

Can we use energy based indicators to characterize and measure the status of ecosystems, human, disturbed and natural?

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Abstract:

The notion of ecosystems was first conceptualized in terms of mass and energy flows. The energy flow approach of H. T. Odum was one of the first efforts to systematically quantify and describe ecosystem behaviour. Following this lead, a number of researchers have investigated the thermodynamics of ecosystems and proposed several hypotheses concerning how energy flow in ecosystems changes with development and in response to external stress. The panel will discuss measures related to the energy and mass flow structure of ecosystems and measures of the second law effectiveness of ecosystems. Particular attention will be paid to the use of surface temperature as a way of characterizing the organizational state of ecosystems.

1. Introduction

Complex systems theory has its origins in the work of von Bertalanffy and others on general systems theory. Central to this theory is the notion that analysis must focus on nested hierarchies of systems. [Allen and Starr 1982] In parallel, the theory of non-linear dynamics suggests that the behavior of complex systems can be quite rich with self-organization, rapid spurts of development, and sudden flips to new states being normal behaviour. [Holling 1986; Kay; Regier; Boyle, and Francis 1999; Ludwig; B. Walker, and Holling 1997] The implication of complex systems theory for ecosystem theory and management have been explored in several recent publications [Jørgensen 1992; Kay and others 1999; Lister and Kay 2000; Ulanowicz 1997; Woodley and others 1993]. This theoretical work has its origin in the nonequilibrium approach of Prigogine [Nicolis and Prigogine 1977; Nicolis and Prigogine 1989].

Kay has put forward a theory of ecosystem development, based on a study of thermodynamics and the development of complex systems (particularly self-organization phenomena). [Kay 2000; Kay and Regier 1999; Kay 1984; Kay 1997; Schneider and Kay 1993; Schneider and Kay 1994b; Schneider and Kay 1994b; Schneider and Kay 1995]. Ulanowicz has put forth a complimentary theory which focuses on the development of mass and energy flow networks in ecological systems. [Kay and others 1989; Ulanowicz 1979; Ulanowicz 1986a; Ulanowicz 1997] Kay has used this theory and other elements of complex systems theory to develop an ecosystem approach for evaluating integrity. [Kay 1991; Kay and

Regier 2000]. Allen has been working for twenty years on hierarchy theory, a dialect of general systems theory that unites thermodynamics and network theory. Hierarchy theory takes into account issues of scale and observer decisions as to type and significance of systems [Ahl 1996; Allen and others 1993; Allen and Hoekstra 1992; Allen and Starr 1982]. Working with Norman, Allen has performed a set of experiments which relate the development of vegetation communities to their thermal behaviour. Luvall has a number of data sets of remotely sensed thermal images of ecosystem. Collectively these researchers are undertaking to meld theory and field observation through experimentation, to treat vegetation as a complex thermodynamic system. The ultimate goal is to understand the functionality and complexity of ecosystems, so that it can be measured and used to develop management and guide policy. (The term ecosystem is used herein to denote natural as well as human urban ecosystems.)

2. Ecosystem organization, exergy degradation, surface temperature, and networks.

Kay and Schneider take a recent interpretation of the second law of thermodynamics and extend it into nonequilibrium regions. For such nonequilibrium circumstances the second law is no longer just the simple statement that entropy increases or that processes are irreversible. Rather the thermodynamic principle is that as systems are moved away from equilibrium by externally applied gradients (temperature difference, pressure difference, etc.), they will

utilize the means available to them to dissipate the applied gradients. Furthermore as the applied gradients increase, so does the system's resistance to being moved away from equilibrium. Simply put, systems have a propensity to resist being moved from equilibrium and a have a tendency to return to the equilibrium state when moved from it. This is can be related to the development of interconnections in ecosystems, as they receive and process energy from the sun. Ulanowicz has developed a series of hypotheses about how these networks of interconnections develop over time.

Ecosystems can be viewed as the biotic, physical, and chemical components of nature acting together as nonequilibrium self-organizing dissipative systems . As ecosystems develop or mature they should develop more complex structures and processes with greater diversity, more cycling and more hierarchical levels all to abet exergy degradation. Species which survive in ecosystems are those that funnel energy into their own production and reproduction and contribute to autocatalytic processes which increase the total exergy degradation of the ecosystem. In short, ecosystems develop in a way which systematically increases their ability to degrade the incoming solar exergy [Kay and Schneider 1992; Kay 1984; Schneider and Kay 1994b; Schneider and Kay 1994b].

In terrestrial ecosystems, surface temperature measurements can be used to demonstrate that ecosystems develop so as to degrade exergy more effectively. The exergy degradation in a terrestrial ecosystem is a function of the difference in black body temperature between the captured

solar energy and the energy reradiated by the ecosystem. (This is discussed in detail in Fraser and Kay [Fraser and Kay, 2000].) Thus if a group of ecosystems are bathed by the same incoming energy, the most mature ecosystem should reradiate its energy at the lowest exergy level, that is the ecosystem would have the coldest black body temperature. The black body temperature is determined by the surface temperature of the canopy of the ecosystem.

Consider the fate of solar energy impinging on five different surfaces, a mirror, a flat black surface, a piece of false grass carpet (e.g.. Astroturf), a natural grass lawn and a rain forest. The perfect mirror would reflect all the incoming energy back toward space with the same exergy content as the incoming radiation. The black surface will reradiate the energy outward at a lower quality than the incoming energy, because much of the exergy is converted to lower quality infra-red radiation and sensible heat. The green carpet will reradiate its energy similar to the black surface but will differ because of its surface quality and different emissivity. The natural grass surface will degrade the incoming radiation more completely than the green carpet surface, because processes associated with life, (i.e. growth, metabolism and transpiration) degrade exergy [Ulanowicz and Hannon 1987]. Its surface temperature will be colder than the black surface or the Astroturf. The rain forest should degrade the incoming exergy most effectively because of the many pathways (i.e. more species, canopy construction) available for degradation. It will be even colder than the grass.

In previous papers Kay and Schneider have discussed Luvall et al's experiments in which they overflow terrestrial ecosystems and measured surface temperatures [Kay and Schneider 1994b; Luvall and others 1990; Luvall and Holbo 1991; Luvall 1989; Quattrochi and Luvall 1999; Schneider and Kay 1994b]. Luvall and his co-workers have documented ecosystem energy budgets, including tropical forests, mid-latitude varied ecosystems, and semiarid ecosystems. Their data shows that when other variables are constant, the more developed the ecosystem, the colder its surface temperature and the more degraded it's reradiated energy.

Work by Akbari, Murphy, Swanton and Kay [Akbari and others 2000] on agricultural plots showed a similar trend. A lawn (single species of grass) had the warmest surface temperature, a undisturbed hay field was cooler, and a field which has been naturally regenerating for 20 years was coldest. These trends were confirmed over three years of observation. Also another field, which was regenerating for 20 years, was disturbed by mowing. Immediately its surface temperature rose significantly, but very quickly it returned to its cooler pre-disturbance value. Very recently Allen and Norman have performed a set of experiments to explore the relationship between development and surface temperature in plant communities. So far their experimental results demonstrate that the surface temperature of plant communities tend to warm when they are removed from their normal conditions. That is plant communities are coldest (degrading the most exergy) when they are in the normal conditions which they are adapted to.

All this is evidence that exergy degradation is the name of the game in ecosystem development.

Recently Luvall and his colleagues at NASA have used these observations about natural ecosystems to develop a "Green Cities" strategy [Lo and others 1997]. This has been applied in several urban centers in the United States. The green cities initiative begins by using the same surface temperature measurements described above to generate a thermodynamic description of the city. Two core tactics in this approach are to use the thermodynamic description to focus on roofing materials and the presence of flora, particularly trees. Both of these can dramatically alter the thermodynamic budget in a city. Using the analysis of surface temperature, areas of the city which could benefit from changes in roofing materials, more flora etc. can be identified.

There is much to be gained from examining ecosystems through the lens of exergy degradation. A number of ecosystem phenomena can be explained and hypotheses concerning ecosystem development can be generated and tested. But there is more to the story. Most ecosystems will have many different options for exergy degradation available to them. Some will have different sources of exergy available. Different combinations of exergy sources and degradation possibilities may be equivalent from a exergy degradation perspective. So the number of possible variations on ecosystem organization, which are thermodynamically equivalent, may be significant. This quickly leads to a complicated set of possible organizational pathways. It is the characterization of these pathways and

hypotheses about how they will develop which has been the focus of Ulanowicz's work.

Over the past fifteen years, Ulanowicz, Kay and Allen have collaborated largely informally, but with the occasional joint publication, on a theoretical basis for discussing complexity and self-organization in living systems. This has led to a series of hypothesis which we have endeavoured to test with the help of Luvall, Norman and Fraser. Specifically these hypotheses are:

1. The ratio of net all-wave radiation to net short-wave radiation will be larger for more developed ecosystems and these systems will have a lower surface temperature.
2. Spatial variation of surface temperature (T) will be less for more developed ecosystems. The spatial variation can be indexed using the beta index [Luvall 1989]. More developed ecosystems will have a larger beta index.
3. In accordance with the ability complex systems to resist outside influence, more developed ecosystems will exhibit a smaller temperature change in response to a given amount of energy input (net radiation). This can be measured using the Thermal Response Number, TRN [Luvall 1989; Luvall 1989]. The more developed ecosystems will have a larger Thermal Response Number.
4. Ecosystems with a more complex set of functional process will emit radiation that mirrors this complexity. The complexity of the ecosystem can be estimated by the Shannon 'entropy' of the

network of trophic flows. This measure should correlate with the "Kolomogorov entropy' of the spectrum of emitted radiation.

Some work has been done to test these hypotheses and so far results have been favourable. However more work needs to be done. Nor has an effort been made to integrate these ideas across significant scale changes. Our current efforts focus on collecting more data to allow us to further refine our understanding of the thermodynamics of ecosystems and to test and integrate our hypotheses across different scales.

3. Complexity and systems.

Normal science biology attempts to gain insights by narrowing the discourse so that variables remain well behaved, and can be adequately treated by linear approximations. Accumulation of a large number of such local investigations facilitates understanding of complicated situations by aggregation to give the larger picture. The scientist quickly becomes overwhelmed by complicatedness because quickly the parts cease to be simply additive to make the whole. The antidote is complexity. Complicatedness only covers structural elaboration, and does not elucidate elaboration of organization, as occurs in true complexity. Pattee identified the elaboration of organization as a process of self-simplification through emergence [Pattee 1972]. Complex organization is able to subsume complicatedness by imposing organizational constraints. Organizational complexity arises out of mere complicatedness when positive feedbacks arise to send the primitive

complicated system unstable. The old simple relationships become overshadowed in the change, but soon new simple, often linear relationships appear as constraints on the positive feedbacks at a new level of organization. These constraints strip away degrees of freedom of the complications of the primitive system, so behavior becomes simpler.

The process of the emergence of complex organization starts with the appearance of non-linearity as we widen the scope of the material system under investigation. Non-linear effects, which can be ignored over a narrow range, can come to dominate the behavior of equations in a wider universe. It is at this point that the original simple relationship become overshadowed. The material system to which the non-linear equation applies appears unstable. For instance, in bridge design spans of a given type of bridge are widened in successively more ambitious projects. About a quarter century after a new type of construction is implemented, the design principles fail, and a particular new bridge falls down [Petroski 1993]. The small influences taken as linear over narrow spans become importantly non-linear in larger spans, as small exponents come to have large effects. Exponents represent a self-reference that can be seen as a positive feedback.

In creating new order, the positive feedbacks take the system away from the old basin of attraction. Eventually the positive feedbacks cause a large enough change of state so that they come to press against some new and persistent negative feedbacks. Often the new negative feedbacks are unforeseen, because they are only

potentialities until the positive feedback comes to be constrained by them. It is the emergence of the new linearizable constraint that is the hallmark of complexity. Non-linearity applies only in the transition between levels, either in emergence of new levels, or when we wish to link the equations of one level to the equations of the level above.

Any positive feedback that moves the systems so it comes to press against the unforeseen negative feedback will suffice. If any one of a large number of positive feedbacks can force new organization, then the conventional focus on the non-linearity of equations in the study of complexity is not always well placed. It is not the details of the non-linear equation that matters, so long as the appropriate negative feedback arises to constrain it. Focusing on how the non-linearity of equations from below lead to new pattern, is a bottom-up style favored at the Santa Fe Institute, and edge of chaos studies. However, we also need to see how the linearizable constraints appearing from above apply.

In the emergence of complexity, the new system remains pinned against the organizing negative feedback by the energy dissipated in driving the positive feedback of the lower level. If the new arrangement encourages energy capture, such as the organization that entrains sunlight in a more focused way in the Neolithic Revolution, then the new relationships and system configuration stands a good chance of persisting as a stable complex system; agriculture persists. Complexity amounts to a series of restrictions placed on what is possible at lower levels. Thus, biology cannot employ anything physically impossible, but it is

the limitations imposed on physics, not the physics itself, that characterizes biological phenomena. Limitations equal constraints that amount to information. Organization is more easily described in terms of what does not happen. By limiting outcomes, complex organizations can achieve simpler and more coherent activity. Since it takes the sentience of the scientist to recognize organization, complexity is often cast in more positive terms that emphasize the achievements possible under complexity, rather than the limitation of low level processes. Even so, there is nothing mystical or vague about emergence and levels of organization.

An example of the linearizing effect of a constraint, that is at the heart of the technical scientific issue we address, occurs in the behaviour of the vegetation canopy. The dependence of individual leaves on light is very nonlinear, whereas the dependence of canopy photosynthesis on light is nearly linear. The constraint of canopy structure produces a near-linear behavior of productivity with light in stark contrast to the nonlinear behavior of individual, isolated leaves. To accomplish an understanding of this linearizing phenomenon, three different types of leaf oriented scientists are required to measure their systems at three levels of analysis: 1) leaf-level physiologists measure physiological properties of individual leaves in detail (i.e. light versus leaf photosynthesis relations), 2) canopy-level specialists measure the canopy productivity as a function of canopy conditions (i.e. light versus canopy photosynthesis), and 3) mechanistic modelers integrate from leaf to canopy scales. From the combination of these three

approaches, we now understand how structure constrains leaf functioning. If we have to do this with every complex system, progress will be very slow. So we must ask, are there some principles that can allow us to grasp such processes quantitatively without having to first work out all the technical details?

For simple systems, subjective decisions are often made by convention and there is a helpful unanimity as to the accepted point of view. This saves time and blunts semantic arguments. In simple systems, normative consensus occurs as to what is structure vs. behavior, discontinuous vs. continuous, rate-independent vs. rate-dependent, qualitative vs. quantitative, and finally what is significant, or even directed change vs. blind, mechanistic process. For complex systems, the scientist has no normative accepted framework, and must decide on the full suite of dilemmas as to structure, continuity, rate and significance. This is because complex systems exhibit not just change of state but also change of structure. It is easy to forget that what is discrete enough to earn the name structure is a decision made by the observer, not a fact of nature. When the scientist observer addresses complex systems, that decision must generally be made as an explicit choice. The reason for being so explicit is that in complex systems, structure melts away as it is overwhelmed by non-linear effects. Moving upscale in a complex system, parameters regularly become variables. Moving downscale, models lose their significance as the lower levels they constrain take over the universe of discourse (e.g. when we come to analyze the chemistry of the

ink, the meaning of the words written with it becomes moot). We have to decide how different the situation has to be before we assert discontinuity. For complex systems, the point appears not to be to less about finding out the truth of the external material system, and becomes more about creating powerful points of view that give insight and prediction unaided by conventional wisdom. In fact, convention gets in the way of dealing with complexity by lodging the treatment of the system at just one level of analysis. The study of complexity must address the subjectivity of scientists as they deal with the issue of organization at several levels.

The accumulation of meticulous normal science, while essential, is not up to the task of prediction and so management when faced with many large systems. The problems presented by physically large environmental systems will not go away by them selves, and so environmental science must take courage and address them. To address these large scale applied issues, basic science must identify the levels of constraint that apply all the way from individual leaves to wide swaths of vegetation remotely sensed from satellites.

The theory on which this research turns starts by noting that when systems are pushed further from thermodynamic equilibrium, the more they will use whatever processes are available to resist being pushed up the gradient [Schneider and Kay 1994b]. There is no need for elaborate justification of this claim, for it is consonant with the second law of thermodynamics. It is reliance on this corollary of the second law of

thermodynamics that sets this research programme apart. Some of the more remarkable processes that resist steep gradients are whirlpools, thunderheads, Bénard Cells, and life itself. They all actively degrade energy sources, and in this way counter the effects of inputs that would otherwise push the local system away from equilibrium and up energy gradients. The thermodynamic gradient that appears central to organizing terrestrial living systems goes from warm planet surface to cold outer space.

Casting life in more positive terms than a simple dissipater of energy, consider the way that terrestrial life uses that gradient to do work. The energy captured in photosynthesis is important but is used primarily to finesse phytochemicals for defense or waxes for cuticles and other such subtleties. Over time it allows the slow accumulation of carbon capital. Photosynthate moves units of information as in pollination or frugivore seed dispersal. But beyond all this, there is still a large amount of movement of materials which is not propelled or arranged by burning high energy carbon. Photosynthesis plainly does not provide enough energy to move to do the heavy lifting that life requires. In an analogy to society, the energy used for electronics is crucial but small in quantity relative to the energy needed to run electrical pumps or transportation systems. Photosynthesis runs plants' "electronics" whereas energy from the sun converted to latent heat runs the "electric engines". Trees simply could not afford to move mineral nutrients and water up trees using photosynthate to run the pumps. It is fortunate that plants can be 85% efficient in capturing

and using solar radiation, and that is what the plant uses to lift the water. Photosynthesis captures a niggardly 2% of sunlight energy, and so is associated with only a small amount of the energy used in biological function.

If plants are using radiation from the sun to drive their more expensive processes, then the more complex and functional vegetational systems should be cooler on their upper surfaces, because heat has been used and dissipated to a greater extent, and hence is not available to heat the plant. Much more energy is degraded in transpiration than is degraded in respiration or sequestered in biomass. Given this observation, perhaps cooling capacity is a more meaningful measure of vegetation function than biomass accumulation, carbon flux or reproductive success. That is the reason this whole project focuses on radiative surface temperature. We measure radiative thermal temperature, not just because we can, but because there are good reasons coming from theory as to why it is the crucial measurement to make.

4. Ongoing work.

The thermodynamics of whole plants: The thermodynamics of whole plants down to their principal organ subsystems is being focused on by Norman and Fraser. The purpose of this part of our research programme is to build an overall first and second law description of individual biological systems. This description will include energy use, exergy destruction, entropy production and energy and exergy flows to the environment. It will provide a theoretical basis for constructing thermodynamic descriptions at larger scales. The approach being taken is to

identify all the exergy degradation mechanisms in different examples of primary producers. Examples of species which are indigenous to a specific set of environmental conditions are to be used, at least in the initial work, as they are most likely to be thermodynamically optimized for the situation.

Vegetation canopies: Recent work by Allen and Norman [Havlicek 1999] has shown that vegetation canopy appears to be a likely unit of investigation. Vegetation appears to function in an orderly fashion, but not that expected from simple aggregation of leaf radiative temperatures. Leaves are integrated with the rest of plant as the stem and roots operate as constraints on individual leaves. Leaves also act as constraints on each other as the whole canopy interfaces the plant with moving air. The remarkable result was an active temperature difference between air and soy beans, the latter being cooler. This work has shown that vegetation in a wind tunnel is coolest in wind speeds to which it had been acclimated. Vegetation is able to use more exergy in conditions that are less stressful.

The next tests were on even-aged soybean vegetation composed of a mixture of plants grown, some in slow wind and some in fast wind. This even-aged mixture showed consistently warmer temperatures at all test wind speeds, compared to the homogeneous vegetation of which the mixture was composed. Growth in fast wind causes shorter plants, and so there were uneven heights despite even age in the mixture coming from growing its components in different wind speeds. Height differences gave an aerodynamically rougher canopy,

which was accordingly warmed by the air. Furthermore, the taller plants were up in the wind, but had been reared in low wind, and this caused the warming of vegetation to be more extreme. However, cooler vegetation was achieved by creating uneven aged mixtures where tall old plants grown in fast wind were indeed up in the wind in the mixed vegetation.

The even aged mixture was “unnatural” because of a slow-wind grown overstory. The uneven aged mixture more “natural” because the overstory had been indeed grown in overstory wind. Both mixtures were equally complicated. However, the more natural mixed vegetation with fast-wind grown plants in the overstory was more complex. This is because the uneven-aged vegetation had proper organization, where overstory has the history to protect the understory, with its understory history of exposure to slow wind.

Suitable normalization between experimental results showed that the fast-wind plants did not behave differently with regard to radiative temperature, no matter which story of the vegetation they occupied. However, slow-wind plants were a full degree cooler if they were in the understory, a condition that their history of growth would suit. Thus complex vegetation is cooler, but merely complicated vegetation is warm. Furthermore, from the different responses of slow-wind and fast-wind grown plants, we know how complexity works. Part of the natural whole in a complex system (overstory in this case) protects the rest of the parts. If the protected parts can increase their function sufficiently to pay for the protection, then the whole is more functional from being complex.

However, if the benefit in function does not meet the cost, then complexity is an expensive luxury. The cost is the slow growth of plants in high wind, the price paid for protection of the understory. The benefit of complex vegetation is the increased function of the protected understory. The increased function of the overstory may or may not meet the cost of conditioning the overstory. In another example from biology, homeothermy allows better food capture, but it is a disaster to be a homeotherm in the cold with insufficient food. In social systems, the payload of administration can be assessed not worth it, and the people walk away from the political structure, and invite the barbarians to take over [Tainter 1988]. In both homeothermy and society, complexity may or may not pay for itself. For these contrived vegetation experiments, complexity, as opposed to mere complicatedness, has been demonstrated, and shown to be to be more functional. We also know how complexity works in this case, with an indication that it is a general principle.

Allen and Norman are continuing their wind tunnel work. The advantage of these systems is that every joule can be accounted for. Also the same measurement, radiative surface temperature, is used in these experiments as is used in the large scale remote sensing work of Luvall. Furthermore, radiative surface temperature is the arbiter of ultimate relationship between the whole planet and outer space.

Radiation Balance and ecological systems: Ecosystems display the influence of thermodynamic principles in their patterns of growth and development. Ecosystems are the

result of the biotic, physical, and chemical components of nature acting together as a nonequilibrium dissipative process that develops in a way that increases exergy use. As ecosystems develop or mature our prediction is that they should increase their total dissipation (use of exergy), and should develop more complex structures with greater diversity and more hierarchical levels to abet energy degradation. In short ecosystems develop in a way that maintains their ability to survive in their environment, while systematically increasing their ability to extract the exergy in the incoming solar energy and use it to expand and maintain their organization. The more exergy that the ecosystem captures the greater its ability to support organizational processes. Thus ecosystem development should be measurable in terms of its rate of exergy use.

The exergy drop (i.e. degradation) across an ecosystem is a function of the difference in black body temperature between the captured solar energy and the energy reradiated by the ecosystem. (This is discussed in detail in: [Fraser and Kay 2000; Kay 2000; Kay and Schneider 1994a; Schneider and Kay 1994b] Thus if a group of ecosystems are bathed by the same amount of incoming energy, the most mature ecosystem should reradiate its energy at the lowest exergy level, that is the ecosystem would have the coldest black body temperature. The black body temperature is determined by the surface temperature of the canopy of the ecosystem.

Traditional techniques of determining leaf/canopy temperatures use thermocouples or hand held infrared thermometers, and

determination of energy budgets requires intensive micrometeorological equipment. Practical constraints of equipment requirements, canopy access, and budgets have limited the number of leaves and spatial area which can be measured in forested areas. However, new methods are now available to measure temperatures over large regions using remote sensing.

Terrestrial ecosystem's surface temperatures have been measured by using NASA's airborne Thermal Infrared Multispectral Scanner (TIMS) [Luvall and others 1990; Luvall 1989] and more recently using the versatile Airborne Terrestrial and Land Applications Sensor (ATLAS) This technique allows assessments of energy budgets of terrestrial landscapes, integrating attributes of the overflown ecosystems, including vegetation, leaf and canopy morphology, biomass, species composition and canopy water status. Luvall and his co-workers [Luvall and others 1990; Luvall and Holbo 1991; Luvall 1989] have documented ecosystem energy budgets, including tropical forests, mid-latitude varied ecosystems, and semiarid ecosystems..

Using ATLAS (next generation TIMS) and TIMS data sets have been collected for a wide variety of forest, urban and agriculture ecosystems, These data sets include:

- calibrated surface temperatures at a 2.5, 5 or 10 meter pixel size.
- incoming solar and longwave radiation measurements.

For selected sites:

- calibrated reflectance from the ecosystems.

- thermocouple leaf and air temperatures.
- incoming solar broken down by wavelength (10 nm).
- incoming solar partitioned into diffuse and global.
- DEM so examine differences in solar loading due to slope and aspect.
- forest community structure.

The hypotheses concerning surface temperature and thermal response number are being examined using these data sets. Some examples of these data sets follow:

Coweeta forest: The 2185 ha Coweeta Hydrologic Laboratory, located in the Nantahala Mountain Range of western North Carolina. The topography of Coweeta is steep; elevations range from 686 to 1600 m with average side slopes of 50%. For a mixed hardwood and white pine plantation we have: 1. Hydrographic data for one year (daily data). 2. One day (measured throughout the day) per week stomata conductance. 3) Leaf thermal couples for year on leaves (measurement every thirty minutes). For the whole basin, we have: surface temp from overflight (Sept one day, three times during day, May one flight). Extensive traditional ecological data is available for the whole site.

Dry tropical forest, Costa Rica: TIMS data were collected at a resolution of 10m, during the dry season, in the Guanacaste region of Costa Rica. The area is composed of intact and degraded forest patches embedded in a matrix of active and abandoned pasture. Surface temperature distributions were established for four landcover types. Areas of continuous forest canopy show lower surface temperature whereas, areas of pasture showed high surface temperatures.

Gradients of canopy closures showed a strong influence on surface temperatures. Measured surface temperatures have been compared with spatial patterns of vegetation within the landscape.

Agricultural sites: University of Guelph, Canada: sites with different degrees of complexity: 1. Lawn, 2. Hay field, 3. Mown old field, 4. 20 year old undisturbed field. For each we have multiple surface temperature measurements for one day of each month for the growing seasons for three years. Also data on Nitrogen applications versus surface temperature for corn.

Corn, cotton, fields. Southeast USA: Data were acquired by NASA's Atlas scanner, on June 26, 1998 and August 4, 1998. Four targets were flown, two in north central Alabama and two in southwestern Georgia. Acquisition was designed to get 2.5 meter spatial resolution twice within approximately 30 minutes.

Urban sites: Surface temperature images of Atlanta, Huntsville, Sacramento and Salt Lake city have been collected by Luvall and his colleagues. This data has been used to develop an understanding of urban heat island effects, that is the thermodynamics of cities as ecosystems. Students, working with Luvall, Fraser and Kay have demonstrated that areas with more vegetation are cooler and that vegetation can be used to break up the formation of urban heat islands. We have just begun to use the new LANDSAT 7 thermal data in this regard and it look very promising.

Analysis of these extensive data sets is allowing us to test our hypotheses concerning energy budgets and the

thermodynamics of ecosystems. In essence this analysis tells us about the macroscopic functioning of the ecosystems.

Foodwebs: An ecological trophic network is a representation of qualitative information about "who eats whom" accompanied by the corresponding quantitative magnitudes indicating "at what rates". When the networks are of sufficiently small dimension, they are often represented graphically as "box- and- arrow" diagrams, and when such depiction becomes unwieldy, as matrices and vectors. Mathematically speaking, the network can be referred to as a "weighted digraph".

In physical terms, each node in the network represents a population of organisms, consisting of a certain biomass with an accompanying constituent exergy. When a predator organism devours a prey individual, the event (depicted as an arrow) represents the transfer of biomass from the predator box to that of the prey and, according to the second law of thermodynamics, this transfer must be accompanied by the dissipation of a given amount of energy. The exact character of the energy thereby released to the environment will depend upon the exergy of the donor and receptor populations and the efficiency of the process. It follows that the spectrum of energies released by an ecosystem should be related to the diversity and distribution of the processes represented by the links in the network.

Ulanowicz has applied information theory to the trophic networks of ecosystems to characterize their status [Ulanowicz 1986a]. For example, the Shannon index can be applied to the

collection of transfers (the links) to quantify the diversity displayed by their number and the distribution of their magnitudes. Similarly, the mutual information inherent in the network topology gauges the aggregate constraints at work in effecting system organization. Hence, these system level indices and their components can be used to compare the trophic status of two ecosystems, or the same system at different times. They can reveal the process of eutrophication at work [Almunia and others 1999; Ulanowicz 1986b], and even be invoked to assess the relative "health" of the system.

It happens that information theory also can be used to analyze the properties of spectra of radiation. The well-known Kolmogorov "entropy" is one such measure [Latora and Baranger 1999]. This prompts the speculation that the Kolmogorov measure of sensed radiation might be correlated with the Shannon diversity of trophic flow magnitudes (known in Network Analysis as the system development capacity.)

The point of this component of our research programme is to search for any strong correlations between these two independent, but similar classes of indices. The discovery of any such connections would allow investigators to use the easily acquired spectral characteristics as surrogates for the much more difficult- to- estimate network indices. Such a connection would open the doors to the much-needed, fast and comprehensive remote sensing of ecosystem status.

5. Synthesis.

The team has data and theory to relate: organs to plants; plants to

canopy in wind tunnels; biotron experiments to controlled vegetation out in the field (crops); simple canopies in the field to uncontrived vegetation in the field at many disparate sites.

Robert Peters in his book, "Critique for Ecology" took ecologists strongly to task for not posing hypotheses that can be tested in operational terms [Peters 1991]. The work proposed here seeks to remedy Peters' mostly accurate criticism. Theory is not being proposed in abstraction. Rather, existing theories are being rendered operational in a way that could yield enormous benefits to the agroecology that seeks to support the human population on a sustained basis. If successful, the proposed work will translate the conceptual domain of the ecologist, who is occupied with observing a multitude of specific processes, into the operational domain of the engineer, who seeks to employ quick measuring devices (EM spectra) for the purpose of guiding practical action.

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