correlate. We began with analysis in *Vensim* to identify characteristic dynamics of a complete leaf cycle and to present an intuitive picture of the intricate roles and importance of the leaf system in causal loop diagrams.

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[2] The Vensim software tool is a Ventana Systems simulation product that facilitates accurate analytical analysis of a desired model dynamics (Ventana Systems Inc. Vensim 2013. Available from: http://www.vensim.com).

Sustainability is as much a matter of existence of a system and its functions, as it is a matter of operation of that system when those functions exist. Accordingly, we explored generative contexts focusing on the critical functions identified in the dynamical study and correlating them with known general functions associated with organismic life. The mathematical biologist, Robert Rosen, defined the causal organization of a self-contained life form as an "M-R System" closing three internal functions aside from those relating it to the environment (Rosen, 1991). Rosen's functional closure in organisms was extended in *R-theory*(Kineman 2016) to include environmental entailments, thereby identifying four kinds of M-R organization that correlate with the general types of life found on Earth (Kineman 2011, 2017). The "4th type" of M-R life, ***Protobiota*** (Hsen-Hsu, 1965), in terms of M-R functions, is a "self-selection" strategist requiring a host. This is the type of life correlated here with the strategy of the leaf. *R-theory* thus provides an analytical framework to look at natural ways in which a system can exist as a whole, self-sustaining, cycle of causes. In such cycles, dynamics and contextual dependence are mutually inverse entailments such that their closure with each other can be formally represented as inter-related "holons" (Appendix I). We applied this logic using worksheets (in Edson *et al.* 2016) and drawing the results in Powerpoint™.

Results

Results were obtained by a two-step process of first identifying a characteristic cycle in the dynamics of the leaf-host system, then analyzing further to infer contextual causes of those dynamics and the system's strategic organization.

Dynamical Process Model (*Vensim*™)

The interrelations between variables ("nodes" in *Vensim* terminology) are visualized in through a series of arrow illustrations ("edges") representing dynamical causes and labeling the initial variables chosen to depict dynamic processes in the leaf system. Dynamics are shown with a solid line, and balancing (control) feedback from recycling (via two pathways) to growth is shown with a dotted line.

<Insert Figure 2>

Figure 2: Complex processes by which leaves sustain and renew life. R= Reinforcing loop; B= Balancing loop (*Vensim* Model)

Table 1 collates the variables we chose giving examples of their roles in various loops of the leaf-host cycle and the multitude of selective factors being balanced in the system.

INSERT TABLE 1 HERE

System Dynamics were modeled in *Vensim* (**Figure 2**) to depict causal loops. We described eight reinforcing (material) processes (R1-R8) related to leaf production and use (in both leafy plant and consumer systems, including human). Within the plant-leaf system there are two loops combining to provide metabolic services via photosynthesis and respiration (R 1-3, 6-8). Although not shown in the diagram, there is also sociological facilitation of these processes, as in agriculture (Figure 1.G), greenhouses, etc. On the return side, senescent material (R5) is recycled to nature via compost, also with a parallel path (R4) through consumers (e.g., Figure 1.H). There is also an implicit control feedback (balancing loop) from senescence to growth (B1), which also has a parallel control feedback from consumption to growth in the consumer system (B2, not shown). Growth is thus controlled by the combined requirements for plant viability and consumer use. We considered only variables (nodes) and their inter-relationships thought to be characteristic or processes that are essential for sustainability, recognizing that there are many more associated processes not considered. Note also that Figure 1 is not a stock and flow diagram, but a causal diagram, attempting to explain material changes in terms of functions.

A leaf is considered as the most important organ of the plant as it provides a platform to assimilate and transform solar energy (Tanaka et al., 2015). Furthermore, the well-being of all biota reflects leaf performance in recycling energy and nutrients back to the biosphere. Input of sunlight, amplified by surface area of the leaf and entrapped by chlorophyll (biochemical synthetic machinery, Figure 1.E), drives the “light cycle” of energy production (R1). Stomata (Figure 1.F) are involved in regulating the absorption and elimination of water through transpiration to maintain temperature and hydration (most water supply is met by absorption through the roots). Additionally, stomata are responsible for the flux of gases such as oxygen and carbon dioxide for photosynthesis (R6) and respiration (R7), the “dark cycle” of energy production. Light and dark cycles combine to provide usable bio-energy in the plant system, necessary for growth. Invariably, the energy must be recycled. The R4 loop depicts recycling of biomass generated by the leaf system via senescence, which ultimately enriches soil fertility, whereas R5 shows a parallel loop recycling via consumers. The balancing loops B1 and B2 are not material processes, but regulators of the overall cycle via senescence and consumer use, respectively. Senescence encourages growth by freeing resources for production of new leaves, while consumption retards it by removing the plant’s metabolic power source. The leaf must then optimize these competing selective forces to meet both needs; plant growth and consumer use. Thus we have a picture of the leaf as a complex relation between two adaptive systems.

From this analysis we learn, for example, that R1, R3 and R4/5 reinforcing loops comprise related variables shown in relation with the growth of biomass; while keeping the other two variables, namely leaf surface and sunlight in equilibrium. Additional supplements in the growth of biomass are carbon dioxide (R7), oxygen (R6) and water (R2). The "process of growth" is always cyclical and never to be perennial (Botkin 1993); therefore, the balancing loop2 (B1 and B2) and reinforcing loops such as R4, R5, R6 and R8 show that the recycling processes for sustenance and rejuvenation of leaves also maintain the necessary habitats. It is clear, then, that the system is maintained through such efficient causal loops. Most studies would stop here, saying that these closed loops form "naturally" and are sustainable; but there is nothing in the dynamics to explain why it is sustainable, only that it possesses these efficient cycles that are apparently sustained by the balancing loops. Indeed, the balancing loops lie outside efficient and material causes that dynamical models are restricted to.

Relational Holon Model in *R-Theory*

The next question we wanted to ask was why such a dynamical system is sustainable; in other words, what principle of sustainability accounts for the overall system organization as a persistent pattern in nature? Indeed we have hints in the balancing loops, but to explore them further we turned to *R-Theory*, which presents a framework for analyzing system sustainability in terms of Aristotle's four causes involved in the relation between dynamics and context (Kineman, 2011; 2012). Sustainability is a question of contextual existence as much as it is a question of dynamical operation. Whereas dynamics tell us what a system does, including feedback loops; contextual relations can tell us how it generates and sustains its functions through strategic organization. These two aspects of the system are related in a whole (for example, ecology is filled with discussions of life strategy in relation to behavior).

According to a new theory of "life Itself" proposed by the mathematical biologist Robert Rosen, the minimum requirement for a system to be alive is that it have a *closed cycle of efficient causes* (Rosen, 1991). This can be achieved with three basic functions for life: metabolism, replication, and repair. Rosen called this kind of causal closure a "Metabolism-Repair (M-R) System" and diagrammed it using Category Theory. Further analysis (Kineman, 2011) showed that an M-R system considered together with its environment (from which it cannot be separated), establishes a fully closed system of five functions (and components that produce them), adding two that relate the system to its environment. These additional functions correspond to phenotype behavior and genotype selection. Subsequent work revealed that there are four ways to achieve such closure when considering the minimum contextual relations (the way their M-R functions are organized and entailed with each other) for basic forms of life. Three of those basic types can be identified with the three most basic cellular (organism) types classified by taxonomists; strategically corresponding to each of Rosen's M-R functions. These are: ***Bacteria*** (replicative strategist), ***Eukaryota*** (metabolic strategist), and ***Archaea*** (repair strategist) (Kineman, 2011). In the course of the present research we were able to identify a fourth type implied by the holon logic, which corresponds to a 'selection strategist'; a type that induces its own selection in another system but at the cost of requiring the host to perform its replication function (Kineman, 2017). This type was also identified in the taxonomic world to classify proto-life. It was given the name ***Protobiota*** (Hsen-Hsu, 1965) because its functions are necessarily incomplete with respect to autonomous organisms. It thus exists and achieves the necessary closure, as a "component" form that can be benevolent or parasitic[3]. Here we are considering the leaf as a benevolent case.

3 As with a virus, which may also rely on the host for metabolic functions.

We looked at the Leaf-Plant-Consumer system in terms of R-Theory's defining entailments in the host according to the protobiotic "component" life type. The selective strategist relies on a host to replicate it (thus selecting it). In this case, its generative host is a leafy plant, but consumers can be facilitative hosts, enabling its replication by returning services and subsidies. We are thus considering leaves produced by their plants and used by consumers that provide important functions related to their replications a single complex, adaptive system. This required refining the details of the loops identified earlier, to conform to relational holon logic (which follows Category Theory).

Figure 3 and **Table 2**, show the general holon cycles that produce, use and recycle leaves via their host plants, various consumers, and decomposition processes. Each cycle constitutes a *sub-system* and together they establish the whole system as a sustainable set of entailments. The sub-systems are numbered L1-L4, and since they form a cyclical hierarchy, they form a 5themergent system (L-5) at the next holarchical level. L-5 is the cycle for leaf-host sustainability, involving: (v) Leaf Usability, (Φ) Leaves, (*f*) Compost, (H) Host Requirements. The leaf as genotype (Φ) represents the complex system's generative code that is subject to the combined forces of both host plant and host consumer selection. These relations reduce to a very basic specification of sustainability corresponding to the primary leaf-host holon, described as L-5; which emerges from closure of the other four.

We must remember, of course, that the model is a generality observed among a very complex set of relations that extend far beyond what is shown. For example, metabolism combines photosynthesis and respiration, L-1a and L-1b, as L-1. These cycles could be analyzed separately. Recycling via plants and consumers are shown as two sub-cycles representing balancing criteria (complementary processes) for sustainability of the leaf in nature. It is the nature of holon analysis that we can focus on whole cycles of interest, showing or hiding various portions of other cycles involved. In this case the environment/biosphere (L0) contains many processes that maintain resources (a), including those that are part of both the organism and the biosphere, as shown for the recycling of compost and the production of glucose. Nevertheless, we can identify the essential processes within the four causalities that constitute a 5th-level whole (living system) as the focus of this analysis, with many more supporting processes than shown here in other sub-systems. For example the entailments responsible for the natural elements and their entailments are not detailed.

<Insert Figure 3>

Figure 3: Leaf-Plant-Consumer Sustainability Relations

Symbols in Figure 3 follow the conventions:

- Dashed lines: Contextual components and mappings
- Solid lines: Dynamical systems and their mappings
- Double box border: Phenomena System
- Single box border: Structure
- Dash-dot box border: Contextual System
- Dashed box border: Function
- Different colors: Each of the six cycles (4 M-R cycles, the system itself, and the host environment)

Table 2: Variables in the Leaf-Host Relation.

<Insert Table 2>

The existence of both an emergent living system (L-5) and requisite universal nature (L0) emphasizes the holarchical nature of this form of analysis, which shows both emergence (the leaf-host system) and immanence of natural order (existence of nature).

Indeed, the theoretical closure of the leaf-host system depends, ultimately, on universal closure in which matter is converted to energy (and, of course, many other transformations). But to emphasize: the power of this kind of analysis is that it allows us to focus on local wholeness and sustainability as a quality of the organization of systems, and to analyze the critical functions for wholeness and thus sustainability.

Leaf-Plant-Consumer Holon

Figure 4 shows the emergent holon for the Leaf-Host component strategist. The relations are the same as in Figure 3 and Table 2, but we are now looking at the essence of its sustainability as a hosted life form. The elements of this cycle are correlated with their general archetypal meanings in **Table 3**.

<Insert Figure 4>

Figure 4: Leaf-Host "Component" Holon

Table 3: Holon Definitions (General and Specific)

INSERT TABLE 3 HERE

Discussion

Our approach went beyond system dynamics to explore higher causes involved in how the system is organized for sustainability; that is, the contextual dependency of its critical functions within a mathematical and biological concept of sustainability. The *Vensim* systems dynamics model revealed an organization that is analogous to Rosen's efficient closure diagram of a living system (Rosen, 1991, Figure 10.4) which also identifies closed loops of efficient functions in a sustainable system. Such dynamics, however, do not tell us how the system produces its own functions, which it must do to be truly sustainable through adaptation and evolution, as organisms are, and thus to exist as a self-sustaining identity. To find an answer to this question we turned to R-theory.

Questions of existence necessarily involve contextual causes; that is, entailments across scale between bounding and bounded systems (as in the concept of the ecological niche). Dynamical causes are "efficient" entailments involving *efficient* and *material* causality)[4], whereas contextual (or boundary) relations are "functional entailments" (Louie, 2013) involving *final* and *formal* causality. The later are required to explain how functions arise and thus how certain kinds of systems can establish their existence.

These models confirm a view of the leaf as a sustainable active component and perhaps niche constructor in host systems. From this perspective, the leaf is self-selecting by stimulating positive feedbacks in its host systems for its replication. Selection of leaf characters takes place in the leaf-producing plant as well as in consumers, because of leaf suitability for various host purposes. Consumers offer positive feedbacks (not detailed), such as depositing seeds, establishing agriculture, protecting plants, removing competitors, even conscious genetic improvement in the case of agro-industry.

Clearly, the component-host system is like an organism in its self-sustaining (self-entailed) organization. The component-host M-R model realizes a sustainable cycle that is alive according to the M-R definition. If we were to speak of the leaf as a strategic agent, the model shows that it is co-opting functions of the host plant, and indirectly

[4]From Aristotle's general view of categories and causality.

consumers, to perform its replication function – to grow out viable and useful leaves, thus meeting two selection criteria. Growth replicates leaves, which in this system represent the genotype of a multiply complex hybrid life form. Leaves are thus acting analogously in the ecosystem, to DNA in organisms (as the encoding of functional relations required to meet host needs); i.e., in the same sense that genes characterize organisms. But there is an unexpected twist.

The genotype (conventionally associated with the structure element of the holon on the right) in this case is not the leaves that are selected for use, but those that remain on the plant to eventually senesce, fall or otherwise form leaf biomass; to decompose as compost, and be recycled to nature to refuel and supply the cycle. It appears that selection for plant viability and selection for consumer use are mirror images that must be balanced for sustainability. In other words, the consumer system is indeed parasitizing host plants for their highest quality leaves, and use of leaves can be at odds with plant requirements; however, the system turns this disadvantage to advantage by subsidies returned from the human host: encouraging growth, regulating harvesting, and providing suitable niches. Such negative feedback control is generally stabilizing in systems, for example in control systems. Here it translates to ecological sustainability. Overall, the plants benefit from being used, and users benefit from keeping the plant viable.

The leaf is thus optimizing a combination of selective and counter-selective pressures. To the extent that the leaf realizes a sub-set of the plant genome, it is optimizing its presence in that genome. With regard to a consumer system, the leaf itself carries the genetic characters for the cycle of leaf use by consumers. Suitability of leaves for consumers translates into positive selection for leafy plants, and vice-versa. Are hosts selecting leaves or are leaves selecting hosts? In a sustainable cycle, it is both.

We can examine relations in even more detail by looking at implicit system closures. This is an extremely valuable aspect of holon analysis: holarchy means that specific complex relations can be singled out from any level, leaving all other relations implicit. We provide an example in **Figure 5**, using one of the student worksheets presented in a recent text on “Systems Research”(Edson et al., 2016). This example shows final closure between leaf production and leaf use (L2 and part of L3), distinguishing in this case between Host Consumers and Host Plants. “Final closure” means exchange of implicit ends (naturally established by prior conditions in causal loops). The implications of leaf production thus become requirements in the user cycle, and the implications of optimizing consumer applications become requirements in the ecology of leafy plants. Implicit ends are thus represented in the systems’ internal models (contextual entailments).

Using only basic holon cycles, Figure 5 shows two intersecting cycles, one for production of leaves by plants (responding to implicit environmental and consumer selection pressures) and the other for use of leaves by co-adaptive consumers (animals, humans, insects, societies, etc.). Environmental selection remains implicit in both cycles. We are looking at two sub-sets of adaptation pressure, each of which acts oppositely on the ecology and evolution of the leaf. The combination of these two cycles is complex, as confirmed theoretically by their ‘closure’ with each other in at least one quadrant. Accordingly, there are four diagrams like this (or combinations thereof) that we can draw as specific mutualisms, showing material, efficient, formal, and final closures; perhaps to assess their strengths versus each other and effect on sustainability, which must be calibrated empirically.

Interpretation of the meaning of each element was a subjective exercise, but the logic of how each archetypal element relates to the others is not. Thus, subjectivity means only that different whole systems can be described if the meanings are mutually adjusted for overall consistency. In a sense, it is like juggling a game of 20 questions where the outcome may not be exactly known. One may start out trying to describe one system and, following the logical entailments, but may end up describing another; then adjustments can be made to get closer to the system of interest. Theoretically, even a system accidentally described will be a natural one if consistency of the holon logic is enforced; and in such an exercise, discovery is possible.

<Insert Figure 5>

Figure 5: Worksheet Example of Causal Closure between Leaf Production and Use

Conclusions

Leaves can be viewed as a key component in sustainable natural and human systems because they support life and have many uses. The models help us understand *how* this is so in terms of dynamics and *why* it is so in terms of organization. H*ow* is through reinforcing feedback loops operating in time and space, and *why* is because the leaf represents a component life-form, the "selection strategist", which is one of the most basic self-sustaining types of life found generally in nature. As a "latent" archetype (Landauer & Dumais, 1997; Poli, 2011), such order is complementary to dynamical feedbacks in the sense of a system attractor. The leaf is subject to separate and opposing adaptive pressures from its host plant and from consumers, thus having to optimize services in a complex selective environment. By meeting both requirements the leaf ensures its replication within or with the assistance of its hosts.

The method of dynamical systems analysis in *Vensim* is helpful for exploring, and even simulating, efficient correlations between variables of a complex system and identifying closed loops of "efficient" causation. Through such modeling we were able to demonstrate the highly intricate nature of the leaf as a critical component in both natural and human systems, providing beneficial services to all biota in a complex and wonderful set of adaptations.

Deeper analysis using *R-theory* was needed to uncover the organizational pattern that may be responsible for sustainability. By working back and forth between the various model perspectives we could get semantic closure, and thus to find the precise elements of the sustainable cycle. This successful demonstration provides us not only with a deeper understanding of the importance of leaves in the Earth's biosphere, but also with a logical candidate for definition of systemic sustainability as a scientific and mathematical concept. Prior to this, sustainability has mainly been approached as a policy agenda, causing controversy and confusion.

Treating "consumers of leaves", as "hosts of leaves"; and thus, considering leaves themselves as a form of genetic code at this generalized level, is not meant metaphorically, but as the natural role that the leaf plays at this level of system organization, literally encoding the models that confer sustainability within its genome. Consumers are providing replication assistance to the leaves that are used, balancing the effect of their removal. Leaves themselves (defined by their genotype) are, in turn, defining the existence and operation of the system by their ability to optimize both criteria. Selection, in this case, involves retaining what is not harvested by consumers to grow out more of what might be useful to both host plants and consumers. All this becomes recorded in the genotype through selection.

The final holon model in Figure 4 represents a minimum entailment for sustainability, so breaking one part of the chain means this Leaf-Host cycle will degrade. As with all four living system types, however, the cycle is self-repairing. Repair, in this case, takes place via recycling. Each of the four sub-cycles, representing metabolism, repair, replication, and selection, and their strategic organization, provide essential information for socio-ecological management, even before assessing the relative dynamics between variables. Knowing the dynamics may help us optimize systems, but it does not ensure that they will exist unless we consider the contextual entailments required to generate their functions and to provide the appropriate selection and control feedbacks. We argue that such knowledge has been tragically missing for lack of methodology, and that exclusive focus on quantitative aspects of systems in science and ecosystem management (leaving context management to policy models) has led to crises of over-exploitation, degradation of essential cycles, and general lack of mutual benefit between humans and nature.

Filling this gap is especially important as we enter a world situation where many systemic boundaries are being challenged. The success of the present approach suggests a precise logical definition of sustainability in category mathematics. Ecosystem management as well as human performed bioengineering can use these methods and design accordingly. Throughout this analysis, we explained phenomena that are already well-known by science, except for why the observed processes occur (aside from a general concept of co-adaptation). No theory has yet been accepted as to what explains sustainably. That mystery may be resolved by a deep understanding of natural order as demonstrated here, by analogy with organisms.

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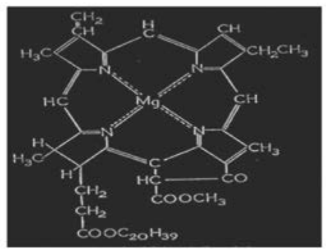
Figure 1:

A. Xerophyte reduced leaf-
Source: Images-
Thumbs-thefullwiki.org

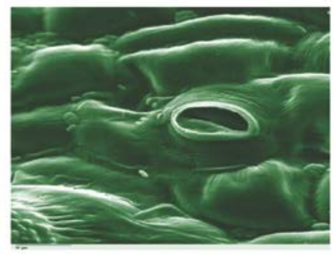
B. Pteridophyte leaves-
Source:myfreewallpapers.net

C. Angiosperm leaves-
Source: ssmrocks.com

D. Aquatic plant leaves-
Source: Phyang.org

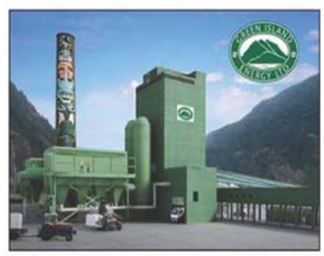


E. Chlorophyll-
Source: www.daviddarling.info



F. Stomata-
source: upload.wikimedia.org

G. Biomass-
Source: www.renergyteda.com



H. Power generating industry
using biomass-
Source: greenilandenergy.com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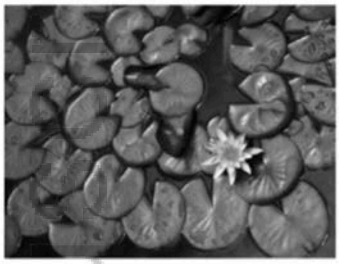
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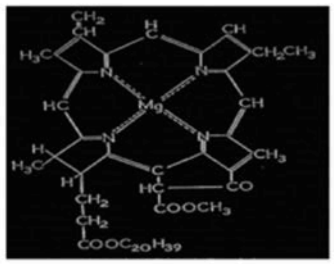
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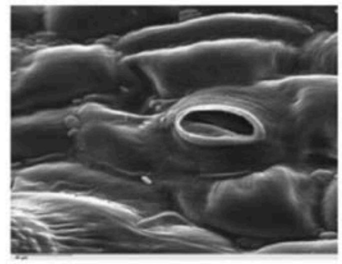
F. Stomata-
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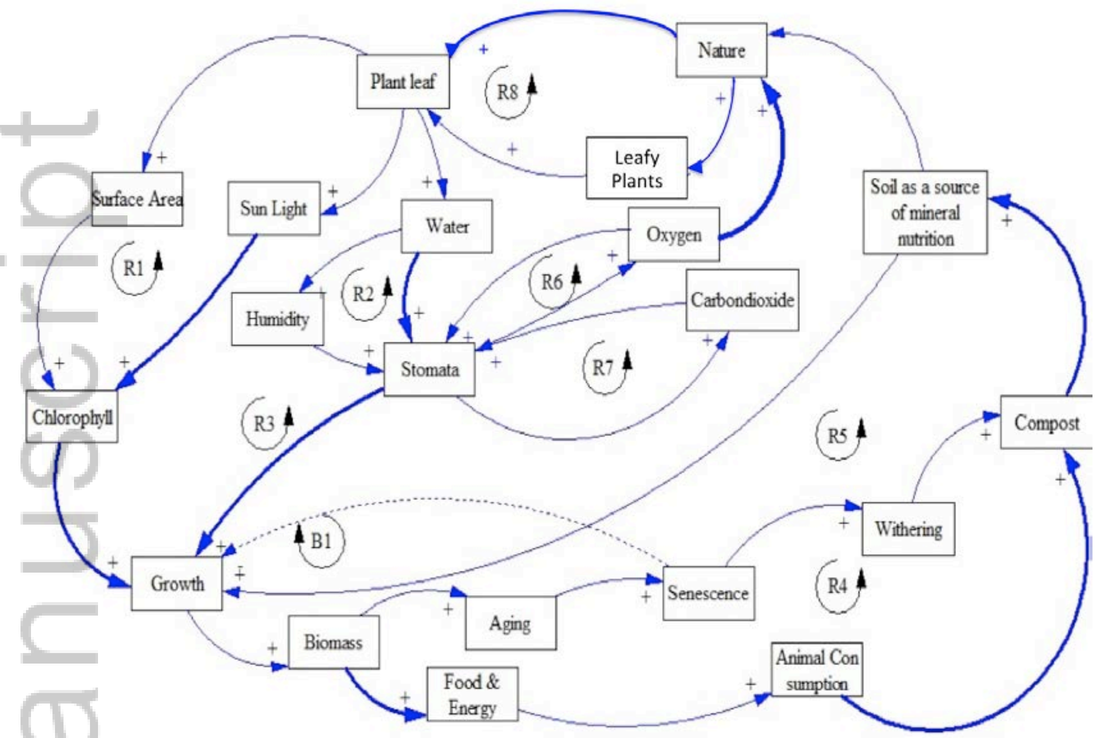
Figure 2:


Nature
Plant leaf
R8
Leafy Plants
Surface Area
Sun Light
Water
Oxygen
Soil as a source of mineral nutrition
R1
Humidity
R2
R6
Carbondioxide
Stomata
R7
Chlorophyll
R3
R5
Compost
B1
Withering
Growth
Senescence
R4
Aging
Biomass
Animal Con sumption
Food & Energy

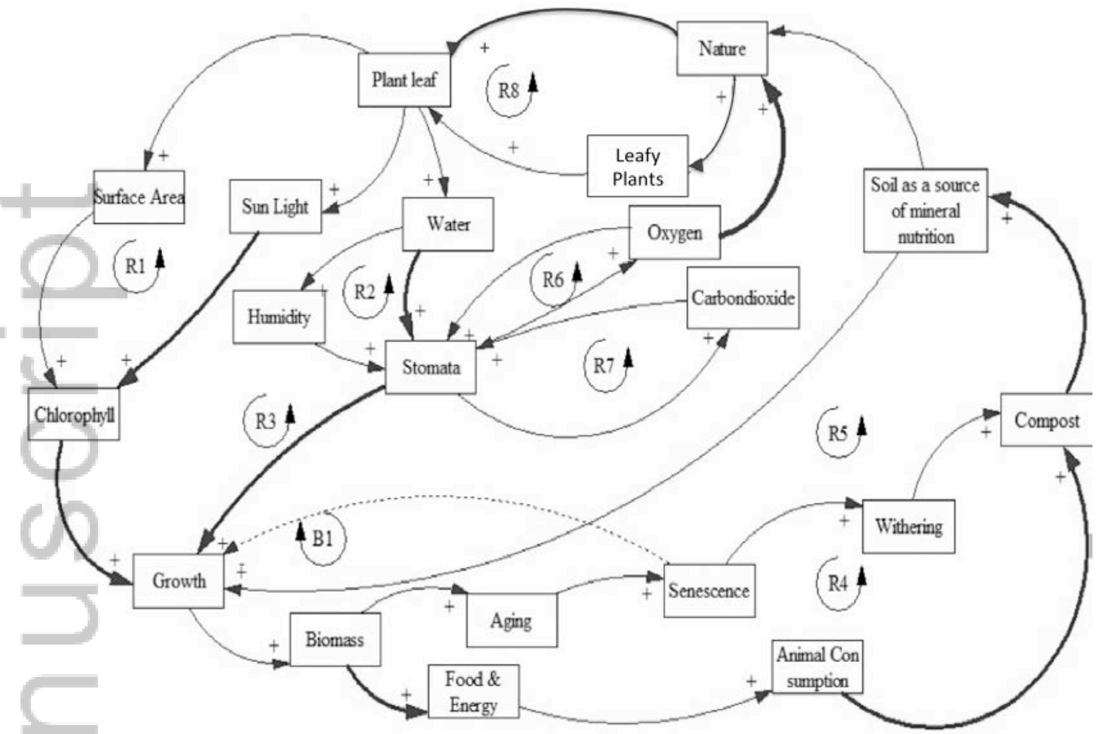

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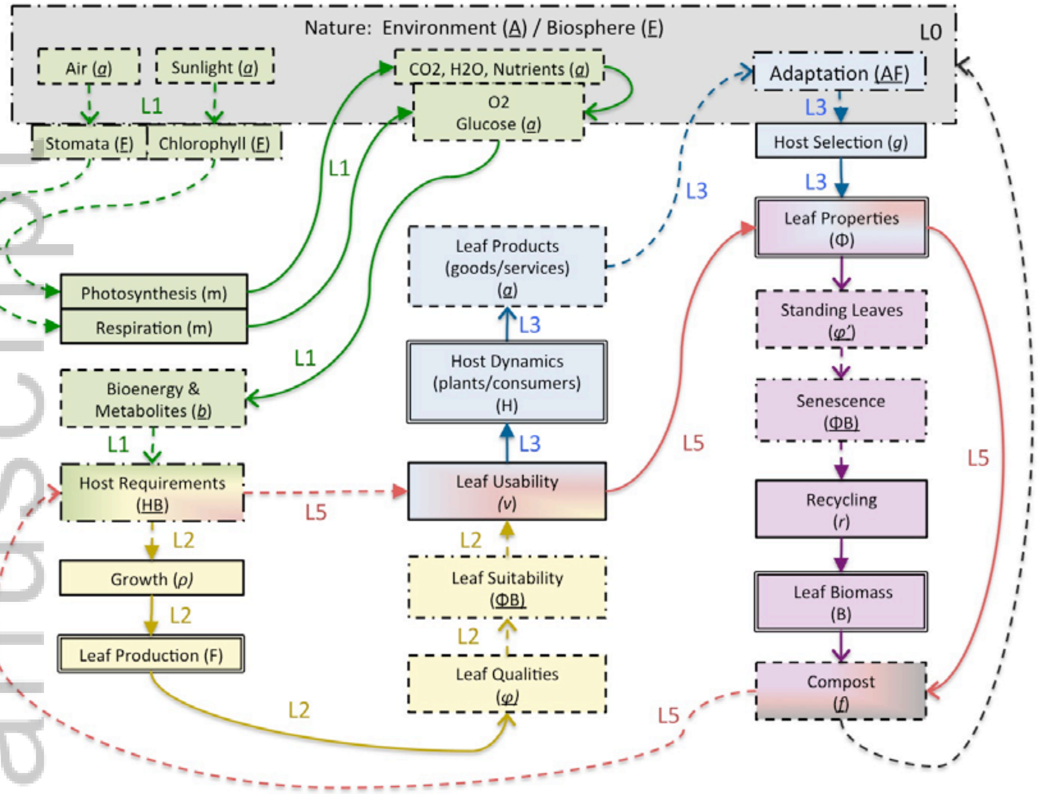
Figure 3:



Nature: Environment (A) / Biosphere (E)
L0
Air (a)
Sunlight (a)
L1
Stomata (E)
Chlorophyll (E)
CO2, H2O, Nutrients (a)
O2
Glucose (a)
Adaptation (AF)
L3
Host Selection (g)
L3
Leaf Properties
(Φ)
L1
L1
Photosynthesis (m)
Respiration (m)
Leaf Products
(goods/services)
(a)
L3
Host Dynamics
(plants/consumers)
(H)
L1
Bioenergy &
Metabolites (b)
L1
Host Requirements
(HB)
L5
L2
Growth (ρ)
L2
Leaf Production (F)
L2
L3
Leaf Usability
(v)
L2
Leaf Suitability
(ΦB)
L2
Leaf Qualities
(φ)
L5
Standing Leaves
(φ')
Senescence
(ΦB)
Recycling
(r)
Leaf Biomass
(B)
Compost
(f)
L5
L5

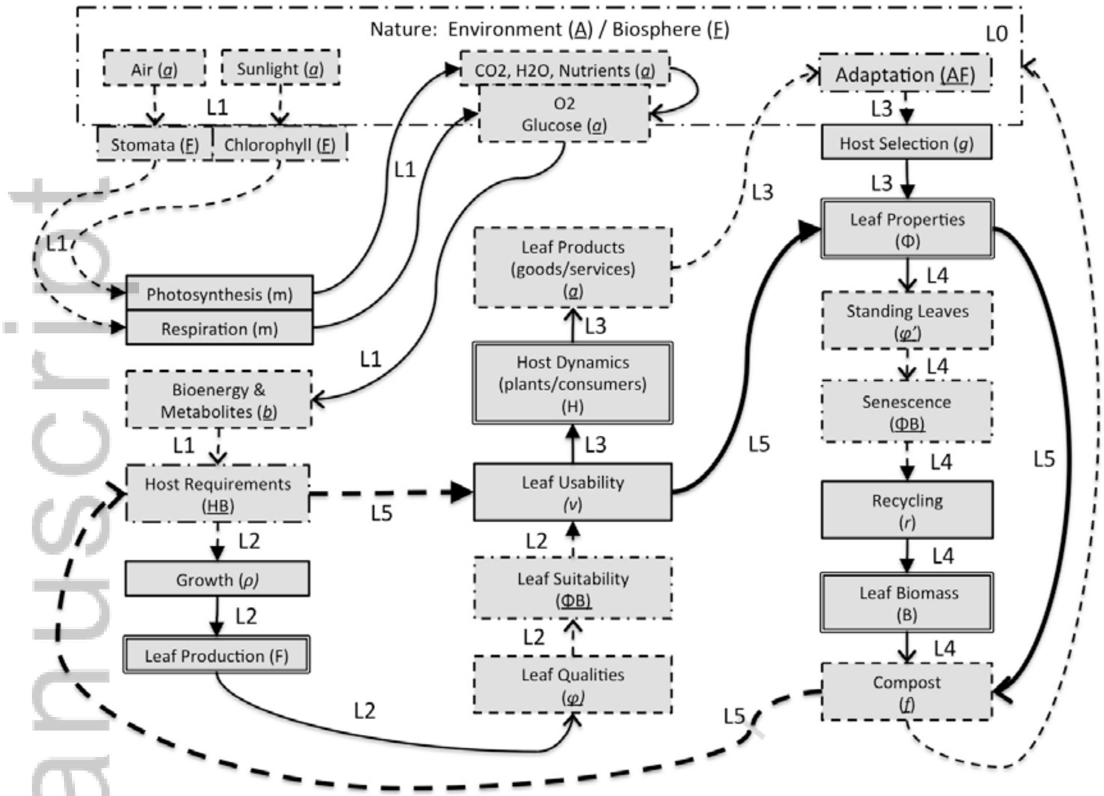


Table 1. Variables within the leaf system reflecting roles and selective factors.

Variables	**Roles**	**Loops**	**Selective Factors**
Plant leaf	Host sustenance, habitat, recycling, and other services	R1 R3 R8	Plant viability, consumer mutualism
Surface area	Interaction with environment	R1	Complex niche relations
Sun Light	Dissipative energy input	R1	Energy conversion
Chlorophyll	Assimilate blue/red light	R1 R3	Photosynthetic efficiency
Water / Humidity	Metabolic solvent and thermal regulator	R2 R3	Water availability, temperature, altitude
Stomata	Gas exchange	R2 R3 R6 R7	Leaf function and respiration efficiency
Growth	Structure/function renewal	R3 R5 B1	Biomass requirements
Biomass	Organic matter	R4 R5 B1	Goods and Services

Aging, Senescence	Metabolic loss of function, Impairment of growth	R4 B1	Timing for optimality of function vs. renewal
Withering	Recycling lifeless material	R4	Biological demand
Compost	Rejuvenates life-cycle	R4 R5	Nutrient quality
Food and Energy	Support life	R4 R5	Leaf quality
Oxygen	Oxidation to derive energy	R6	Photosynthesis in biosphere
Carbondioxide	End product of oxidation of biological foods and an ingredient for green energy	R7	Source for photosynthesis
Leafy plants	Host for Leaves	R8	Balance of nature, growth, adaptation, and selection
Organic Consumers	Trophic pyramid, goods and services to plants	R4 R5	Consumer population and health

Table 2:

Loop ID	Participating Variables	
L0 (R0)	**Nature**	
	Strategic Resources (*a*, *f*)	(Recycled Elements)
	Natural Order (AF)	(Systems Sustainability, e.g. L1-L5)
	Natural Functions (*implied*)	(Physical and Ecological Services)
	Environment and Biosphere (A, F)	(Dynamic Mechanisms)
	Physical (*a*) and Living (*f*) forms	(Environment, Biosphere)

Loop ID	Participating Variables	Loop ID	Participating Variables
L1a (R1, R2, R3)	**Light Cycle**	**L1** (R1, R2, R3, R6, R7, R8)	
	Sunlight (*a*)		
	Chlorophyll (/area) (F)		
	Photosynthesis (*m*)		**Metabolic Energy Cycle**
	CO_2, H_2O, nutrients (A)		Compost (*f*) / Nature (R0)
	Energy (glucose) (b_0)		Leaf Performance (stomata and chlorophyll) (F)
	Bioenergy/Metabolites (*b*)		
L1b (R6, R7, R8)	**Dark Cycle**		Photosynthesis/Respiration (*m*)
	Air (*a*)		Natural Elements (*a*)
	Stomata (/area) (F)		Bioenergy & Metabolites (*b*)
	Respiration (*m*)		Functional Requirements (H)
	O_2, glucose (*b*)		
	Bioenergy/Metabolites (*b*)		
	Host Requirements (H)		
L2 (R4, R5, B1)	**Replicative Growth Cycle**	**L3** (R4, R5, B2)	**Adaptive Selection Cycle**
	Host Requirements (HB)		Leaf Usability (*v*)
	Growth-Subsidy (*ρ*)		Host Dynamics (plants/consumers) (H)
	Leaf Production (F)		Leaf Products (goods/services) (*a*)
	Leaf Qualities (*φ*)		Adaptation (AF)
	Leaf Suitability (ΦB)		Host Selection (*g*)
	Leaf Usability (*v*)		Leaves (Φ)
L4 (R4, R5, B1,	**Repair/Replacement Cycle**	**L5** (R8)	
	Leaves (Φ)		**Leaf-Consumer Behavior Cycle**
	Standing Leaves (*φ'*)		Host Requirements (H)
	Senescence (ΦB)		Leaf Usability (*v*)

B2)	Recycling (decomposition) (*r*)		Leaf Properties (Φ)
	Leaf Biomass (B)		Compost (*f*)
	Compost (*f*)		

Loop ID	Participating Variables	
L0 (R0)	**Nature**	
	Strategic Resources (*a*, *f*)	(Recycled Elements)
	Natural Order (AF)	(Systems Sustainability, e.g. L1-L5)
	Natural Functions (*implied*)	(Physical and Ecological Services)
	Environment and Biosphere (A, F)	(Dynamic Mechanisms)
	Physical (*a*) and Living (*f*) forms	(Environment, Biosphere)

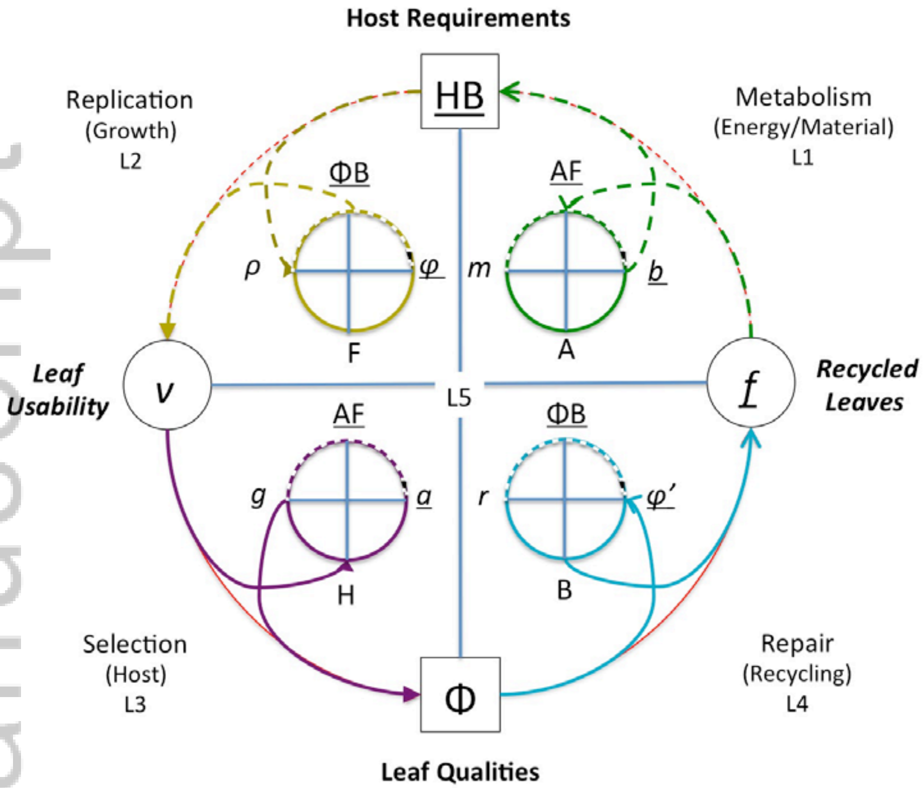
Loop ID	Participating Variables	Loop ID	Participating Variables
L1a (R1, R2, R3)	**Light Cycle**	**L1** (R1, R2, R3, R6, R7, R8)	
	Sunlight (*a*)		
	Chlorophyll (/area) (F)		
	Photosynthesis (*m*)		**Metabolic Energy Cycle**
	CO_2, H_2O, nutrients (A)		Compost (*f*) / Nature (R0)
	Energy (glucose) (b_0)		Leaf Performance (stomata and chlorophyll) (F)
	Bioenergy/Metabolites (*b*)		
L1b (R6, R7, R8)	**Dark Cycle**		Photosynthesis/Respiration (*m*)
	Air (*a*)		Natural Elements (*a*)
	Stomata (/area) (F)		Bioenergy & Metabolites (*b*)
	Respiration (*m*)		Functional Requirements (H)
	O_2, glucose (*b*)		
	Bioenergy/Metabolites (*b*)		
	Host Requirements (H)		
L2 (R4, R5, B1)	**Replicative Growth Cycle**	**L3** (R4, R5, B2)	**Adaptive Selection Cycle**
	Host Requirements (HB)		Leaf Usability (*v*)
	Growth-Subsidy (*ρ*)		Host Dynamics (plants/consumers) (H)
	Leaf Production (F)		Leaf Products (goods/services) (*a*)
	Leaf Qualities (*φ*)		Adaptation (AF)
	Leaf Suitability (ΦB)		Host Selection (*g*)
	Leaf Usability (*v*)		Leaves (Φ)
L4 (R4, R5, B1, B2)	**Repair/Replacement Cycle**	**L5** (R8)	
	Leaves (Φ)		**Leaf-Consumer Behavior Cycle**
	Standing Leaves (*φ'*)		Host Requirements (H)
	Senescence (ΦB)		Leaf Usability (*v*)
	Recycling (decomposition) (*r*)		Leaf Properties (Φ)
	Leaf Biomass (B)		Compost (*f*)

	Compost (*f*)		

Table 3: Holon Definitions (General and Specific)

Generic M-R System Elements	**Leaf-Plant-Consumer Elements**
Whole sub-systems:	
Φ – *Genetic*	Leaf properties
F – *Strategic*	Leaf production
A – *Resource*	Natural Resources (CO2, H2O, etc.)
B – *Corporal*	Leaf Biomass
H –*Host (or E – Environment)*	Leaf Hosts (Leafy Plants and Consumers)
Contexts:	
ΦB –*Existence (model)*	Suitability & Senescence
AF –*Strategy (model)*	Self-Selection
H or E – *Adaptive Context*	Host Requirements
Functions:	
m – metabolism	Photosynthesis & Respiration
r – repair	Recycling
ρ – replication	Growth
g – selection	Host Selection
v –behavior	Leaf Usability
Structures:	
a –resources	Leaf Products (goods and services)
φ – genetic code	Leaf Qualities
φ' – selected code	Standing Leaves
b –corporal structure	Bioenergy &Metabolites
f – repair structure	Compost (Recycled Leaves)

Figure 4:



Host Requirements
HB
Replication
(Growth)
L2
Metabolism
(Energy/Material)
L1
ΦB
AF
ρ
φ
m
b
F
A
Leaf
Usability
v
L5
f
Recycled
Leaves
AF
ΦB
g
a
r
φ'
H
B
Selection
(Host)
L3
Repair
(Recycling)
L4
Φ
Leaf Qualities

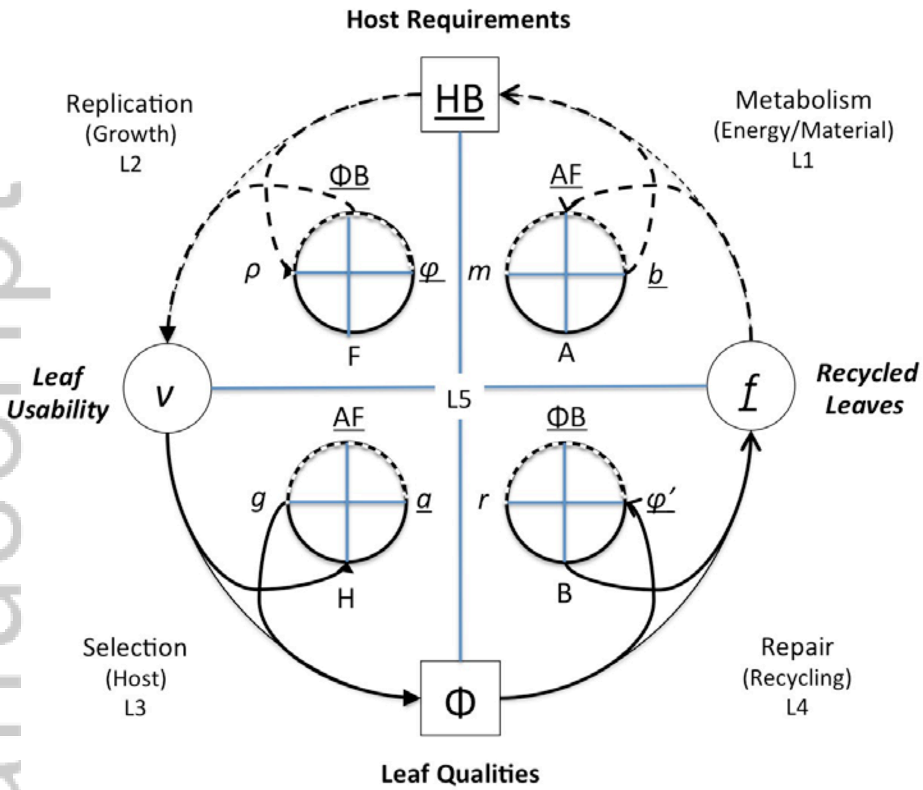
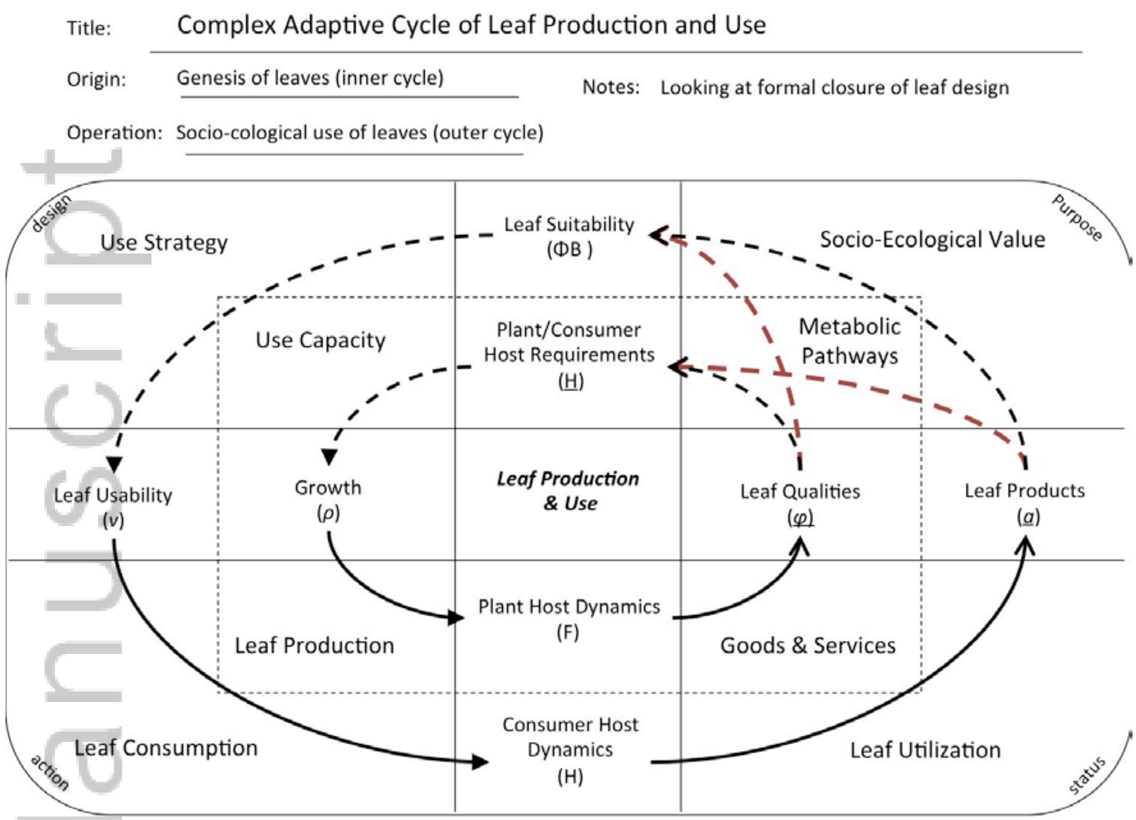

Host Requirements
HB
Replication
(Growth)
L2
Metabolism
(Energy/Material)
L1
ΦB
AF
ρ
φ
m
b
F
A
Leaf
Usability
v
L5
f
Recycled
Leaves
AF
ΦB
g
a
r
φ′
H
B
Selection
(Host)
L3
Repair
(Recycling)
L4
Φ
Leaf Qualities

Figure 5


Title: Complex Adaptive Cycle of Leaf Production and Use
Origin: Genesis of leaves (inner cycle)
Notes: Looking at formal closure of leaf design
Operation: Socio-cological use of leaves (outer cycle)
design
Use Strategy
Leaf Suitability (ΦB)
Socio-Ecological Value
Purpose
Use Capacity
Plant/Consumer Host Requirements (H)
Metabolic Pathways
Leaf Usability (v)
Growth (ρ)
Leaf Production & Use
Leaf Qualities (φ)
Leaf Products (a)
Plant Host Dynamics (F)
Leaf Production
Goods & Services
Leaf Consumption
Consumer Host Dynamics (H)
Leaf Utilization
action
status

Title: Complex Adaptive Cycle of Leaf Production and Use

Origin: Genesis of leaves (inner cycle)

Notes: Looking at formal closure of leaf design

Operation: Socio-cological use of leaves (outer cycle)