# Transformity and Simulation of Microbial Ecosystems

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## ABSTRACT

Evaluating emergy and transformity in models of microbiological systems raises questions about scales, organic aggregates, the transformity of microbes, and the concept of detritus. Microbial networks were studied with simulation models for EXTEND and TRUEBASIC. The paper explains an intellectual approach to complex systems in which verbal models are diagrammed with object-oriented energy systems symbols (program EXTEND) connected on screen for simulation without thinking about mathematical equivalents. New object-oriented blocks were programmed for microbes of different scale. In addition to the passive computation of emergy and transformity in dynamic simulation, these models include transformity ratios in growth equations to control the efficiency of access to organic energy aggregates of different scales. Availability of sunlight decreases with transformity and scale of producers. Data on microbes and organic matter in marshes were used to estimate the transformity for a microbe's share of global emergy. The exponential growth of autocatalytic consumers levels off as their increasing scale and transformity diminishes their efficiency in using energy aggregates of small scale. Transformities from simulation are compared with those calculated with other methods. A plot of energy and transformity represents detritus on the scale of energy hierarchy.

## INTRODUCTION

This paper uses emergy calculations and computer simulations to understand the transformity of microorganisms, their populations, and their relation to solar insolation, non-living organic substance, and scale. Between the size of a solar photon and the plant and animal structures visible to the naked eye are realms of several orders of magnitude. Solar transformity, which has been recognized as one of the measures of scale, ranges from one for incident solar energy to a thousand or more for woody structures. But when emergy evaluations are made of larger ecosystems, the microbiological components are often aggregated so that higher transformities result, sometimes combined in the pool of soil organic matter or the pool of organic matter in aquatic ecosystems that is often called detritus.

Many micro-organism cells are hardly larger than solar photons (less than 1 micron = 1 micrometer = $10^{-6}$ meter), whereas the wave length of invisible light is 0.4 to 0.8 microns). A priori, considering the tiny size, one would expect such cells to have very small transformities. However, tiny organisms cannot long survive except as part of a population that is sustained by group processes and reproduction.

There is a hierarchy of energy transformation in any population of organisms (Odum, 1983, 1996). Many small eggs, larvae, or seedlings develop and eventually generate a few large adult trees or animals. Thus, transformity increases along the successive growth stages, since more energy is used in the early stages, as required to support the few units at the top. The population as a whole is represented by its genome of inherited information and the environmental emergy required to sustain its life cycles. Similarly, microbial population and the organic structures that support it may be expected to have a higher transformity than its individual microbes.

When dynamic simulation models are assembled using object-oriented blocks, it is possible to connect a higher organism such as a fish population with small energy flows per area directly to the large energy inflow of sunlight for that area. The result is an unrealistic rapid growth of fish. Such models dramatize the dependence of energy transformation efficiency on the scale of organic aggregates, which is not recognized in those models. We already know from energy and emergy evaluations of real systems that follow the laws of energy hierarchy that transferring energy from one scale to another requires a large consumption of available energy. Energy of sunlight to support a fish has several levels of energy transformation, each involving a concentration from its distribution on one scale to a more concentrated center of less energy of the next higher scale.

Many of our simulation models (Odum, 1996; Odum and Odum, 2000) have included a computation of the emergy and transformity of the flows and storages of systems models, but these calculations were passive, not set up to affect the equations for the main state variables and processes. Since transformity is a measure of scale, simulation equations can be written so that inter-scale energy transformations are controlled by transformity. But what are the appropriate transformities of the microbiota on the small scale? How are these different from transformities of microbial populations and the microbes in organic detritus pools in larger scale view?

This papers uses sample calculations and computer simulations to help understand the transformities of micro-organisms and the several scales on which their populations operate and are interpreted.

## Transformity and Microbial Scales

### Scales of Micro-Organisms

Aquatic ecosystems of the oceans and large lakes contain a microscopic world of tiny plants and animals in sizes ranging over 5 orders of magnitude (0.2 micrometers to 2 millimeters). Summarizing decades of research on the diverse, microscopic life in the clear, low nutrient waters of the ocean and large lakes, Caron and Swanberg (1990) reviewed knowledge of the species, their physiological roles, and their ecological relationships. This is sometimes called a protistan microworld.

In general, the smaller the species is, the smaller is its area of support and influence, the faster it processes energy, and the quicker its biomass is replaced. Some idea of the organization of these ecosystems can be understood by drawing the network of organic energy flows that connect photosynthetically producing units and consuming units, with scale increasing from the small-fast on the left to the larger-slower species on the right (Figure 1). The photosynthetic organisms are shown with bullet-shaped "producer" symbols. The consumer organisms are shown with the hexagon shaped symbols. These organisms are connected by their food pathways to form ecosystems. The network has producers and consumers of different sizes from 0.2 micrometers (mm) to 2000 micrometers.

Both the producers and the consumers have designs in which the energy stored and materials released are fed back (to the left) to augment (multiply) the energy intake. In this way, the design is sustained because the feedbacks from growth and reproduction increase the intake of energy.

## Transformity and Scale

The ecosystem runs on sunlight energy transformed by the photosynthesis of the algae and other protists into organic matter that feeds the microscopic consumers of many kinds. As the sun's energy is captured and transformed into organic matter, it is concentrated spatially as it is passed to the right along the food web. The amount of potential energy available to support life is used up by the processes of conservation and concentration, being degraded into used heat energy that is shown passing out the bottom of the diagram in Figure 1. Thus, the quantity of energy decreases in each step (Figure 2), but the quality and concentration of the converted energy increases at each step. A useful index of the increased energy quality is the quotient of solar energy incoming divided by the energy outflow. This ratio is called the solar transformity. It increases with each step through the energy web, as shown with some order-of-magnitude values in Figure 2.

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Protistan networks are examples of the fundamental energy hierarchy of the universe, in which many Calories of energy on one level are required to make a few Calories of higher quality energy at another level. Thus, a chain of such transformations has a step down in the flow of energy in each conversion. In a protistan energy web of the ocean, these energy transformations occur within individual organisms of each species, all based on abundant but low concentration solar energy.

The first step in photosynthesis captures photons of light that are very broadly dispersed in time and space. Regardless of the size of the photosynthetic organism, the first step involving chlorophyll organelles is at the low quality end of the energy hierarchy (shaded structure in Figures 1 and 2a). However, the species range in size over 5 orders of magnitude. The long producer symbols in Figures 1 and 2 show how the larger photosynthetic organisms include more energy transformation steps than the short ones. The larger (longer) producers accumulate and concentrate organic matter, although there is less energy remaining in the whole population after the series of transformations. The larger photosynthetic organisms have more consumption steps within their body. Consumer functions operate respiration:

organic matter + oxygen ---> carbon-dioxide + water

the same process in the stand-alone consumers, that utilize the smaller photosynthetic organisms.

## Concept and Transformity of Detritus

Ogawa et al. (2001) summarize bacterial production of detritus. Microorganisms and their organic energy sources are adsorbed or attracted to surfaces. Labile substances are metabolized, building microbial structure, not only the individual cells, but also the larger organic film structures, many of which pass into the environment as films, particles, and other units of larger size and turnover time. Viruses are important in converting the individual microbes into more resistant organic matter. Some of these fall downward in aquatic ecosystems, sometimes called an organic "snow." Much of the organic matter in the sea is in the form of less-labile organic structure, with surfaces that act autocatalytically to support the active microbes. In the process, organic carbon fixed by photosynthesis is recycled in a loop through consumers.

Producer cells as they age become dead organic matter. Consumers eating food egest unassimilated organic remnants. For example, zooplankton capturing smaller algae have unassimilated organic matter that is discarded back into the water as faecal pellets. Such particulate organic matter is concentrated enough to support bacteria. The diagram in Figure 1 shows some organic matter particles coming from all the independent consumers. The pool of organic matter with its components of different transformity is often called detritus, a nutritive mixture found in most if not all ecosystems.

Flow into the detritus pool of coastal waters of Louisiana were calculated by Bahr, Day and Stone (1982) and the transformities evaluated by several means (Tennenbaum, 1988, Collins and Odum, 2001). In Figure 3 these have been plotted on a power-transformity plot, which shows a wide range of transformities and energy quality in contributions to that transformity pool. How much of the range in this example is real and how much is caused by approximations in the data is not known. If detritus contributions are in proportion to the energy hierarchy, a decrease of quantity with higher quality is to be expected. However, it might be reasoned that higher levels in food chains aggregate and leave more organics. F3

Evaluations of detritus inputs yield relatively high transformities ($10^5$-$10^7$ solar sej/J), as high as the animals that generate them. This is consistent with the high concentrations of the organic matter as it is released. Detritus as observed in a microscope is partly composed of bacterial and other living micro-organisms engaged in its use and decomposition (2-25% of biomass). What is the transformity of these microbial cells considered separately on their small scale?

Microbial Share of Global Empower

For the most part, the earth is covered with a thin blanket of organic detritus in the oozes of lake, estuaries, deep columns of the open oceans, sea bottoms, and in the soils of the land. The microbes are known to be associated with particles, where a good part of their consumption is of dissolved organic substances, partly adsorbed and otherwise associated with the particles. Some of the consumption process is carried out by extra-organismic enzymes.

Using George Knox's recent review of literature on the composition and processes of detritus (Knox, 2001), order of magnitude calculations were made of microbes per unit area and their turnover times in Figure 4. Data on weights and numbers of microbes at the surface of salt marsh from P.A. Rublee (1982) were used. How typical the organic detritus over salt marsh is of the other ecosystems remains to be tabulated. For our purposes microbes are considered by size and metabolism, although species with quite different DNA histories may be involved together. F4

Figure 4 shows the stock of detritus, and within, the 1% that is living microbes. The global daily emergy budget was divided by the area of the earth to show the emergy supporting a square meter on the average. Biomass estimates of detritus and microbes were put on a common basis of kilocalories per square meter and metabolic rates on kilocalories per square meter per day. As shown in the figure, a microbe's share of the global emergy is tiny, with a small solar transformity of 265, possibly appropriate to the small scale of single microbes considered as individuals.

A population of organisms has higher transformities than its individuals because of the greater emergy that has to support life cycles, interactions, dispersal mechanisms, organic structures, and particles developed as part of microbe functions. As already explained (Figure 3), detritus as a higher level structure has even higher transformities, reflecting the valuable components that develop over longer periods in which the component microbes are turning over more frequently.

## Transformity in Simulation

Dynamic computer simulation usually shows the temporal patterns and indices that are the consequence of models and their numerical values of storage and flow which have been assigned. In addition to plots of the main state variables and processes, we have been adding emergy-transformity equations to simulation programs for some time so that the programs plot emergy, empower, and transformity also (Odum and Petersen, 1995; Tilley, 1999; Odum and Odum, 2001). Equations for an autocatalytic consumer unit are shown in Figure 5. (Examples are microbes, animals, parts of plants, fuel burning, engines, cities, etc.) F5

The emergy in a flow is the product of transformity and the energy flow. Three simulation equations are used for emergy storage (Figure 5b). While the energy in a storage is increasing, the emergy is the sum of the input emergy minus those transferred for use. Emergy is constant if the stored energy is constant. Transformity of storage is the sum of emergy accumulated divided by the energy accumulated. A storage accumulates energy and emergy when the inflows are greater than the outflows. If there is a transfer of the storage out of the system, its share of energy and emergy goes with it. Some storage drains away due to the second energy law. When a simple model of storage is approaching a balance between its inflows and outflows, it is in the range where fluctuations of the smaller scale part of the system determine the actual storage level of energy, emergy, and its transformity. In other words, in the more complex real world, emergy and transformity stop increasing before the simple model would level off. If the model doesn't include the small scale part of the network, it is convenient to add a limit (1% in the example of Appendix C) to stop accumulating emergy in the zone that would be controlled by the smaller scale.

Emergy decreases when energy of storage diminishes, however it happens. Rate of emergy decline is the product of storage transformity and rate of energy decrease. These previous emergy-transformity simulations are "passive," since they do not affect the rest of the dynamic simulation.

However, transformity is a measure of the hierarchical position of an energy flow or storage and is an indicator of what other kinds of energy can interact. A corollary of the energy hierarchy concept is that energies on one scale with one transformity self organize to interact with one or two levels above and below, so that they amplify. But energies with very different transformities cannot interact to effectively use each other. A bass fish cannot grow on sunlight. The difficulty in converting solar energy with low transformity into electric power or other high quality energy in one step, may be explained by the very different scales of technology and solar energy. Carnivores can eat smaller animals but cannot use solar energy efficiently without intermediate transformations that cascade and concentrate. Many dynamic simulation models do not have these scale characteristics built in. Transformities of organisms are dynamic properties because they change value when the organism grows and changes its scale of support and influence.

In this paper, however, we add the ratio of the food transformity to the consumer transformity to control the efficiency of productive energy transformations (Figure 5c).

(Transformity of energy source Q)/(Transformity of consumer A) = $(Tr_Q/Tr_A)$

Thus, these simulation programs not only calculate emergy and transformities but use the transformities to control the efficiencies of each component according to its scale and that of its energy supply. The factor of 10 is multiplied so that the quotient's effect on the use of an appropriate energy source one scale smaller will be neutral. In other words, $(10^*Tr_Q/Tr_A) = 1$.

In addition, the higher the consumer the more inherited structure and mechanistic programs it has for operating as the center of a larger territory. For example, larger birds have the structures to feed over larger areas. Since it takes available energy to operate these concentrating mechanisms, more of their energy is diverted from net growth. The larger units have lower net production efficiencies.

As shown in Figures 1 and 2, producers range from tiny nanoplankton size up to plant cells or colonies visible to the eye. As shown in Figure 2, the larger producer units have more successive energy transformations built into their organic structure, with less net production output at the end of the interior food chain. In order to represent these differences in producers in simulation models that explore relationships of different networks and connections of sizes, each producer unit is characterized by Eff, an efficiency factor, that is inherently smaller in the producer species with larger units.

In this paper, two software programs, EXTEND and TRUEBASIC, are used to simulate energy systems models, their emergy and transformity. They use transformity ratio and the internal efficiency factor EFF to control each species energy transformation role in the network.

## Verbal-connectivity Thinking with EXTEND

One of the purposes of this paper is to show how verbal thinking can generate simpler overview comprehension of systems networks and the consequences of the designs by arranging simulation to follow from network diagrams without mathematical thinking. With the program EXTEND it is easy to program object-oriented symbols so that when connected on the computer screen, they automatically set up the mathematical relationships for simulation. At least for some people, this fosters a higher level comprehension of network designs (Figure 6-10). See our book "Modeling for All Scales" (Odum and Odum, 2000) for discussion of alternative approaches from mind to models. Although not expensive, this book has a CD that contains the program EXTEND, version 4. Figure 6 illustrates symbol use that shows the relationships with interior pathways. Figures 8 and 9, with solid-shaded symbols, allow the mind to focus on the larger scale. F-6

A demonstration example of transformity control is provided using the Simulation software EXTEND (Imagine That, 6830 Via del Oro, Suite 230, San Jose, California 95119. Web Site http://www.imaginethatinc.com). With EXTEND users may make their own blocks which are programmed to simulate systems when the icons are connected on screen and given calibration values. When blocks are connected, they share information including their transformities. The blocks are stored in "library" files with the extension .lix, and the assembled systems models are saved with the extension .mox. Examples of simulation models and their output in EXTEND are given in Figures 6-8. Details on loading and running EXTEND are in Appendix A.

### Passive Simulation of Emergy and Transformity

The equations for simulation of emergy and transformity of a structural storage in a dynamic simulation are given in Figure 5b. The simulation of the consumer and its growth is not affected, but the additional equations and the connected plotters for transformity, emergy, and/or transformity provide graphs of these properties. Chapters 11 and 19 in "Modeling for all Scales" (Odum and Odum, 2000) explain several simulation models with passive emergy evaluation, including models of international economic exchange.

### Simulating Cross-scale Efficiency with Transformity

In this paper, EXTEND models are given that use blocks with the energy intake and conversion controlled by the transformity ratio. The demonstration model in Figure 6a (ConsTr.mox) has a consumer growing on unlimited quantity of energy (large and constant concentration). But the ability to use that energy depends on the scale and packaging. The blocks of the model are in the library file (MicrLib.lix). The consumer block in the middle had its script written with the equations of Figure 5c, including the transformity ratio and EFF factors for control of energy conversion efficiency.

The consumer block "Transform consumer" is connected to two plotters on the right, an arrangement that causes two graphs to plot, the quantity of energy in the stored assets and its transformity (Figures 6b and 6c). The block on the left supplies a constant force source (constant concentration) with a dialog box in which you can type the strength of the source Q and its transformity $Tr_Q$.

### Demonstration of Transformity Control with Simulation

If adequate energy is available at the appropriate concentration, an autocatalytic consumer and a constant force source generate exponential growth (Figure 6b). If however, the energy source is not in concentrated packages appropriate to the consumer, it will have lower transformity, the transformity quotient will be too small, and the unit does not grow. The simulation model in Figure 6 was run with Eff held constant to study the effect of transformity source on the growth of one species. The initial run (Figure 6b and 6bc) was run with the transformity in the dialog box of the source set at 1000. When the consumer is higher in the hierarchy, initial transformity is large (1000 to 100,000); it does not grow when the energy source transformity is 200 or less. Increasing the concentration of the food energy (higher transformity) or decreasing the scale of the consumer start (lower starting transformity) will restore growth.

Another Consumer block in the MicrLib.lix library is named "Transformity consumer" and is the same as the "Transform consumer" except its icon is colored solid, hiding the pathways and mathematical relationships. You can substitute this block in the model and hide the complexity of details. Highlight and delete one block, copy the new one from the library, and connect pathways as before. This system is already assembled as model ConsTran.mox.

### Transformity in Producers of Different Scales

Whereas the reception of solar energy photons is inherently small scale because of the low concentration of solar photons, the size of the living organisms that carry out photosynthesis range from microns to meters. Figure 1 showed how the small and low concentrations of dispersed producers are connected to a food chain of consumers forming an energy hierarchy that converges and concentrates with increasing transformity. The larger producers on a larger scale have more steps of energy processing and concentrating within single individuals. More of the concentrating, storing and increasing transformity occurs within their structures, which are the center of larger territory of support and influence. With more energy transformation steps required, the energy stored in producer biomass is less. In other words, the efficiency of net production is less, but the transformity is greater.

To represent the producers of different size appropriately in simulation models, these differences in efficiency and transformity have to be included in the equations and their calibration. Two changes were made in the producer of Figure 7 to adjust to scale. F7

### Inherent Efficiency Factor in Producers

Eff, the fractional efficiency factor already used in consumers (Figure 5) is included in the net production term of producers (Figure 7c). Larger producers have larger territories from which they draw their nutrients and scattered light. The larger the producer, the lower the Eff term.

### Rates and Turnover with Scale

The larger scale producers develop larger biomass and slower turnover times. In the simulation model, increasing the value of the biomass used for calibration is one of the adjustments required to fit flows and storages to scale (Figure 7d).

### EXTEND Simulation Comparing Producers of Different Scale

Three producer blocks (Nanoprod, Microprod, and Mesoprod) were programmed for EXTEND, each representing a different scale. Each uses the same model and equations of Figure 7 except for the two changes. The efficiency concentrating factor EFF was increased, with values 1.0 ,0.5 and 0.25, respectively. The calibration biomass was also increased with values 1, 10, and 100 g/m$^2$.

A model (ProdCons.mox) was assembled with three blocks (Figure 8a), each running on a separate source-limited (renewable) solar energy source. The simulation results show the larger the scale of the unit, the more storage-structure developed, and the longer the growth time required (Figures 8b). The larger the scale the higher the resulting transformity (Figure 8c). F8

These blocks are versatile in generating oxygen as well as organic growth. Their consumption process uses oxygen. The blocks can be used to simulate the day-night sequences. However, in Figure 8 carbon-dioxide and oxygen were not connected. These blocks were programmed with a substitution of equations so that they would operate with or without the input of carbon-dioxide and with or without the input of oxygen.

## EXTEND Simulation Comparing Consumers of Different Scales

Three consumer blocks like that in Figure 6 were made to represent consumers adapted to operate at increasing scales by reprogramming the "consumer transformity" block with larger biomass, and higher inherent transformity adjusted by making the Eff factors less. These blocks have solid color icons and were labeled: ConsNano, ConsMicr, and ConsMeso. All their calibrations were the same except for the biomass calibration to adjust scale (1, 10, 100 g/m$^2$). Figure 9 uses pictorial icons of pig farm wastes for the energy source, and an artistic sketch of a waste pile to represent a storage. When these blocks were run in parallel, each with its own steady energy source (source concentrations similar), the storages that developed and the transformities of the storages increased with the scale adjustments in the same order as expected (Figure 9b and c). Each of these blocks were given two input consumption and production functions and connectors so they could be used in branching energy networks.

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## Simulating Microbial Networks with EXTEND

With producer and consumer blocks containing the properties of scale (calibration biomass and the transformity control ratio), network models can be assembled to understand the interplay. For example, Figure 10 shows an EXTEND model MicrWeb.mox with two producers (small scale Nanoprod and larger scale MesoProd) and two consumers (small scale ConsNano and larger scale ConsMicr). Simulations were run with different combinations:

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With the two producers both using and competing for the sunlight with transformity of 1 (no consumers connected), the small scale producer prevails, the other going extinct. Biomass and transformity of the nano-producer is small.

Adding the small scale consumer to use the nano-producer depletes its population, and the larger producer prevails with larger biomass, transformity, and longer growth time. However, connecting the small scale consumer to use both producers returns dominance to the small producer.

When the larger scale consumer is connected to the small producer or to both, it reduces the steady state stock of the small producer, but not enough to displace its dominance over the larger producer.

When the small scale consumer was connected to the small scale producer and the large scale consumer connected to the large scale consumer, some oscillations were observed, and small changes in coefficients cause change in the prevailing population.

## Emergy Simulation with TRUEBASIC

Energy systems models are readily simulated with some form of BASIC. Our book "Modeling for all Scales" has a hundred programs for simulating energy systems models with QUICK BASIC and CHIPMUNK BASIC. Chapter 11 explains the simulation of emergy and transformity in BASIC software. Because TRUEBASIC is simpler, inexpensive, and available for all PC and Mac computers, we have converted several hundred programs to TRUEBASIC. This paper includes TRUEBASIC programs that use transformity ratio for the control of energy flows. Appendix B has more details on the use of TRUEBASIC, and Appendix C contains listing of the program.

Consumer -Food Transformity (Program TrCons.tru)
A TRUEBASIC program for relating autocatalytic growth to the transformity of energy sources is supplied in Appendix C for simulating the growth equation in Figure 11a. Varying the transformity of the energy source determined whether there is growth or not, as already explained with Figure 6 using EXTEND. As a unit grows in storage, it diminishes its turnover time, increases its transformity--and thus increases its scale. Larger dimensions require more concentrated food packages of larger transformity and scale. Autocatalytic growth on a constant force (unlimited energy) source normally accelerates in exponential growth (Figure 11b). However, when energy available is only moderate, a unit with the transformity control ratio levels its own growth because its increasing size, concentration, and transformity makes its former dilute energy source no longer sufficient for further growth. Note the example in Figure 11c, which was simulated with the TRUEBASIC program ScaleExp.tru (Appendix C).

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## SUMMARY

The microbial components of the environment include individual microbes, populations, microbial associations with particles, and complex combinations of living cells and detrital storages. The transformities apparently range from 100 for a single cell to $10^6$ for the aggregates, as they are viewed from the human scale. Transformity measures the concentration of organic matter and microbiota into particles and packages, and thus the availability as an energy source to units of larger scale. The ratio of transformities of input to that of consumer can be used in computer simulation programs to represent the scale effects. Knowing the total available organic matter is not enough. Computer programs that continuously compute the transformities may use them to represent concentration and scale effects on energy flow in networks.

## APPENDIX A: USING EXTEND TO ASSEMBLE AND RUN A SIMULATION

1. Load EXTEND to your hard drive and use its Installer. After installation, double click on its icon to Open EXTEND.

2. To bring up a model that is already assembled, use the FILE menu to locate its name, and double click to open. As it loads, a library of blocks may be loaded first, after which the model appears on the screen. However, the program may ask you to locate the appropriate library file. Locate the folder and click on the appropriate library for this model. After that library is loaded, the model that uses these blocks will appear. You can use the LIBRARY menu to see the name of the library that has been loaded. You can see its contents in a strip of icons by releasing the mouse on the "open library window" command.

3. To assemble your own system of blocks on a model screen, use the file menu to open a NEW worksheet (model screen). To get the blocks which are to form the system, move the mouse pointer to access OPEN in the Library menu. Find the folder with the appropriate library and click to install that library. Use the mouse and the LIBRARY menu to open the list of blocks. One after another, release the mouse button on each block to be placed on the screen for the model. Include a plotter icon. Use the mouse to arrange the icons in order of energy hierarchy, with the plotter icon to the right.

4. The small squares attached to each icon are connectors to transfer data from one block to others in your system. The output connectors (black boxes) on the right of a block send flows out. The input connectors (white boxes) on the left take flows in. Connect the icons with pathways representing the flows of energy, materials, and information. When the mouse is held over a connector box, it becomes a "pen" for drawing. Draw a line with your mouse held down to connect the icons. The line goes from the output box of one icon to the input box of the next icon. The line will be dashed until there is a good connection. For items to be plotted as output graphs, connect a line from output connector to a plotter input. The plotter has four input connectors; it can keep track of four sets of changes in different units and draw four lines on the graph.

5. Most of the icon blocks have numerical values to set. These may already be set in the model you opened. You can double click on each icon to see the DIALOG BOX in which the values are indicated. You can retype these numbers to make changes. For a new model you will probably calibrate the model by entering new numbers.

6. Use the RUN menu to select the time span for the run and the iteration interval (dt). Then RUN the program. A graph appears for each plotter that you have used. To read the values in output graphs, move the mouse across the graph, which moves a hair line indicating its position. The numerical values at each position are plotted on the top line of the table just below the output graph.

7. Various adjustments can be made to label and color the lines on the graph. Click on the graph control tools at the top of the window of the simulation graph. Plot lines can be assigned to a second vertical scale on the left. If you want to rescale a graph (quantity on vertical coordinate or time on horizontal coordinate), click on the graph number and type in the new number in the box which appears.

8. To print, choose PRINT in the FILE menu, select what you want to print (program, output graph, etc.), and click on the Print button. (Caution: if you want to print only the graph and not the table, be sure the box for Plot Data Tables is not checked. If it is, you will get hundreds of numbers.)

9. To save a new model, select SAVE AS in the FILE menu. To save something you have already saved with the same name, select SAVE in the FILE menu. To close without saving changes, select Close under the File menu.

10. To copy a graph, click on the graph to select it and choose Copy Plot from the Edit menu. The graph will automatically go into the Clipboard. From there you can paste it into any word processor, draw, or paint program.

## APPENDIX B: USING TRUEBASIC

To program and simulate in a simple classical way, instructions are supplied here for using TRUEBASIC, an inexpensive program available for all the versions of PC WINDOWS and

Macintosh. (TRUEBASIC, Inc., Hartford, Vermont, 05047-0501; http://www.truebasic.com). The commands are simpler than QUICKBASIC, and programs fit both Windows and Macintosh.

Use its installer on the TRUEBASIC DISK to put TRUEBASIC on your hard drive. Open TRUEBASIC by clicking on its icon. Use its FILE menu and the NEW command to open a blank screen ("edit screen"). Type in the program. Run the program with the RUN command in the RUN menu.

To load a program that has already been saved, use the FILE menu and the OPEN command. Then type the name of the program in the dialog box provided (for example type EMTANK.tru). The "edit" screen appears with the program. Run the program from the RUN menu.

The result of the run appears in the "output" screen. To save and print the result, copy that screen to clipboard and paste into WORD or into a drawing program. Or, screen dump by pressing PRINT SCREEN on the PC or press the keys APPLE-SHIFT-3, which puts the picture into a hard disk file "Picture1". Call up and print the picture with a drawing program or simple text.

If the output screen is called up with the WINDOWS Menu before the run, it can be sized smaller with the mouse and shifted to the side. Thereafter, the output graph will fit within the adjusted box when it runs. After a run, it is necessary to click on the output screen to get back to other operations. To go to other programs such as WORD without exiting TRUEBASIC, type NEW in its dialog box. It will open a blank screen, and also allow you to go to other programs. After a run, you have to click in the output screen, before you can do anything else.

To transfer a program from Macintosh to Windows or vice versa, use clipboard to copy program to WORD on a PC formatted disk. Move the disk to the PC, open TRUEBASIC and use the clipboard to copy from WORD to a TRUEBASIC screen. To transfer from PC, use a clipboard to copy the TRUEBASIC program to PC Word on a PC disk. Move the disk to the Macintosh, open the TRUEBASIC on the Macintosh and copy the WORD listing to a TRUEBASIC screen.

To convert Line commands that are not boxes (without B), a QUICKBASIC Line command such as: 60 LINE (0,90)-(240,90),3 plots a line from the coordinates in the first parenthesis to the one in the next parenthesis, followed by a 3 to indicate a color. In TRUEBASIC, use the PLOT command to indicate the coordinates of the points at the start and end of the line, with a semi-colon in between which instructs the program to draw a line between the points: 60 PLOT 0, 90; 240, 90. The line will have the color of the last color instruction line above it.

Colors of the graphics are designated with the SET COLOR command followed by the name of the color in quotes. SET COLOR "green". That color will prevail until the program comes to another SET COLOR statement. If there is no color statement then the color is black. Instead of the name of the color you can use its number. Colors available are: 0 = black, 1 = blue, 2 = green, 3 = cyan, 4 = red, 5 = magenta, 6 = brown, 7 = white, and 14 = yellow. Some colors that are available only by using numbers are: 8 = gray, 9 = bright blue, 10 = bright green, 11 = bright cyan, 12 = bright red, 13 = bright magenta, 15 = bright white.

## APPENDIX C: MODEL IN TRUEBASIC FOR RELATING AUTOCATALITIC GROWTH TO TRANSFORMITY

```
10 Option Nolet
20 ! ScaleExp.tru
25 ! Model of Exponential growth and transformity
30 Clear
40 Set Color "Black"
50 Set Window -30, 310, -30, 310
60 Box Lines 0, 300, 0, 90
63 Box Lines 0,300,100,190
67 Box Lines 0,300,200,300
70 Q = 10
80 St = 5.0! Starting Transformity Of Storage
90 Em = St*Q
100 F =3 ! External Source, Constant Force Type (5 Is Exponential)
110 Sts = 1! Solar Transformity Of The Source
115 K0 = .7
120 K1 = .07
130 K4 = .05
140 K5 = .02! Outflow Which Carries Avalble Energy And Emergy
150 Dt =  0.1
160 St0 = .5 !Scaling Factor For Transformity
170 T0 = .3! Scaling Factor For Time
180 Q0 = 3! Scaling Factor For Storage
190 Em0 = 100 !Transformity For Emergy Storage
300 !Start Iteration With Plotting
310 Set Color "Green" ! For Storage
320 If Q/Q0 < 90 Then Plot T/T0, Q/Q0
330 Set Color "Blue" ! For Transformity
340 If  St/St0 < 200 Then
345 Plot T/T0, 100 + St/St0 ! Transformity Of Storage
350 End If
355 Set Color "Red" ! For Emergy
360 If (Em/Em0) < 300 Then
370 Plot T/T0, 200 + Em/Em0
375 End If
380 Dq = ((10*Sts)/St)*K1*F*Q -K4*Q - K5*Q ! Storage Equation
390 If Dq > .01 Then
400 Dem = Sts*((10*Sts)/St)*K0*F*Q - K5*Q ! Emergy Equation
410 Else
420 Dem = St*Dq
430 End If
440 Q = Q+Dq*Dt
450 If Q < .001 Then Q = .001
460 Em = Em + Dem*Dt
```

```
470 St = Em/Q
480 T = T+Dt
490 If T/T0 < 300.0 Then Goto 300
500 End
```

## NOTES: CALCULATIONS MADE FOR FIGURE 4

Global solar empower of the whole geobiosphere 15.84 x $10^{24}$ sej/yr for area of earth, 5.12 $10^{14}$ $m^2$ or 3.08 x $10^{10}$ sej/$m^2$/yr (8.44 x $10^7$ sej/$m^2$/day) = 20,162 semkcal/$m^2$/day.

Energy of microbe biomass to 20 cm (Rublee, 1982 in Knox, 2001)
(31.83 g carbon/$m^2$)(2 g dry/g C)(5 kcal/g dry) = 318.3 kcal/$m^2$

Detritus to 20 cm where microbes are 1% of organic biomass energy
Biomass: (31.83 g C/$m^2$)(2 g dry/g C)(100) = 6366 g dry/$m^2$
Energy: (318.3 kcal/$m^2$/microbes)(100 kcal detritus/kcal microbes)
= 31,830 kcal/$m^2$

Number of microbes:
(20 $cm^3$/$cm^2$)(5 x $10^9$ ind/$cm^3$)(1 E4 $cm^2$/$m^2$) = 1 E 15 ind/$m^2$

Energy per individual microbe:
(318. kcal/$m^2$)/(1.0 x $10^{15}$ microbes/$m^2$) = 3.18 x $10^{-13}$ kcal/individual
Stored emergy in bacteria to 20 cm
(4.1 days)(2.02 E4 semkcal/$m^2$/day) = 82,820 semkcal/$m^2$

Emergy/individual:
82,820 semkcal/$m^2$)/(1 E15 ind/$m^2$) = 8.28 x $10^{-11}$ semkcal/ind
Transformity of microbe stock:
(82,820 semkcal/$m^2$)/(318.3 kcal/$m^2$) = 260 semkcal/kcal

Detritus metabolism = consumption of microbial processes
1.0 mg oxygen/g detritus/hour (0.7 to 1.4)
(1.0 E-3 g $O_2$/g detritus/hr)(24 hr/day)(5 kcal/g)(6366 g detritus/$m^2$)
= 764 kcal/$m^2$/day

Assumed efficiency of conversion to microbe live biomass = 10%
Microbial production = (764 kcal/$m^2$/day)(0.10) = 76.4 kcal/day

Turnover time of microbes: (318 kcal/$m^2$)/(76.4 kcal/$m^2$/day)= 4.2 days
Turnover time of detritus: 32,000 kcal/$m^2$)/(764 kcal/$m^2$/day) = 42 days

Solar transformity of microbes: (20,162 sekcal/$m^2$/day)/(76 kcal/$m^2$/day) =265 sekcal/kcal
Solar transformity of detritus: (20,162 sekcal/$m^2$/day)/(760 kcal/$m^2$/day) = 2650 sekcal/kcal

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# LEGENDS FOR THE FIGURES

Figure 1. Energy systems diagram of a Protistan web with components from left to right in order of scale (size and territory). Bullet-shaped symbols are producers; hexagon shaped symbols are consumers; hexagon symbols within the producers represent metabolic functions of organism physiology; shaded symbol are pigmented units carrying out photosynthetic production with sunlight.

Figure 2. Components, energy flow, and transformity of photosynthetic organisms of different size running on sunlight. (a) Examples of microbes arranged by scale increasing from the left; (b) energy flows decreasing with each transformation to larger scale; (c) solar transformities (= emergy/energy) measuring energy concentration and quality for each scale.

Figure 3. Characteristics of the components of detritus of Louisiana coastal waters from Bahr, Day, and Stone (1982) plotted on a graph of annual energy flow and solar transformity.

Figure 4. Possible role of micro-organisms in processing dissolved and particulate organic matter as part of detritus. Values were adapted from Rublee (1982) as reviewed by Knox (2001). See Notes.

Figure 5. Energy systems diagram and equations for the "transform consumer" unit used for simulations in Figure 6. The "transform consumer" block is an autocatalytic consumer with one energy input from the left, a flow of byproducts (example: unassimilated food) from the right connector (org. flow), a flow of materials released (example: nutrients) from the connector at the lower right, and two connectors for pathways of energy transfer to other units. A is the quantity of assets (biomass) stored. Growth is proportional to the ratio of input transformity to that of the assets $(10*Tr_Q/Tr_A) = 1$, thus representing the degree of concentration of the organic matter (whether dissolved, colloidal, small particles, large biomass).

Figure 6. Simulation of autocatalytic consumer growth with energy sources of different transformity with programmed blocks for EXTEND. (a) Screen view of assembled model; (b) exponential growth of stored assets when energy concentration (transformity) is large enough relative to the concentration and scale (transformity) of consumers; (c) plot of increasing transformity with growth.

Figure 7. Model of producers preprogrammed in computer simulation blocks for EXTEND. (a) Energy systems diagram and equations; (b) equations to simulate emergy and transformity without affecting the dynamic relationships in a; (c) efficiency adjustments to recognize more energy transformations within one structure; (d) change of the biomass used in calibration as a way of adjusting rates to change scale.

Figure 8. Use of EXTEND to compare three producers modules that operate at different scales. (a) Model showing units receiving identical energy sources; (b) growth of producer storages; (c) accompanying transformities of storage.

Figure 9. Using EXTEND to compare consumers of three different scales. (a) Model with each consumer supplied a similar pool of renewed energy; (b) comparison of growth; (c) comparison of transformity of storage.

Figure 10. EXTEND model use to compare different connections between producers and consumers.

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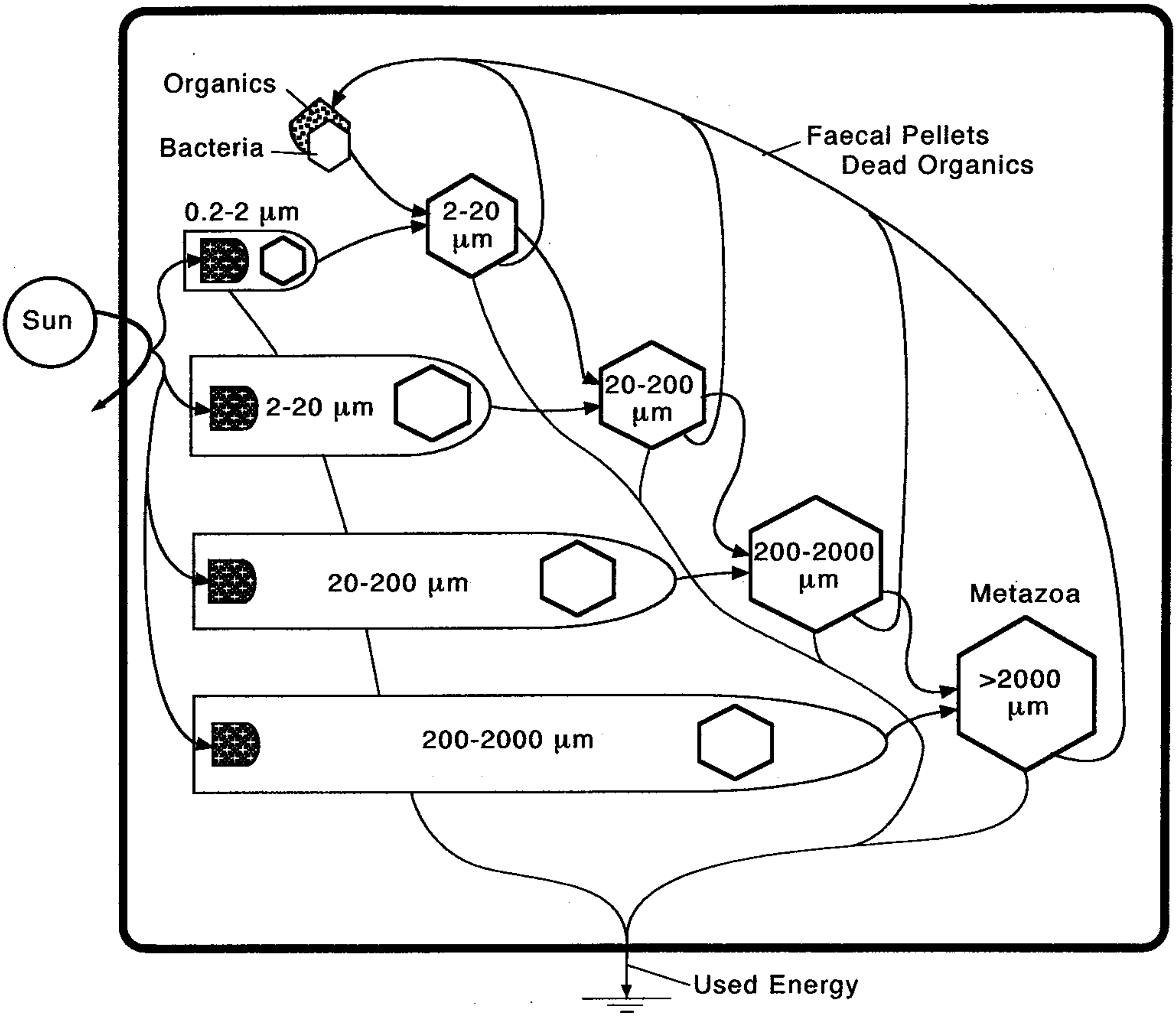

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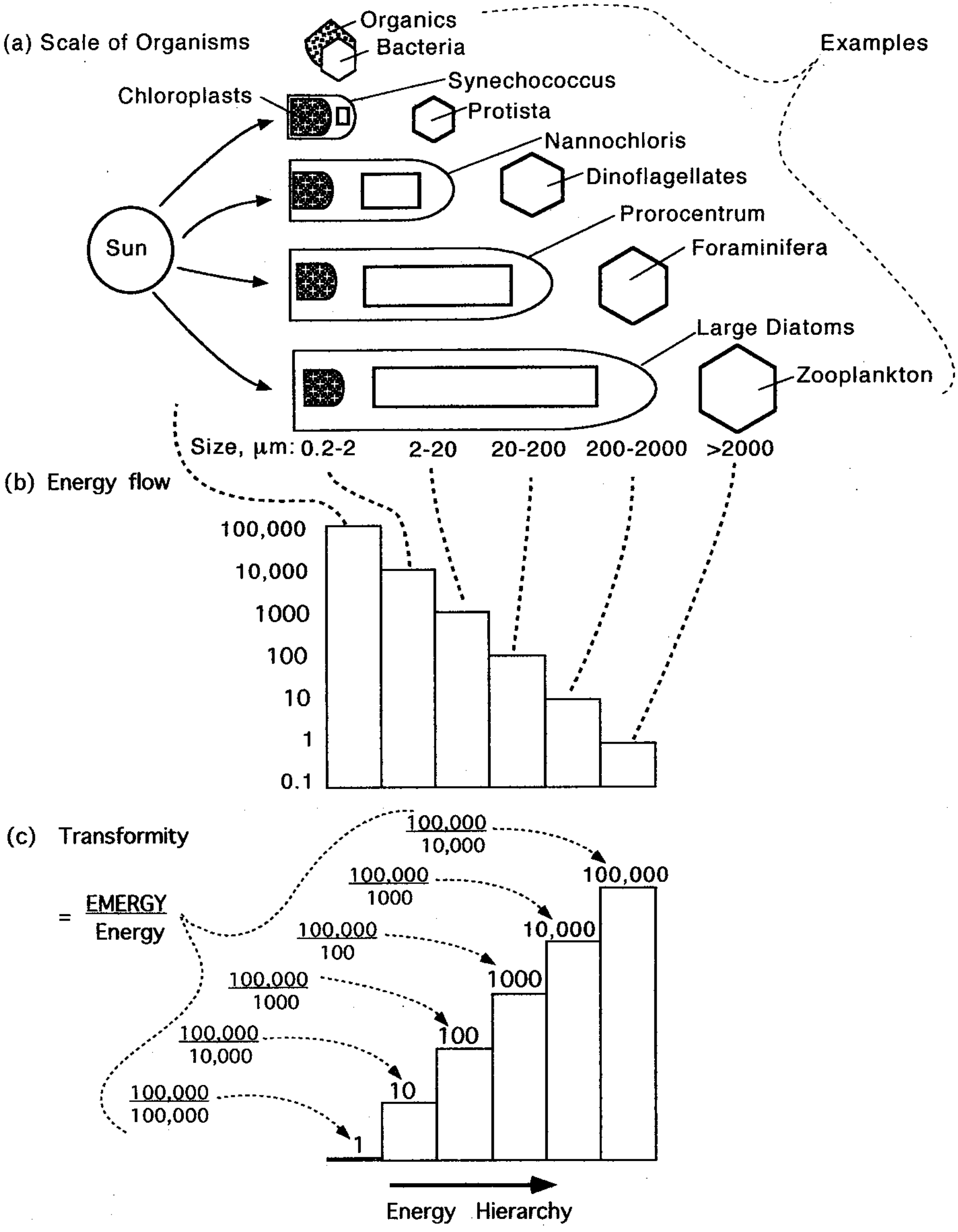

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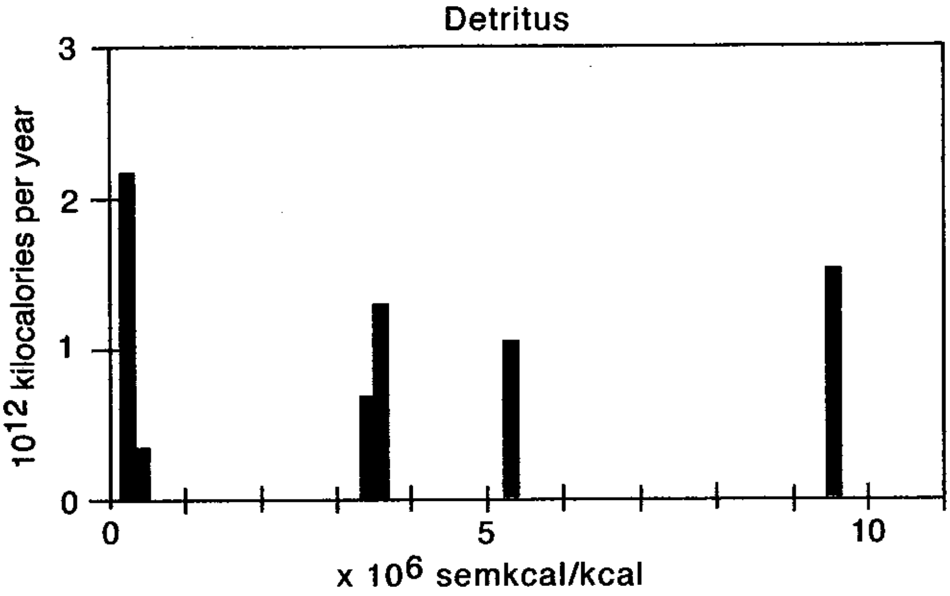

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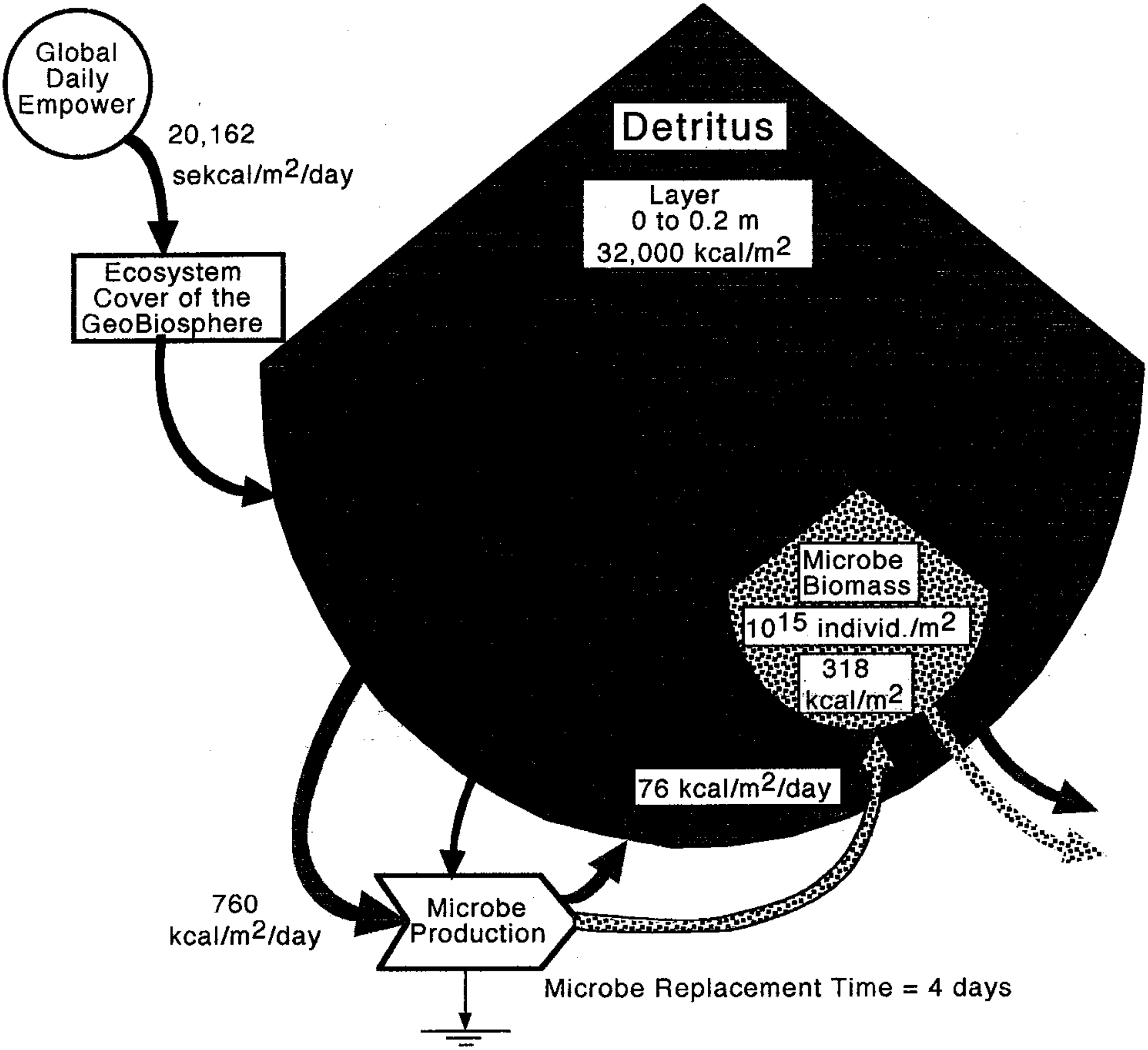

$$\text{Solar Transformity of Microbes} = \frac{20{,}162 \text{ sekcal/m}^2\text{/day}}{76 \text{ kcal/m}^2\text{/day}} = 265 \text{ sekcal/kcal}$$

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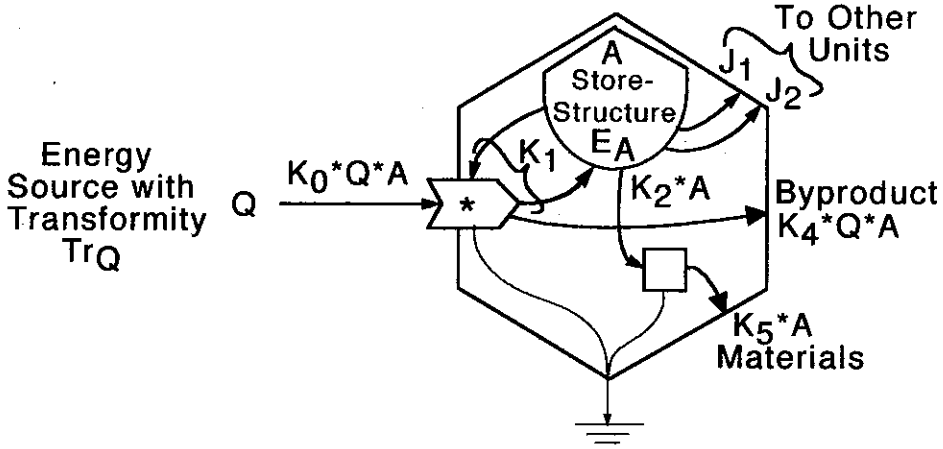
## (a) Dynamic Simulation Model



$$dA/dt = K_1*Q*A - K_2*A - J1 - J2$$

## (b) Passive Rate Equations for Emergy Store $E_A$:

When $DA/dt > 0$,: $dE_A/dt = Tr_Q*K_0*Q*A - Tr_A*J_1 - Tr_A*J_2$

Where $Tr_A = E_A/A$

When $DA/dt = 0$,: $dE_A/dt = 0$

When $DA/dt < 0$,: $dE_A/dt = Tr_A*dA/dt$

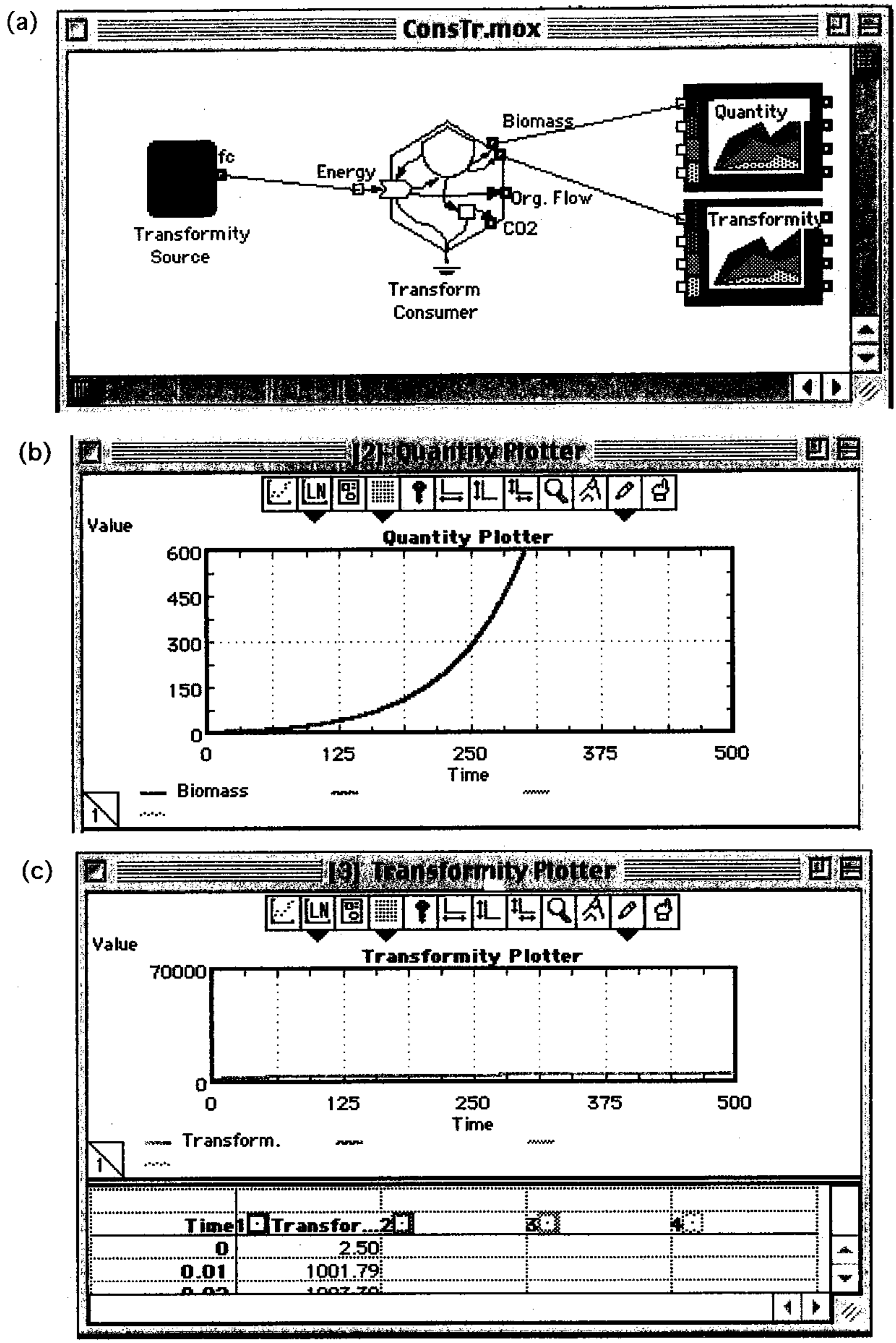
## (c) Transformity Ratio ($Tr_Q/Tr_A$) Controlling Use Efficiency:

Assets Equation: $dA/dt = (10*Tr_Q/Tr_A)*K_1*Q*A - K_2*A - J1 - J2$

Emergy Storing Equation:

When $DA/dt > 0$, $dE_A/dt = (10*Tr_Q/Tr_A)*Tr_q*K_0*Q*A - Tr_A*J_1 - Tr_A*J_2$

Figure 5. Energy systems diagram and equations for the "transform consumer" unit used for simulations in Figure 6. The "transform consumer" block is an autocatalytic consumer with one energy input from the left, a flow of byproducts (example: unassimilated food) from the right connector (org. flow), a flow of materials released (example: nutrients) from the connector at the lower right, and two connectors for pathways of energy transfer to other units. A is the quantity of assets (biomass) stored. Growth is proportional to the ratio of input transformity to that of the assets ($10*Tr_Q/Tr_A$) = 1, thus representing the degree of concentration of the organic matter (whether dissolved, colloidal, small particles, large biomass).



| Time 1 | Transfor...2 | 3 | 4 |
|---|---|---|---|
| 0 | 2.50 | | |
| 0.01 | 1001.79 | | |

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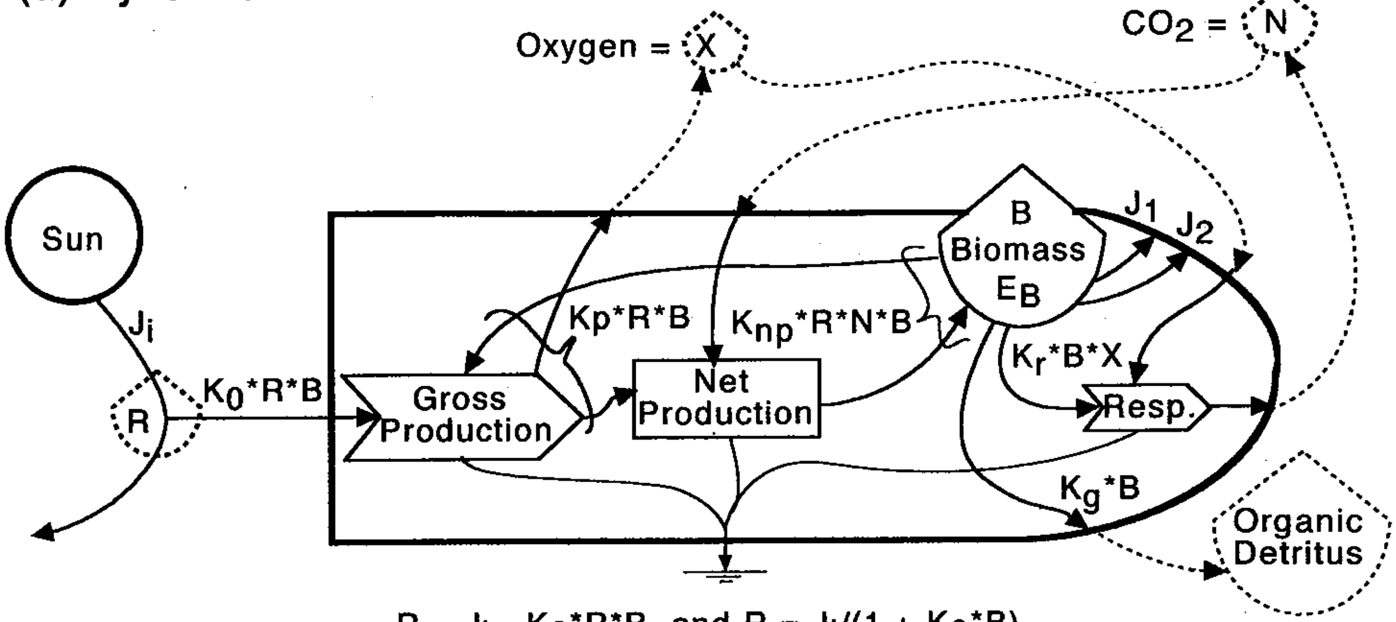


$R = J_i - K_0*R*B$ and $R = J_i/(1 + K_0*B)$

$$dB/dt = K_{np}*R*N*B - K_r*B*X - K_g*B - J_1 - J_2$$

## (b) Passive Rate Equations for Emergy Storage $E_B$

When $DB/dt > 0$
$dE_B/dt = Tr_R*K_0*R*B + Tr_N*K_2*R*N*B + Tr_X*K_X*B*X - Tr_B*J_1 - Tr_B*J_2$

Where $Tr_B = E_B/B$ and $Tr_R$, $Tr_N$, $Tr_X$, $Tr_B$ are Transformities

When $DB/dt = 0$,: $dE_B/dt = 0$

When $DB/dt < 0$,: $dE_B/dt = Tr_B*dB/dt$

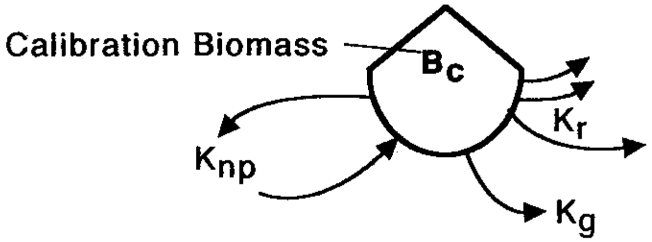
## (c) Equations Use Eff to Adjust Energy Conversion to Scale:

Biomass Equation: $dB/dt = \mathbf{Eff} * K_{np}*R*N*B - K_r*B*X - K_g*B - J_1 - J_2$

Where **Eff** = efficiency, reduced by energy used to concentrate biomass

## (d) Calibration of Biomass Adjusts Rates to Scale,

Increasing $\mathbf{B_C}$ Reduces Rate Coefficients (K's) and Turnover Time



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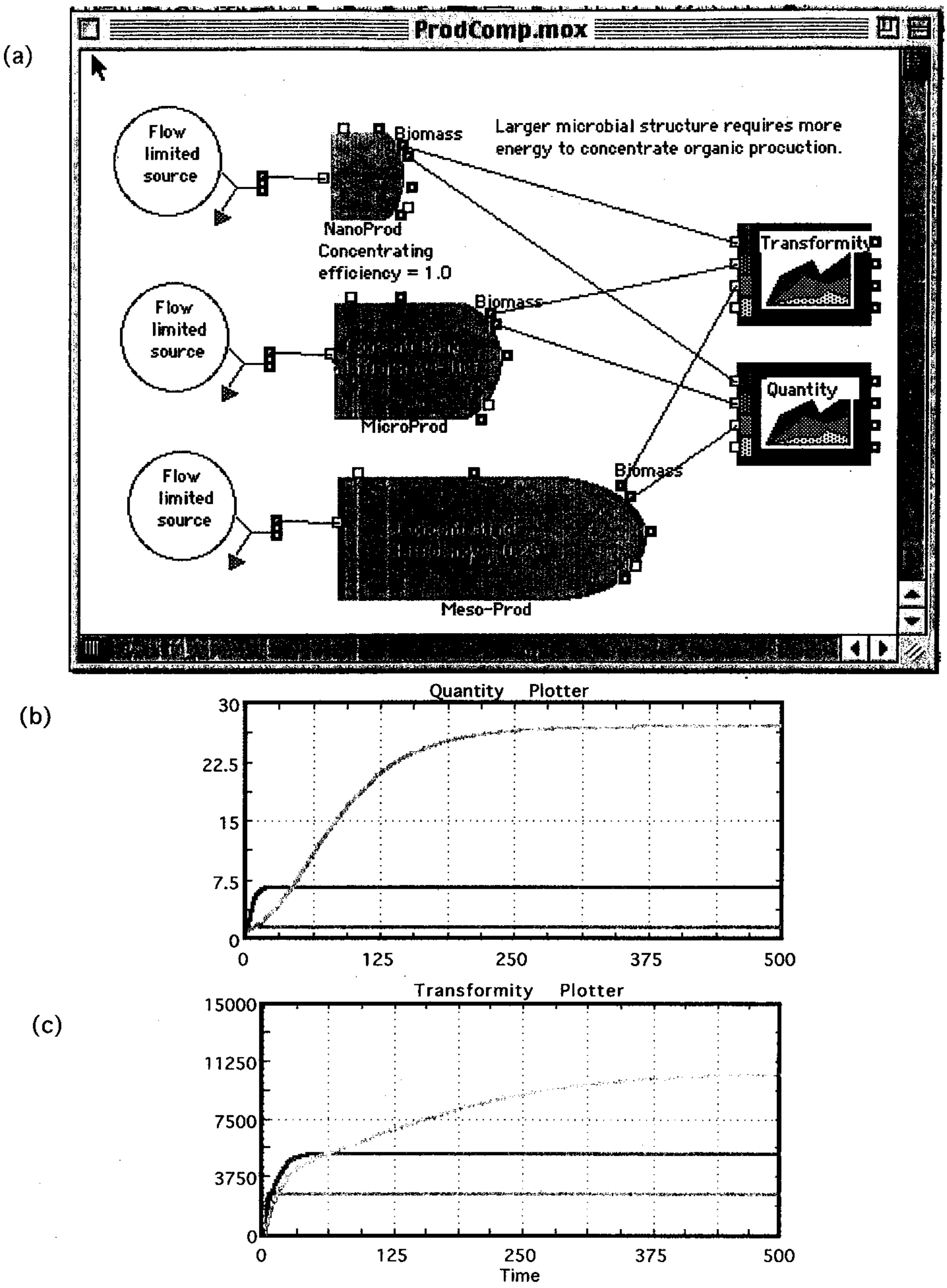

Larger microbial structure requires more energy to concentrate organic procuction.

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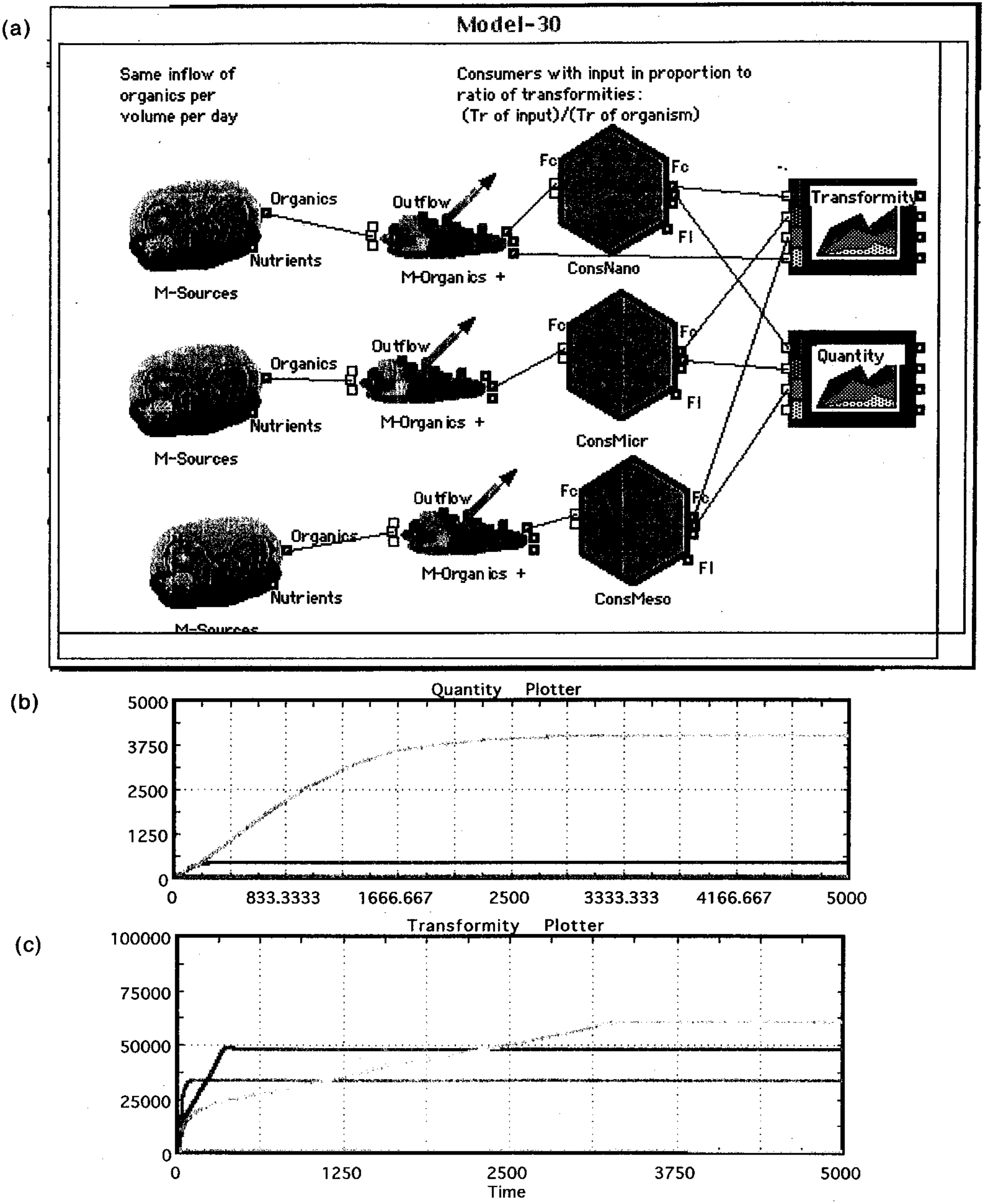

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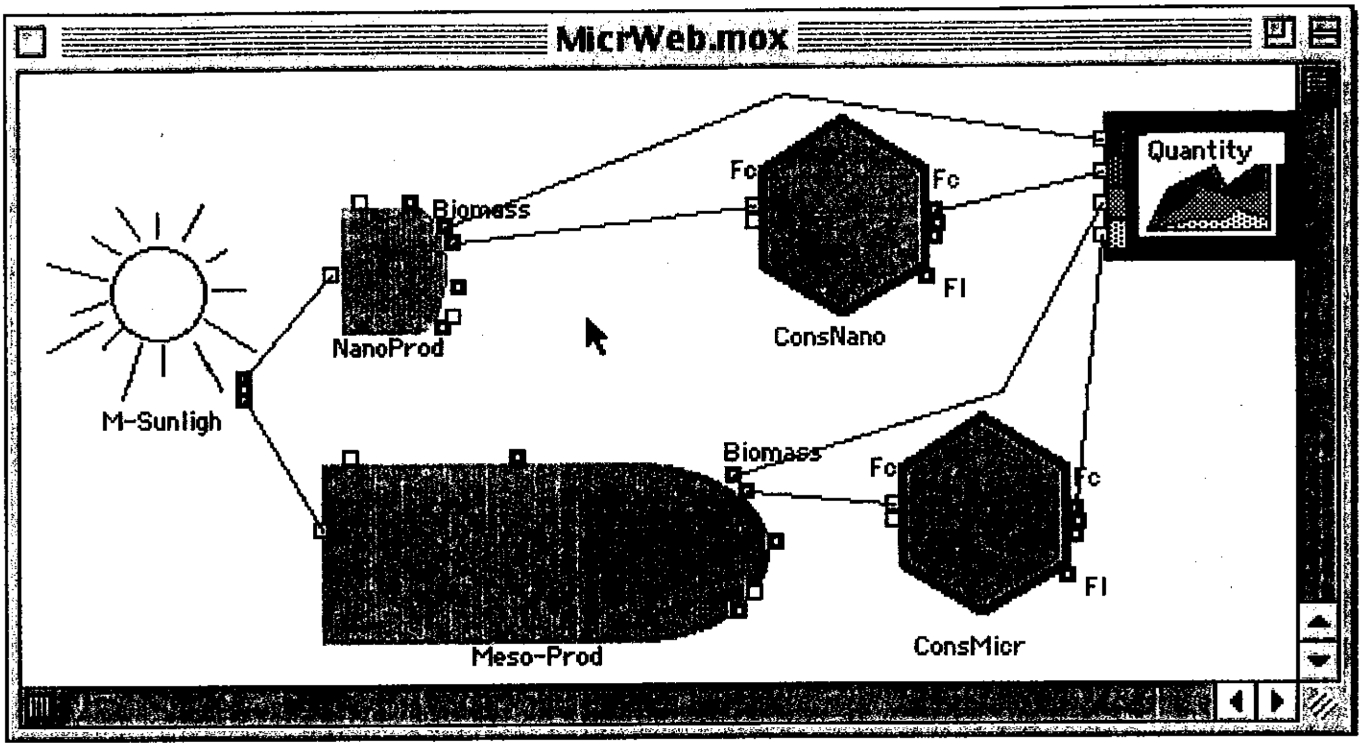

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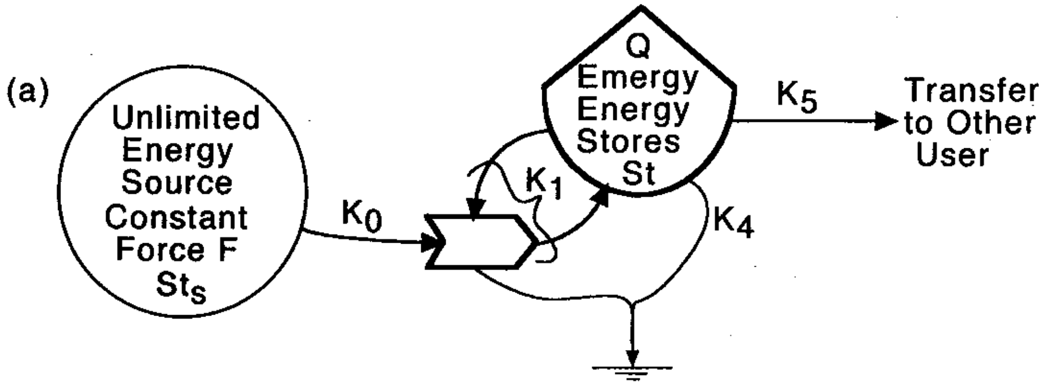
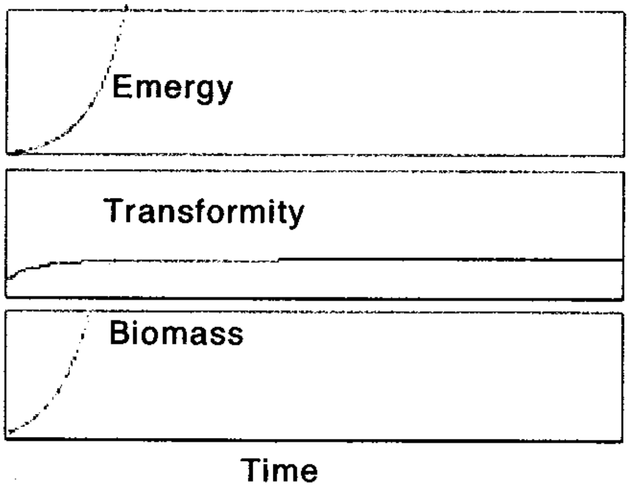


$$dQ/dt = (10*St_S/St)*K_1*F*Q - K_4*Q - K_5*Q$$

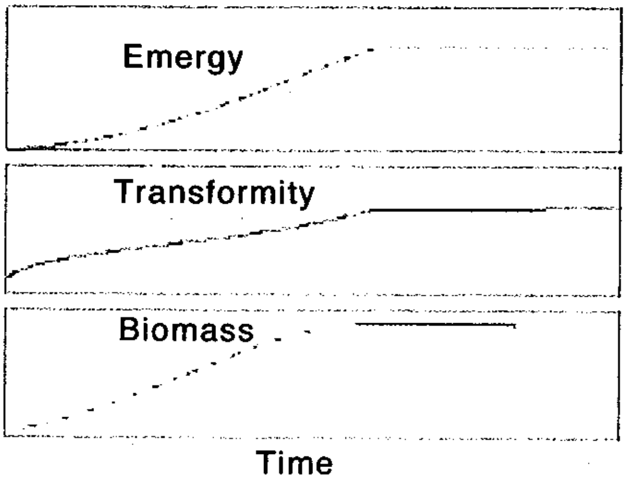
where Sts = Source Transformity

St = Store Transformity = Em/Q

(b) Exponential Growth on Constant Force Energy Source



(c) Growth Levels Because of Increasing Transformity



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