14. Tropical Forest Systems and the Human Economy

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Abstract. Twelve minimodels of tropical forest systems and their interfaces with the economy were used to visualize the changing patterns of forest use and to make public-policy recommendations about sustainable forest management and economic development. To maximize wealth, systems designs were recommended that mutually reinforce production and use. Microcomputer simulations and EMERGY (energy of one kind required directly and indirectly to produce a product) evaluations of these models were made on four scales: (1) a single forest stand, (2) landscapes with many stands, (3) tropical forests in international trade, and (4) tropical forests in the global carbon budget. Emdollars (EM$) of gross economic product estimated from solar EMERGY evaluations were: $19 for an average small tree, $2250 for a typical climax tree, $90,000 for a virgin forest hectare, and $59 billion for 153 populations of tree species. A minimodel, CLIMAX, showed the essence of complex tropical forest succession and management for maximum gross production, efficiency, diversity, and soil restoration with a minor yield of selected trees. In contrast, the minimodel CADAM showed the essence of a simplified tropical forest managed for net production, biomass, and yield with more intensive use of fuels, goods, and services. The minimodel RESERVE included a reseeding cycle of succession and restoration from reserve plots of a complex tropical forest as a means to maximize economic yield in the long run. Minimodels of nutrient supply and recycling showed self-organizational accumulation of recycling materials controlling the rate of succession, eventually eliminating nutrient limitations. The minimodel MATCHUSE, for forest harvest with and without competing species, showed the fallacy of models of economic yield based on a single species without competitors and without consideration of the reinforcement required for sustainable production. The minimodel INTSALE showed the relative benefit of domestic use versus export sales of forest products. Simplified models of the global carbon dioxide cycle showed that permanent removal of vegetation cover causes a major increase in atmospheric carbon dioxide but that this would be entirely reversed by a 20% restoration of the world forest cover.

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Managing forests for domestic use, restricting the free-market stripping of world vegetation, and active restoration of tropical forest cover through the preservation of patches of complex forest will maximize the economic benefit to tropical nations, stabilize world carbon dioxide, and restore a pattern of sustainable forestry now and as world fuel resources decline.

Introduction

All over the world, tropical forests are being reorganized to interface with the human economy. Through economic development, the resources of lands and climate are being combined with purchased materials and services based on fossil fuels. This chapter considers the roles tropical forests play in the global system of humanity and nature. Figure 14.1 summarizes the environmental interface between forests and economic use using the symbols explained in Fig. 14.2.

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The rapid deforestation of the world's tropical forests, which has been alarming for its ecological and economic consequences, requires that scientific and public-policy priorities be given to forest restoration. To be successfully sustainable, forests must receive reinforcement from the larger global economy. Reinforcement of a forest system occurs when it contributes to the larger global system and receives commensurate contributions in return. In Fig. 14.1, contributions of the forest lands and climate are from the left, and reinforcement is the feedback from the right. Economic systems are sustainable only by reinforcing their environmental basis (maximum-power principle, Lotka 1922, 1925).

As the Earth's resources that have previously accumulated become less available after the present consumption frenzy, the forest systems that are now develop-

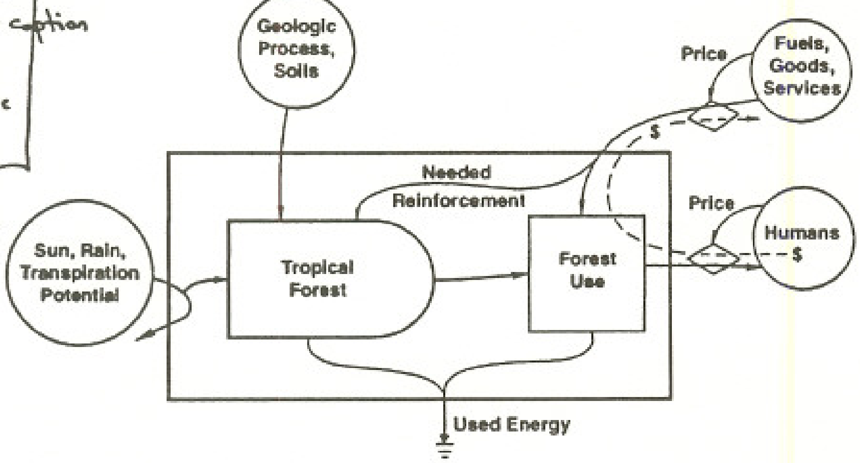
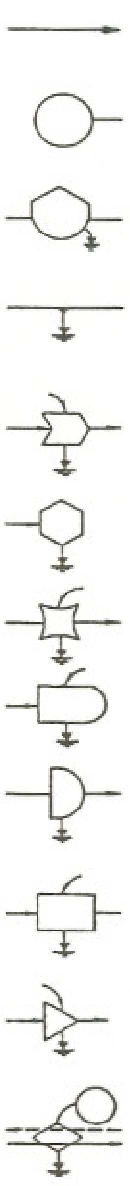


Figure 14.1. Relationships between tropical forest production and economic use, showing main external energy sources (circles), energy dispersal in used form, and flow of money (dashed line). For explanation of system diagrams, see Fig. 14.2.



Energy circuit. A pathway whose flow is proportional to the quantity in the storage or source upstream.

Source. Outside source of energy delivering forces according to a program controlled from outside; a forcing function.

Tank. A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.

Heat sink. Dispersion of potential energy into heat that accompanies all real transformation processes and storage; loss of potential energy from further use by the system.

Interaction. Interaction intersection of two pathways coupled to produce an outflow in proportion to a function of both; control action of one flow on another; limiting factor action; work gate. One or more "x's" inside the symbol means the inputs are multiplied.

Consumer. Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow.

Switching action. A symbol that indicates one or more switching actions.

Producer. Unit that collects and transforms low-quality energy under control interactions of high-quality flows.

Self-limiting energy receiver. A unit that has a self-limiting output when input drives are high because there is a limiting constant quality of material reacting on a circular pathway within.

Box. Miscellaneous symbol to use for whatever unit or function is labeled.

Constant-gain amplifier. A unit that delivers an output in proportion to the input I but changed by a constant factor as long as the energy source S is sufficient.

Transaction. A unit that indicated a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is shown as an external source.

Figure 14.2. Energy symbols used in overview system diagrams (Odum 1983).

Gradual Production and Pulsed Consumption

When viewed from a larger scale, production is gradual, acting over a broad area. The products of production accumulate and are then consumed, often with a sharp pulse of action. Pulses in forests include tree falls, landslides, storms, earthquakes, and epidemic consumption by insects. The hypothesis to account for the prevalence of pulsing consumption is that performance in the long range is reinforced by abruptly resetting productive growth and redispersing nutrients. A system that keeps greater gradients in its energy transformations may transform more energy than one with a steady state.

Hierarchical Distribution of Gaps

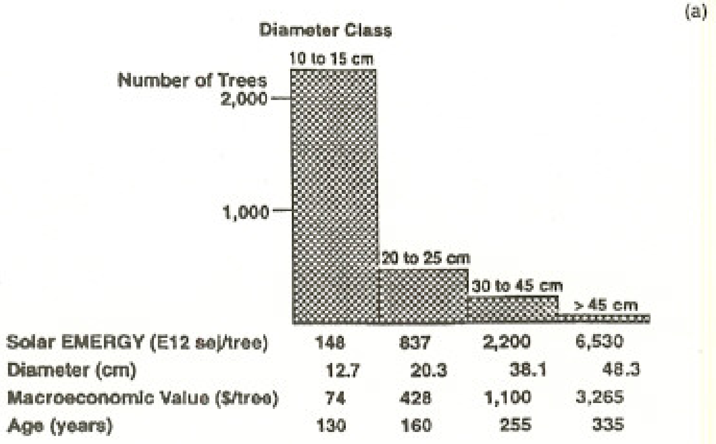
A gap in a forest develops when a tree or group of trees falls. With many individual trees falling in the course of their normal patterns, there are many small gaps. Larger gaps occur with larger-scale processes such as landslides, storms, fires, consumer epidemics, shifting cultivation, and economic uses. In the hierarchies of nature and humanity, size and time are correlated. Larger units take longer for their cycles of growth and pulsing consumption. If gaps are hierarchically distributed, then a graph of the quantity of gaps and gap size may have the shape of the graphs in Fig. 14.3, which shows that small gaps are more frequent.

Transformity, the EMERGY per unit, may be used as a general scaling factor for hierarchies (Table 14.1 with forest examples). The example in Fig. 14.3a is the familiar timber age graph of a forest with values of EMERGY, diameter, macroeconomic dollars, and age. Many seedlings contribute to form fewer saplings, and these to form fewer crown trees. Higher emergies are found in Fig. 14.3a for trees of larger size. EMERGY per area devastated may be assigned for the pulses of forest consumption, as in Fig. 14.3b, which relates number of forest gaps to the transformity of their formation. Where the source of pulsing action is drawn from storages within the system, solar transformities were calculated as the solar EMERGY used up by the pulse. For example, a tree has the stored EMERGY of many years, a main energy source when a tree falls and decomposes.

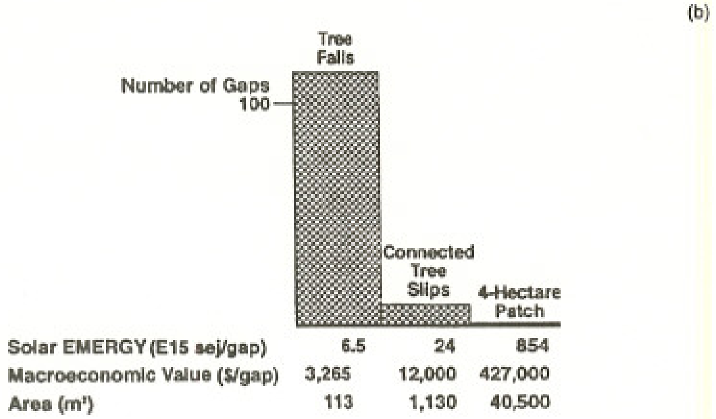
Where the source of action is from outside the forest plot, as with a hurricane, geological action, or human work, part of the EMERGY comes from stores in the stand and part from the outside disturbance. Transformities of larger-scale forces were obtained previously from EMERGY evaluations of earth-scale systems (Odum and Odum 1983, Odum 1986, 1987, 1988).

Hierarchical Levels in Simulation Models

A simulation model probably has to have at least two levels of hierarchical structure because the small, dispersed components are controlled and organized from the centers of larger systems. Whereas the real world has a wide range of hierarchical levels from atoms to stars, a simulation model normally has only two



Trees



Forest Gaps

Figure 14.3. Hierarchical spectral diagrams of forest components using data from the rain forest study at El Verde, Puerto Rico (Odum and Pigeon 1970): (a) Number of trees based on Table 3, p. I-201, and Table 4c, p. I-202; solar EMERGY per area per year based on Gibbs free energy of 2.3 mm/day transpiration multiplied by a transformity of 15,000 solar emjoules (sej) per joule; solar EMERGY of trees derived from annual rate of solar EMERGY times age times area of crown; crown area derived from basal area using graphs from Chapter B9, p. B-105; macroeconomic dollars obtained by dividing solar EMERGY by 2 E12 solar emjoules per 1989 U.S.$; (b) forest gaps include gaps from the fall of mature trees, the slip of a linked plexus of 10 mature trees, and a 40,500-m^2 devastation; solar EMERGY of a gap was calculated as the EMERGY of the forest plot removed in making the gap. Macroeconomic value is also called emdollars.

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Table 14.1. Solar Transformities of Forest Inputs and Components

Component or Input	Solar Transformity[a] (solar emjoules/joule)
Direct solar insolation	1
Light winds	663
Rain	~~1,800~~ 15,000
Leaves	3,185
Young plantation wood	6,700
Old mature rain forest wood	40,000
Soil profile and organic matter	63,000
Motor fuel	66,000
Electric power	200,000
Forest labor	7,600,000
Phosphate fertilizer	10,000,000
Genetic inheritance of tree species DNA:	
Species maintenance	726,000,000,000
Species evolution (10,000 years)	4,800,000,000,000,000

[a] Calculated by dividing the annual solar EMERGY required to make each item in solar emjoules by the energy of the product in joules (Odum 1986, 1987, 1988).

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or three levels. When one has chosen a particular time and space scale, other levels are not important. Fluctuations by much smaller components are filtered out with no effect on the scale of interest. Units of much larger size only affect the window of interest when they pulse, and the pulsing action can be imposed on the model as an external catastrophic event.

There is also a practical reason for not including more than two or three hierarchical levels in a model. If many levels are included, the computer time involved in the smaller oscillations becomes too large for rapid and inexpensive simulation when extended to the longer times for the phenomena of the larger systems levels. Aggregating small phenomena allows larger time steps to be used, which reduces run times and costs manyfold.

Use of Energy System Diagrams to Understand Models

At least for certain types of people, system network diagrams facilitate the human perceptive overview, showing kinetic relationships by the symbols and typical configurations used; energetic relationships by the pathways of flow, storage, and transformation; and hierarchical positions by the location, going from left to right, on the diagram. The energy language symbols used for the overview are those given in Fig. 14.1. The diagrams automatically determine the equations used for mathematical modeling. For each of the forest system diagrams, a microcomputer simulation model is given with the graphic results of simulation runs. The simula-

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tion models are simple BASIC language programs and are available from the author. Without programs, readers cannot really tell how mechanisms and data calibrations were used. The programs can also be used for considering "what if" manipulations on microcomputers of other researchers and for teaching.

The relationships of many small items that contribute to and become organized by larger realms with centers of higher status in hierarchy are shown by positions from left to right on the energy system diagrams. For example, many leaves contribute to fewer limbs to a few trunks. Solar transformity is a general energy-based measure of hierarchical position. A useful graph for representing components of a hierarchical system is the hierarchical spectral diagram with quantity plotted as a function of solar EMERGY per unit (Fig. 14.3a).

Simulation Methods

Microcomputer simulation of minimodels uses a methodology given previously in great detail (Odum 1983) or in shorter form (Odum 1989). Small overview models were studied as controlled experiments. Results were what would happen if the factors placed in the model were the only ones varying, others being held constant. An energy system diagram was drawn, numerical values of flows and storages were placed on pathways, coefficients were calculated, a BASIC language computer program was written, and successive runs were made, changing one factor at a time to find out "what if?"

EMERGY Evaluations and Definitions

After an energy system diagram was drawn, EMERGY evaluations were made of pathways of interest. Solar EMERGY of each pathway of interest was calculated in customary units and then multiplied by solar transformities (Table 14.1), solar EMERGY/dollar ratios, or solar EMERGY per gram ratios to convert data to flows of solar EMERGY (Table 14.2). Often included in an EMERGY analysis table is a final column that indicates how much of the gross national product (GNP) can be attributed to the line item. Expressed in GNP dollars, this is called macroeconomic value. Annual solar EMERGY and macroeconomic values are given in Table 14.2, and the stored values in Table 14.3. EMERGY ratios are given in Table 14.4. The alternatives that will succeed are those that are likely to maximize EMPOWER of the entire system (the forest system and that larger system in which it is embedded). Good management policy anticipates these. For convenience, terms used in EMERGY analysis and synthesis are defined as follows:

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Energy hierarchy is the way in which energies of different types interact according to how much of one type is required to generate another. Different kinds of energy include sunlight, fuel, food, electricity, and human service, listed in order of increasing rank in the natural hierarchy of energy types.

Solar EMERGY is defined as the solar insolation required directly and indirectly to generate a product or process. Its unit is the solar emjoule, abbreviated sej.

Table 14.2. Annual Contribution of EMERGY-Based Value of 1 ha of Tropical Forest

Component	Calculation[a–f]	Raw Data	Solar Transformity[g] (sej/unit)	Solar EMERGY (E12 sej/yr)	EM$[h] (1989 U.S. $/yr)
Environmental inputs					
Direct sun	a	5.85 E13 J	1	58.5	29
Wind	b	9.20 E9 J	6,230	57.3	29
Rain (transpired)	c	4.19 E10 J	15,000	629.6	315
Economic inputs to a tropical forest plantation					
Goods and services	d	U.S.$60	2.0 E12	120.0	60
Fuels	e	7.80 E8 J	5.2 E4	40.5	20
Human esthetic–recreational use, Luquillo Forest, Puerto Rico					
Visitation energy	f	7.18 E7 J	7.6 E6	546.0	273

[a] (3830 kcal/m^2 · day) (365 day/yr) (1E4 m^2/ha) (4186 J/kcal).

[b] (0.6 kcal/m^2 · day wind absorbed) (1E4 m^2/ha) (365 day/yr) (4186 J/kcal) = 9.2 E9J/yr.

[c] (2300 g/m^2 · day transpiration) (5 J/g Gibbs energy) (1 kE4 m^2/ha) (365 day/yr).

[d] Costs $60/ha · yr.

[e] Fuels used at Jari, Brazil, per hectare.

[f] (810,000 visits) (4 h ea) (2500/24 kcal · h) (4186 J/kcal)/19,648 ha = 7.18 E7 J/yr human use · ha;
(29 E15 sej/U.S. person · yr)/[(2500 kcal · person) (365 day/yr) (4186 J/kcal)] = 7.6 E6 sej/J.

[g] Direct and indirect solar insolation required per joule; determined in previous studies from evaluation of world energy and economic systems.

[h] Solar EMERGY/ha · yr divided by U.S. EMERGY/$ ratio 2 E12 sej · 1989 U.S. $ (Odum 1995).

Table 14.3. EMERGY-Based Values of Storage in Various Components of Tropical Forests

Component	Calculation[a–f]	Solar EMERGY (sej)	EM$[g] (E12 sej 1989 U.S.$)
Plantation monoculture			
10 years, 1 ha	a	1.50 E15	750
Mature forest $ soil[h]			
300 years old, 1 ha	b	1.80 E17	90,000
Average tree	c	3.80 E13	19
Dominant climax tree	d	4.50 E15	2,250
Endemic tree species	e	7.70 E20	3.8 E8
All 153 tree species	f	1.18 E23	5.9 E10

[a] Formation in 10 years with average solar EMERGY half of that at the end of growth, which is half the metabolism of the mature forest: (6.0 E14 sej/ha · yr) (0.5) (10 yr) = 1.5 E15 sej/ha.

[b] Average EMERGY used in formation taken as that after 100 years: (6.0 E14 sej/ha · yr) (300 yr) = 1.8 E17 sej/ha.

[c] Assumed average tree over 10 cm dbh at 50 years old and 12.7-m^2 crown area: (6 E14 sej/ha · yr) (12.7 E4 ha/tree) (50 yr) = 3.8 E13 sej/tree.

[d] (6 E14 sej/ha · yr) (0.05 ha/tree) (300 yr) (0.5) = 4.5 E15 sej/tree.

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[e] (6 E14 sej/ha · yr) (128 ha/species) (10,000 yr) = 7.68 E20 sej/species.

[g] EMERGY and macroeconomic value of rain forest trees at El Verde, Puerto Rico evaluated by the preponderance of solar EMERGY, of rain transpired: (2140 g/m^2 water transpired · day) (5 J free energy/g) (365 day/yr) (1 E4 m^2/ha) = 3.9 E10 J/ha · yr; solar transformity of rain = 1.54 E4 sej/J; (3.9 E10 J/ha · yr) (1.54 E4 sej/J) = 6.0 E14 sej/ha · yr.

[h] Solar EMERGY divided by U.S. EMERGY/$ ratio (2 E12 sej/1989 U.S.$).

Table 14.4. EMERGY Indices for Tropical Forest Wood Production in an Underdeveloped Country with Low EMERGY/\$ Ratio[a]

	EMERGY index	
Item	Plantation	Complex Forest
Net EMERGY yield ratio	2.20	12–200
EMERGY investment from wood harvest	2.70	0.14
EMERGY investment from visitation in Puerto Rico	—[b]	0.87
EMERGY benefit/cost to local purchaser	1.80	12.00
EMERGY benefit/cost to seller	0.89	0.14
EMERGY benefit/cost to purchaser in developed country	1.12	7.10

[a] Studies on Jari, Brazil, by Odum et al. (1986).

[b] Data are not available because plantations are not normally visired by tourists.

Solar transformity is the solar EMERGY required per energy unit. It is the solar EMERGY required divided by the energy of the product or process. Its unit is the solar emjoule per joule, abbreviated sej/J.

Solar EMERGY per gram is the solar EMERGY required per unit mass.

Solar EMERGY per dollar is the solar EMERGY required per unit currency converted to U.S. dollars for that year.

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EMDOLLAR value (Em\$) is the solar EMERGY divided by the U.S. EMERGY/dollar ratio for that year. It is also called macroeconomic value.

Net EMERGY ratio is the EMERGY yield divided by the EMERGY required from the economy.

EMERGY investment ratio is the EMERGY coming from the economy divided by the free contribution from the environment.

EMPOWER is the EMERGY flow per unit time of one or more pathways.

E notation is the way in which microcomputers represent large or small numbers using E followed by the number of zeros. This notation is compact and easy to type and read. For example, 673,000 is represented as 6.73 E5, which is the same as 6.73 times 10 to the power of 5. For numbers less than 1, E– is used, followed by the number of decimal points to the right of zero. For example, 0.0000673 is represented as 6.73 E–5, which is the same as 6.73 divided by 10 to the power 5.

Forest Systems on Different Scales

Forest Stand Systems

A great variety of successful tropical forest systems exist, ranging from little-disturbed complex forests to intensively managed monocultural forest plantations.

Minimodel diagrams and simulations are helpful in showing the contributions and limitations of each.

Complex Forest Production, Growth, and Diversity

The basic process of starting a forest is given in Fig. 14.4a and simulated in Fig. 14.4b. This simulation was calibrated with data from the tabonuco forest at El Verde, Puerto Rico (Odum 1964, 1970; Chapter 4, this volume).

After a forest is cut, seeding of a few species adapted for rapid colonizing growth develops gross plant production, which begins to accumulate biomass in wood and soil. Most of the gross production by a few species goes at first into net gain of organic matter. As biomass builds up, more and more users of this biomass develop, including roots, limbs, trunks, flowers, fruits, animals, and microbes. These many consumers have roles that reinforce production, such as nutrient recycling, pollination, seeding, pruning, and regulating populations and building diversity with division of labor among species for more efficiency. Diversity, the number of species per individual counted, has a quadratic energy requirement that may conform to rules of information maintenance and retrieval. Adding a species

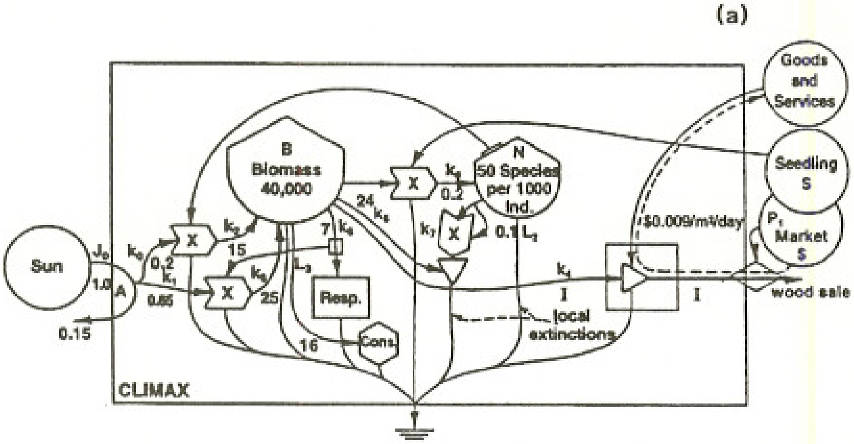

Figure 14.4. Overview of production, growth, succession, and diversity of a forest plot after clearing. The mature stage has a small, regular, steady yield of useful products without much reinforcement to the forest system. (a) System diagram. Abbreviations: A, albedo; B, biomass; N, diversity; X, multipication; S, seeding; P_1, price of forest product; P_g, gross plant production; P_n, net plant production; I, sales of wood; cons., consumers; Resp., respiration; J_o, normalized inflow of light; ks and Ls, coefficients; numbers are calibration data. Equations for program CLIMAX: $R = J_o - k_oRN - k_1RB$; therefore, $R = J_o/(1 + k_oN + k_1B)$. $P_g = k_2RN + k_3RB$. Sales $= p_1k_4B$. $dB/dt = k_2RN + k_3RB - k_5N^2 - k_6B - L_3B - k_4B$. $dN/dt = k_8SB - k_7N^2 - L_2N$. (b) Simulation of typical growth and climax; (c) same as b, but with substantial loading of use without reinforcement; (d) same as b, without available seeding of species; (e) same as b, with pulsing imposed by destruction (stress) from external actions (e.g., landslides, hurricanes, volcanoes).

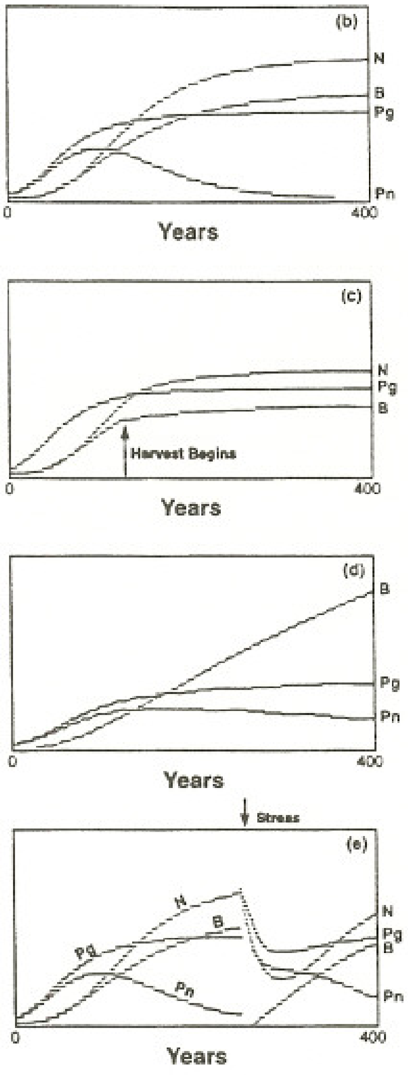

Figure 14.4. *(continued)*

either causes energy to be diverted because of competition or to be utilized to prevent competition by maintaining a separate niche.

In time, the consumption equals the gross production, and net ecosystem production becomes small or nearly zero. This can be called the climax stage, retaining an older name for a quasisteady state of maximum development (Fig. 14.4b). Figure 14.4c shows light removal of single trees on a regular basis, starting after the most rapid growth period. The forest develops a climax with somewhat lower biomass, diversity, and gross production.

In Fig. 14.4d, availability of seeding is limited because a high-diversity forest is too far away to supply the seeds or the animals that transport seeds. With low diversity, more of the energy goes into deposition of organic matter than into diversity maintenance. Gross production is less, but net production is more than in Fig. 14.4b, effects of limiting diversity. Some forests developing far from seed sources form tropical scrub with few species. Sometimes this condition is called arrested succession. More energy goes into biomass and less into diversity.

High net production that is diversity limited resembles agricultural objectives, providing the product is economically usable. Agriculture is a domesticated ecosystem in arrested succession. Usually, however, tropical scrubs tend to be composed of weed species and are not yet developed to yield economic products. They are not even good for biomass yields because the organic matter is dispersed and not yet concentrated into woody packages. The use of widely dispersed biomass may require too much cost. Without the normal diversity of animals, the organic matter does not get processed into soil structures and may accumulate or attract fire.

Figure 14.4e shows the effects of external actions such as landslides and hurricanes. Here, steady-state climaxes may not last long because of disturbance caused by the pulsing oscillations of surrounding, larger systems that remove structure and cause succession to be set back.

Tropical Forest Production and Nutrient Cycles

The model in Fig. 14.5a, also calibrated for the tabonuco forest at El Verde, displays the necessary nutrient materials that are incorporated and cycled. Whereas the model in Fig. 14.4 assumed adequate nutrients and considered effects of species seeding, the model in Fig. 14.5 assumes adequate seeding and considers nutrient roles. An early version was given by Burns (1970) using an analogue computer.

Figure 14.5b starts the model's growth with low initial amounts of biomass and available soil nutrients. Because oligotrophic rainwaters and deep-leached sediments are low in nutrients initially, the nutrient level rises very gradually. As the organic system develops increased biomass, the nutrient levels maintained by recycling increase also.

Figure 14.5c has the pattern in a reasonably mature forest at El Verde in 1970, which was still adding basal area and biomass. In the rain forest at El Verde, there was an annual pulse caused by differences in cloud-cover-controlled light. There were differences in production that showed up in leaf flushes and fruit production, even though the effects were too small to be easily visible to the casual observer. The differences in solar energy input were filtered out by the large biomass in trees and soils (Fig. 14.5a). In the model, the action of the pulse of production affected the available nutrients as shown in Fig. 14.5c. In the short run, the forest controls soil nutrient levels.

In Fig. 14.5d, the model was run for 88 years with a low rate of nutrient inflow from rain and weathering. Then the nutrient inflow rate was increased, and the

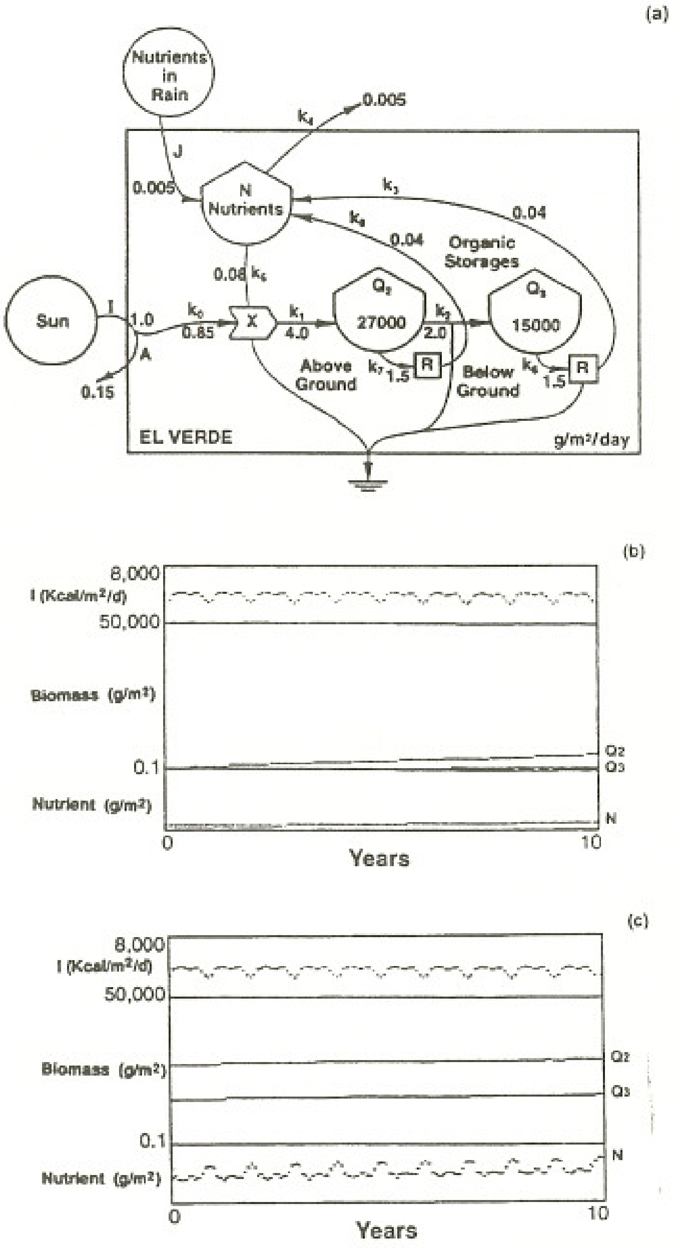

Figure 14.5. Processes of production and nutrient recycling (*R*) in a tropical forest with program FACTORS. (a) System diagram with abbreviations: *A*, albedo; *I*, sunlight inflow; *N*, nutrients; Q_2, aboveground biomass; Q_3, belowground biomass. Equations for program FACTORS: $R_o = I/(1 + k_oN)$; $dN/dt = J + k_3Q_3 + k_8Q_2 - k_4N - k_5R_oN$; $dQ_2/dt = k_1R_oN - k_2Q_2 - k_7Q_2$; $dQ_3/dt = k_2Q_2 - k_6Q_3$. (b) Simulation of program for El Verde, Puerto Rico, in early stages; (c) simulation of El Verde, Puerto Rico program, at near-climax state; (d) simulation of growth with increasing rates of nutrient inflow; (e) simulation of FACTORS2, with gross production a function of nutrient inflow and light intensity (recycle pathways omitted).

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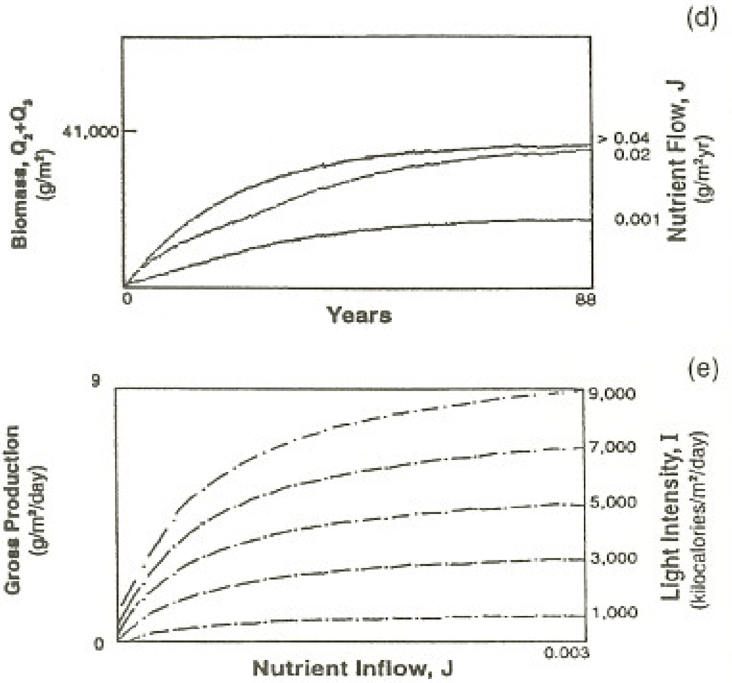

Figure 14.5. *(continued)*

model run again, with a faster rate of biomass growth. When nutrient inflow was very small, the ultimate biomass that was possible was limited to the lower curves in Fig. 14.5d. However, runs with inflows greater than 0.04 g/m^2 · yr had no further effect on growth. With recycling supplying most of the needed nutrients, the forest became energy limited. The forest model developed an increasing nutrient recycle that maintained high availability, overcoming any specific limitations. The only necessary nutrient inflows required were those to keep up with losses. In the model, as in nature, the very large amount of recycling made the forest control its own nutrient levels, almost independently of the concentrations of inflow. Gross production was unaffected by nutrient inflow over a very wide range of time and concentration.

In Fig. 14.5e, runs were made without the recycle pathways (k_3 and k_8) of the model in Fig. 14.5a. With the production process isolated from recycling, only gross production, light, and nutrient inflow–outflow were operating. Gross production was graphed as a function of increasing nutrient inflow for different light intensities. Textbook limiting-factor curves resulted when production was increased by either light or nutrients (Fig. 14.5e). The simulation carried out the relationships of two concurrent production factors given by Rashevsky (1938). The action of limiting factors was measured as the derivative of the response of production to an increase in that factor. A well-developed system keeps all its production inputs at similar sensitivities.

With the recycling included, the system raises the nutrient levels out of the strongly limiting range. Thus, after a period of development, the forest is no more limited by nutrients than by sunlight but is limited by the total input resource. The adaptation to change coefficients so as to maximize the utilization of resources may occur through substitution of species, because different species have different rates for the same process.

Models and Forest Production Indices

Many indices have been used to classify climate and soil factors contributing to primary production in forests. Earlier work usually dealt with two or three properties at a time, such as rainfall, temperature, and insolation. Such indices are really outputs of the models used to represent the basic forest production. For example, the simulation of two factors in Fig. 14.5e is the production function within the model in Fig. 14.5a. In other words, simulation-model outputs are indices of the way the factors operate within a system.

Climatic classifications of a tropical forest use two or three factors at a time, especially transpiration and rainfall. Rather than correlate forest characteristics with factors considered separately, the system approach uses the production function of the model to integrate the input factors. Because the model expresses the results of interaction, the model's production output is the index of factor interaction to be correlated with observed productivity.

When the main physiological processes of tree growth are included in a system diagram, the subsystem for "trees" within Fig. 14.6 results. Leaf heat budgets, leaf transpiration, and the interactions with root processes are included. The transpiration potential of the climate is the Gibbs free-energy difference between the rainfall on the roots and leaf water potential maintained by the wind and the atmospheric water vapor pressure.

The EMERGY of the inputs to the production process is another way to summarize the inputs with weighting of the resources according to one kind of energy basis. The evaluations in Table 14.1 were made by summing the independent inputs. The main input by far is the rainfall, which has a large transformity because it represents the energy transformations over the ocean and the transport work in bringing rain to land. Thus, the EMERGY production rate is a useful index of tropical forest contribution, both direct and indirect, to real wealth.

Yields from a Climax Tropical Forest

Climax tropical forests are complex, and they yield many valuable products and services that can be derived without general clearcutting. Individual trees can be removed to mimic the same kind of opening in the crown that occurs when an individual tree falls. Such gaps provide additional species, structural diversity, and means for maintaining a population of replacement trees.

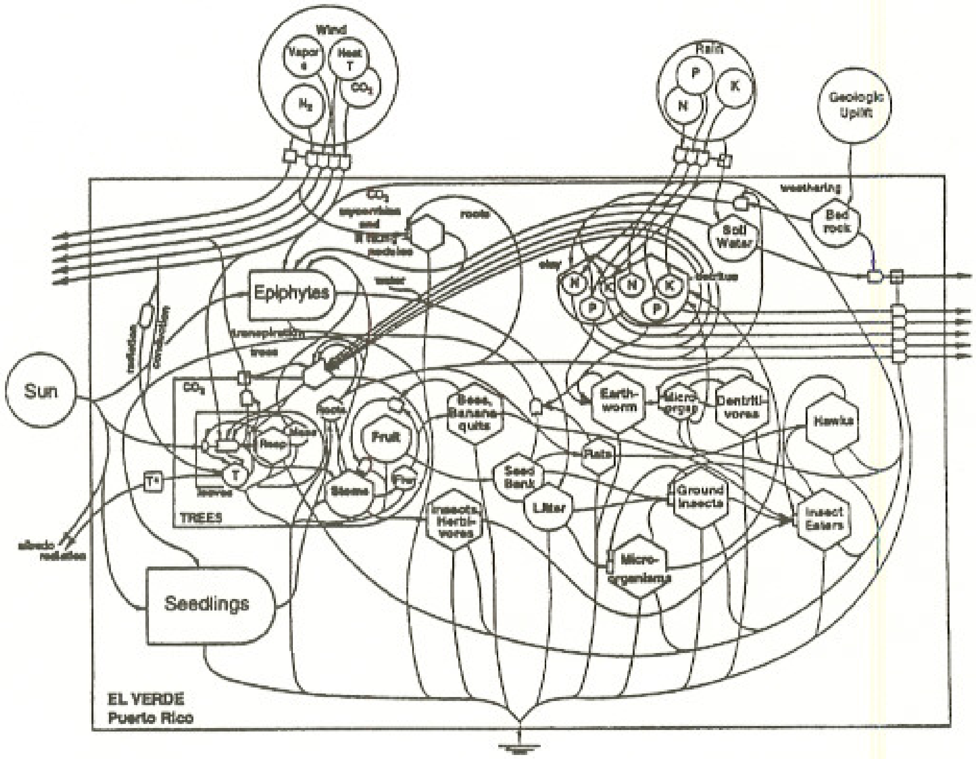

Figure 14.6. Diagram of a moderately complex model of main components, processes, and ecosystem organization of a tropical forest.

Other forests yield products such as Brazil nuts, pharmaceuticals, or rubber. These uses draw from the organic budgets and energy of the forest. They may be reinforced by human labor to manage the forest to produce more of the usable products. Without this reinforcement, the use may diminish the stocks of what is usable.

The overview simulation model in Fig. 14.7a is shown with yields (also see Optimal Use for Maximum Forest Contribution, below), which are sustainable because there are reinforcements back to the forest from the economic process (Fig. 14.2). The EMERGY indices discussed next deal with the magnitude of reinforcement necessary for sustainability.

EMERGY *Indices of Tropical Forests*

Some EMERGY evaluations of a tropical forest are assembled in Tables 14.2 and 14.3 and also expressed in macroeconomic dollars for perspective. Contributions of environmental work to the economy are included in Table 14.2. The output of yields, cleansed air and waters, esthetics, wildlife, microclimate, etc., are by-

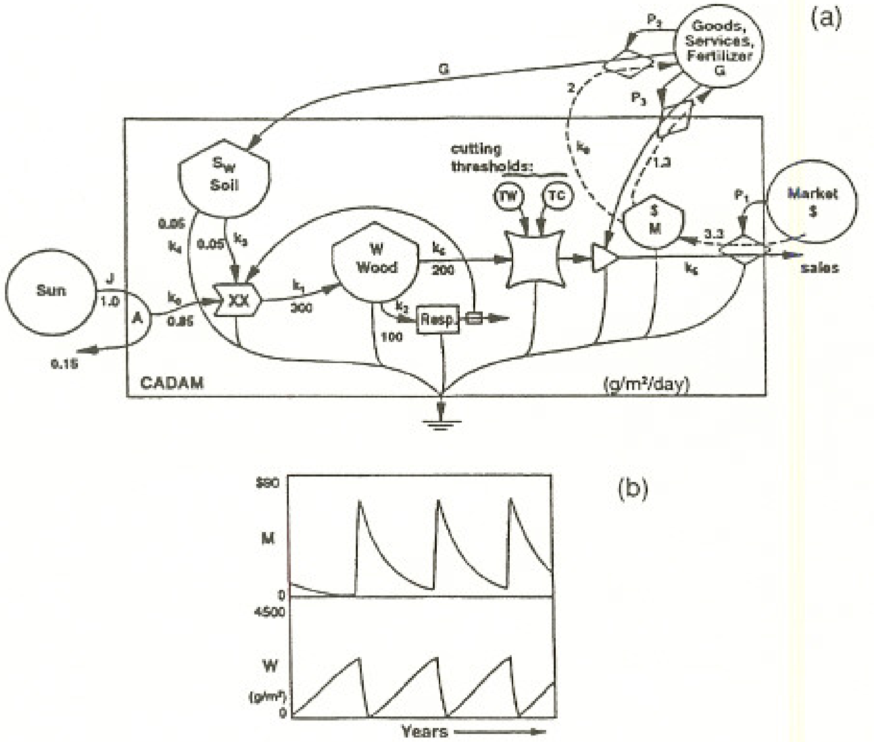

Figure 14.7. Forest plantation growth and harvest and their relationship to economic use and management, calibrated for cadam (kadam), *Anthocephalus chinensis*, in Puerto Rico. Abbreviations: M, working capital; J_o, light inflow; A, albedo (remaining light); S_o, soil; G, goods, services, and fertilizer; p_{1-3} are prices; X, on–off flux depending on threshold; XX, multiplier; Tc and Tw, threshold to start and stop cutting; W, wood in forest stand full scale, 4500 g/m². Equations for program CADAM: $R = J_o/(1 + S_wW)$; $dS_w/dt = k_9M/p_2 - k_4S_w - k_3RS_wW$; $dW/dt = k_1RS_wW - Xk_5W$; $dM/dt = p_1Xk_5W - p_3Xk_5W$ ‸ k_9M; $X = 1$ if $W > T_w$; $X = 0$ if $W < T_c$. (a) System diagram, program from Odum et al. (1986); (b) simulation of typical cycle of harvest and yield.

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products of the single-system process evaluated in EMERGY units. The EMERGY advantage to the buyer is the ratio of EMERGY received to that in the buying power of the money expended.

The EMERGY investment ratio indicates whether a system is likely to be economical. A system is economical if it gets more free environmental resource EMERGY than must be purchased. In other words, a system is economical if its EMERGY investment ratio is less than the ratio for the local regional economy. The regional ratio rises as a region is being developed but will fall again in the future as the world's fuels and mineral resources become less available and more expensive.

By giving each forest system a rating on the scale of economic development intensity (investment ratio in Table 14.4), we can indicate when each kind of forest system will be most appropriate for various stages in the timetable for using up nonrenewable resources. Intensive forest plantations are sustainable as part of developed economies (within developed countries or as international suppliers to such economies). However, less intensive forest silviculture will be normal as the world investment ratio declines. Apparently, the decline is starting already with the recent decrease in world fuel consumption.

Forest Production and the Web of Animal Consumers

Consumers in a tropical forest include the limbs, trunks, flowers and fruits, animals, and microbes. Some are small with a fast turnover and a small territory. Others are higher in the hierarchy with slower turnover and larger territories. The presence of a hierarchical consumer web introduces the possibility of consumer epidemic pulses. Predator–prey-type oscillations may cause a whole ecosystem to fluctuate. The spruce budworm oscillation in coniferous forests is an example. Traditional theory suggested by Elton (1926) is that high diversity interferes with simple consumer–production oscillations. The model in Fig. 14.6 has a consumer web and thus contains more of the complexity of a tropical forest than the overview minimodels in Figs. 14.4 and 14.5.

The forest at El Verde, Puerto Rico, is unusual in that it develops larger populations of the smaller carnivores. The forest has a deafening level of frog calls, conspicuous lizards on all the trees, and very low levels of insect populations. At El Verde, some of the intermediate carnivores are missing, perhaps because of the insular isolation. However, top carnivores, such as hawks, can get to the insular forest by flying, possibly helping to keep down levels of intermediate carnivores.

Plantation Forests

With tropical forest plantations, the arrested succession condition in the system of Fig. 14.4d is harnessed by supplying the seeding of one or two species of successional trees, thus domesticating the low-diversity yield system. Figure 14.7 is a tropical forest model calibrated for the cadam (also called kadam), *Anthocephalus chinensis,* plantations in Puerto Rico. Similar models were provided by Christianson (1984) for forest plantations at Jari, Brazil.

As the simulation in Fig. 14.7b shows, there is rapid growth followed by cutting and sale of the product. The money received is used to finance the next cycle, pay debts, fertilize, reseed, and weed once or twice. The higher the price of the product, the more money is received. Thus, proximity to the market determines the price available to the forest operation in the field. In the plantation system, plantation stands distant from markets will not be able to charge as much for the actual timber in order to compete. As the price of fuels and fertilizers rise worldwide because of increasing scarcity, the cost of most items that forest plantations have to purchase will increase, and the plantations may become uneconomical. Costs of goods and services ultimately depend on cheap fuel, and cheap fertilizer depends on the availability of rich deposits. As the best world deposits are used up, the cost of inputs rises faster than the price of forest products. In other runs of the model in Fig. 14.7, cash available (M) declines when (P_2) and/or (P_3) rises faster than (P_1). Consequently, yields have to decrease because there will not be sufficient cash flow to maintain yields.

Overstory–Understory Yield System

Much of the traditional agriculture of tropical forest regions was from understory tree crops: coffee, tea, tapioca, cacao, etc. In days when most of the labor was by hand, the main structure of the tropical forest was retained to hold the soils, maintain a mineral cycle, fix nitrogen, regulate the microclimate, maintain conditions for insect and bird diversity to provide stability, and shade out runaway weed growth. The forest overstory was trimmed annually to bring in enough light to allow understory trees to produce enough fruit and leaf products to sell.

In recent years, intensive production of these tree crops has been obtained by eliminating more of the overstory and providing the necessary services formerly done by the tree cover by means of purchased inputs of fertilizer, pesticides, and machine labor.

The model in Fig. 14.8a is an overstory forest system calibrated with the help of Dr. Paulo T. Alvim, Comissão Executiva de Plano da Lavoura Cacaueira, Itabuna, Brazil for the cacao production system in coastal Brazil. The simulation run of Fig. 14.8b starts with small biomass in overstory, litter, and cacao. Growth of the overstory without trimming eventually reduces the cacao growth and economic earnings. Trimming of the overstory is simulated by increasing coefficient k_4 (Fig. 14.8a). Less overstory and more cacao result (Fig. 14.8c), although the nutrient (N) cycling is less.

When the price of cacao (P_1) is increased, more fertilizer can be added, and nutrient levels will be higher, growth will be faster, and the tendency to shade out the cacao will be greater. Yields will not be higher, but earnings will be increased.

Forestry Stand Models

The overview models of forest plots in this chapter concern total production potentials, sustainable cycles, and their relationship to the worldwide economy. On a different scale, important tropical forest simulation models are being developed to represent tree stands, their growth, and yield to cutting. For example, Miyanishi and Kellman (1988) simulate the response of tropical tree species to fire in Belize. Lynch and Moser (1986) develop a model for the basal area of mixed forest stands. Pienaar and Turnbull (1973) use a Von Bertalanffy growth model for basal area and yield in even-aged stands. Daniels and Burkhart (1988) review whole-stand models, size-class distribution models, and individual tree models for predicting and managing forest stands for yield.

The intent and utility of stand models for a particular forest that are calibrated for local conditions are to provide an accurate prognosis of stand growth, harvest, and regrowth for various conditions of planting, fertilization, and other land manipulations available to stand managers. With these models, the power of the

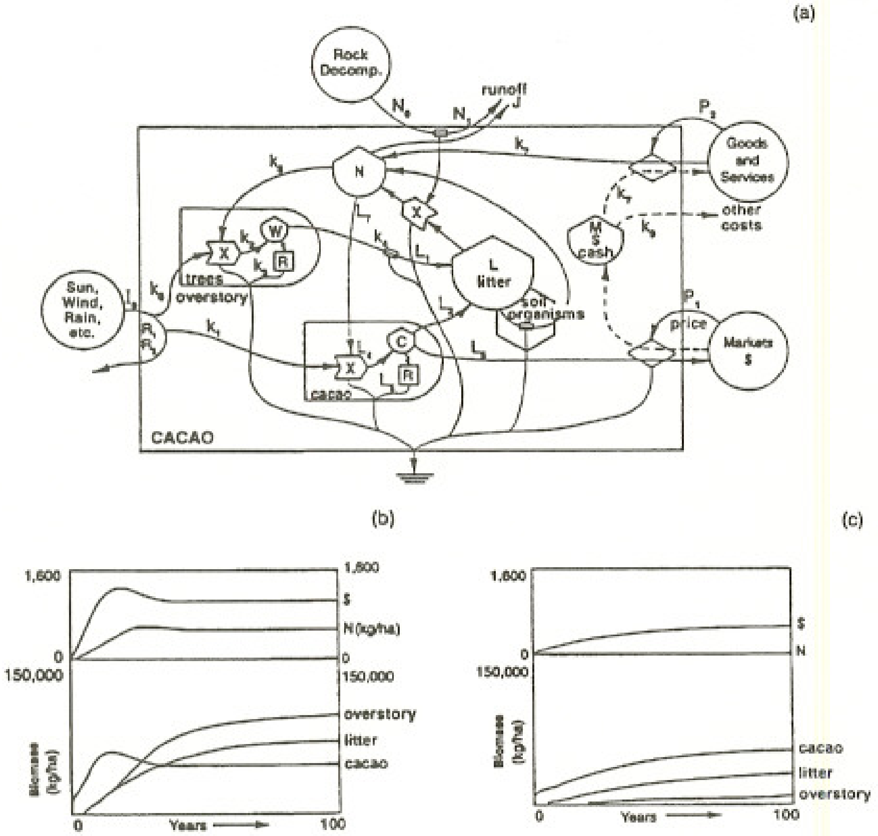

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Figure 14.8. Overstory-understory yield system calibrated for Brazilian cacao (*Theobroma cacao*). Abbreviations: $\underline{N}_o$, nutrients from rocks; I_o, light intensity; J, phosphorus outflow; M, working capital; W, biomass of overstory trees; C, biomass in cacao trees; L, ground litter; N, nutrient such as phosphorus; R, respiration; R_1, light below crown; R_2, unutilized light; N_1, unutilized soil grains; P_1 price of harvested beans; P_2, price of goods and services purchased; X, multiplication; L_1 and L_2, litterfall; L_3, L_4, and L_5, within-organism transfer of nutrients; L_6, export of cacao; L_7, import of nutrients; J, runoff. (a) System diagram, with equations for program CACAO: $R_1 = I_o/(1 + k_oN)$; $R_2 = R_1/(1 + k_1N)$; $N_1 = N_o/(1 + k_9L)$; $dW/dt = k_2R_1N - k_3W - k_3W$; $dL/dt = L_1W + L_2C - L_3L - k_{10}N_1L$; $dC/dt = L_4R_2N - L_5C - L_6C - L_2C$; $dM/dt = P_1\,k_6C - k_9M - k_7M$; $dN/dt = k_5N_1L + k_6L + k_7M/P_2 - k_8NR_1 - L_7NR_2 - J$. (b) Simulation of typical growth and plantation establishment; (c) effect of decreasing overstory (shade) trees.

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computer can be used to interpolate between field measurements to provide performance tables with high predictability for the calibrated situation.

Landscape of Multiple Stands

Next, consider a larger scale, one containing many forest plots, each in a different stage of growth, use, and rotation. In models of composite overview, we consider the rotation of land from one stage to another. In these models, land area in each stage is represented by a storage symbol (tank). The sum of the total land is held constant during the simulations.

Mixtures of Plantations and Complex Forest

Figure 14.9 represents a landscape with some areas in plantations (see Fig. 14.7) and some areas of complex forest (see Fig. 14.4). The two models were joined into a single model by linking the two types of systems by land rotation. As shown in Fig. 14.9a, the seeding process of the complex forest tends to incorporate plantation lands (Ap) back into complex forest lands (Ac), and economic success (Mp) causes more investment, which converts Ac into Ap.

Figure 14.9b shows a simulation with low prices caused by a long distance to markets. The result is a loss of plantation area as money is lost. Wild regrowth is faster than economic development. In Fig. 14.9c, with higher prices, the plantation area increases, expands, and takes over the complex forest lands as profits increase. The tropical forests of the world are now being incorporated into the frenzied economics of developed countries while fuels for transport are still moderately cheap. The yield system prevails during these times.

Mosaic of Lands in Rotation between Economic Use and Fallow Restoration

The land-use system in Fig. 14.10a represents the pattern of rotating land between economic use and release for automatic reseeding and restoration through a fallow period. Shifting agriculture is an example of this rotation that has been a traditional means of subsistence living in the forested tropics.

As shown in the overview (Fig. 14.10a), the rate of reseeding depends on the close proximity of a complex forest with high diversity of plants and their animal means of seeding and transport. Without the nearby availability of seeding, the regrowth is only from wind-blown seeds, and an arrested succession may occur with a long delay in restoring economic potentials. This overview model shows why retaining diversity areas, with gene pools of complex forest, is essential to maximizing economic yields.

The overview model (Fig. 14.10a) shows the proportions of land areas in different parts of the cycle: (R) reserve land with high-diversity seed sources and animals for dispersal; (B) bare area being seeded; (S) seeded area undergoing ecological succession; and (A) area in agricultural or forestry use delivering a yield with economic value. Simulation indicates the yield to be obtained for a set

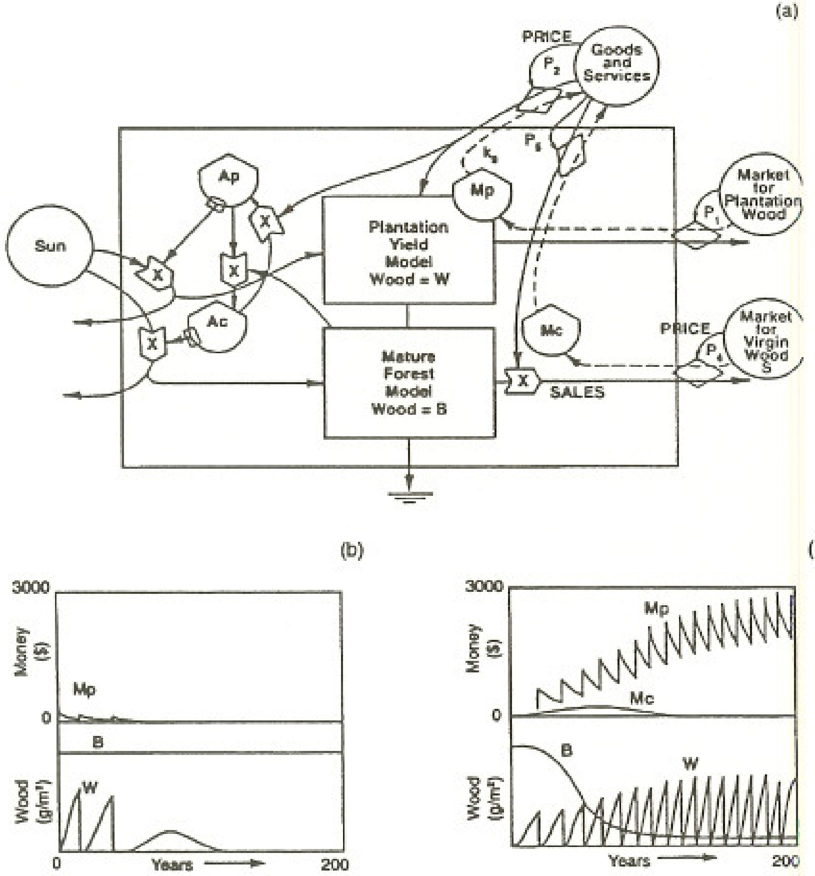

Figure 14.9. Composite system of plantations and complex forest areas and their control by economic price; program from Odum et al. (1986). Abbreviations: *Ap*, plantation lands; *Ac*, complex forest lands; *Mp*, working capital for plantations; *Mc*, working capital for products from the mature forest; *W*, wood in plantation stands (full scale, 4500 g/m^2); *B*, biomass in mature forest stands (full scale, 45,000 g/m^2); P_1, price of plantation wood; P_2 and P_5, price of goods and services; P_4, price of products from mature forest; *X*, multiplication; *k*, transfer coefficients; *K*, total land area. Equations as in Figs. 14.4 and 14.7 linked by conservation of area, *A*: $dAp/dt = Ack_9Mp/P_3 - kBAp$; $Ac = K - Ap$. (a) Energy system diagram; (b) simulation with low prices causing decline in economic use and increase in areas of forest regrowth; (c) simulation with high prices causing an increase in plantations and a loss of complex forest.

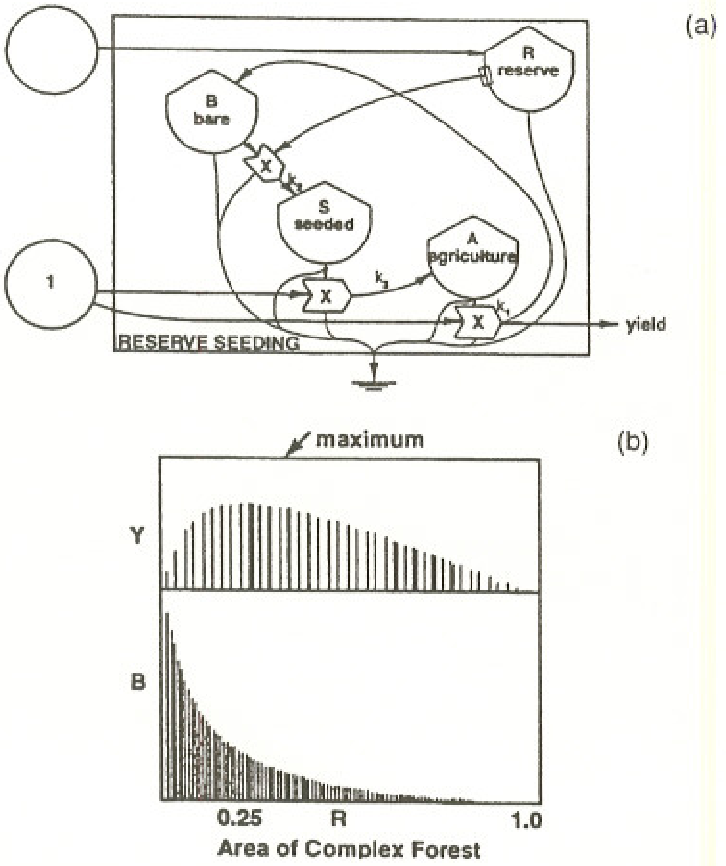

Figure 14.10. Model of land rotation between economic use and fallow restoration, RESERVE. Abbreviations: A, area in agriculture or plantation use; B, bare area; S, seeded area; R, area of complex forest reserve with high diversity plants, animals, and microorganisms for restoring soil; Y, economic yield; X, multiplication; k, transfer coefficient. (a) System diagram with equations: $R + B + S + A = 1$; $Y = k_4A$; $dB/dt = k_1A - k_2BR$; $dS/dt = k_2BR - k_3S$; $dA/dt = k_3S - k_1A$. At steady state, $dB/dt = dS/dt = dA/dt = 0$, and $A = k_2R(1 - R)/k_1 + (k_2 + k_1k_2/k_3)R$. (b) simulation of a set of runs determining what size area of complex forest maximizes economic contributions with values appropriate to El Verde, Puerto Rico.

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of rates for each area. Figure 14.10b shows the steady-state yield for different sizes of reserve area (R). A maximum sustainable economic yield is found with an intermediate-sized area reserved for reseeding the soil-building restoration.

The economic use may be a forestry plantation. Where plantations develop a fairly complex natural understory, the economic yield potentials of the land may not be lost as fast as with some kinds of agriculture with less biodiversity.

More intensive patterns of shifting agriculture in recent years involve higher population densities, more purchased inputs during the period of economic use, and economic pressures to put more lands into use than can be sustained by the rotation (Myers 1984). In other words, people desiring to purchase the goods of a higher-EMERGY-level existence begin to rotate too fast and export more than is sustainable. Without adequate rotation time, even subsistence fails, and it is often replaced by cattle ranching and other export-oriented uses.

Simulation Model of Hierarchy of Gaps in Tropical Forests

Shugart (1984) reviews simulation models that generate a mosaic of forest trees and gaps from individual trees growing and falling. Doyle (1981) applied the model to predict gaps at El Verde with disturbance acting to make more tree-fall gaps. These models generate some larger-scale patterns from the behavior of single trees, but mechanisms at only one or two levels of hierarchy are recognized. Richardson (1988) simulated spatial hierarchy with a pulsing model that generated hierarchy. Producers and consumers alternated pulses of growth.

The discussion of Fig. 14.3 suggested that many levels of hierarchical organization of a tropical forest may be reflected in the distribution of gaps (locations where there has been pulsed consumption followed by the start of regrowth). The applicable theory is that self-organizing systems have their spatial dimensions in proportion to the pulsing intervals, both a manifestation of an energy hierarchy. The hierarchies in natural forests may be on the same principle as the landscape organization under forest use. A simulation model relating energy, space in gaps, and oscillatory frequency results in a quantitative hypothesis relating kinetics, energetics, and geometric pattern. Although it is considered here for forest gaps, the model should be pertinent wherever there are self-organizing systems developing energy hierarchies.

The gap-hierarchy model is diagrammed in Fig. 14.11a, and according to the energy language convention, hierarchical position is indicated from small and rapid on the left to large and slow on the right. The diagram shows the mechanisms of the model. Land was rotated between forested area (F) and gaps (areas without forest) and grouped in four sizes (A, B, C, and D). Tank A represents the many small gaps generated by tree falls. In the simulation, the rate of flow from forest to small gaps was proportional to the forested area but varied by a random number generator.

Gaps of a larger size in tank B were generated by a program subroutine representing the driving function (*H*) generated by the larger, outside system, which has pulses representing storms, landslides, etc., of medium scale and frequency. The program generated the outside driving function (*H*) with a submodel (predator–prey–type oscillator with variables H and H_1). Another such oscillator (variables H and H_1) on a slower time scale was used to generate the pulsing stresses H_1 that produce major cleared areas on a long period in category D. Gaps of intermediate size (tank C) were generated by an oscillation caused by predator–prey relationships between U and W, simulating internal clearing mechanisms such as epizootics. Graphs of the driving functions H_1 and H, internal oscillating pair (*U*), and areas of gaps A, B, C, and D are shown in Fig. 14.11b.

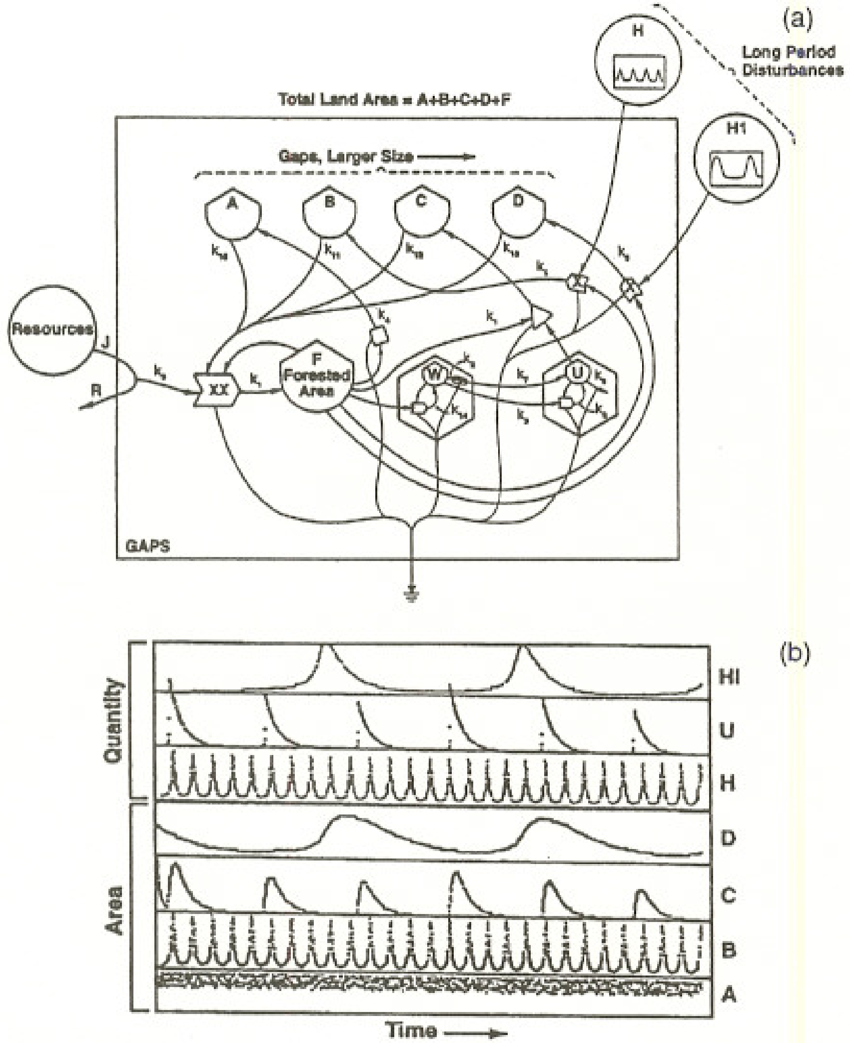

Figure 14.11. Model of gap generation and restoration in a tropical forest, GAPS. (a) System diagram. Abbreviations: A, area of tree-size gaps; B, area of multitree gaps; C, area of several-hectare gaps; D, area of major clearings; U, predator–prey type of oscillatory, epidemic-generating gaps within the forest; F, area in forested cover; TA, total area; G, total gap area; H and H_1, outside factors with long-period oscillations; Q, wood; Q_1, competing biomass; J, input of light; R, remaining light unused; k, transfer coefficients; X and XX, multipliers; M, state variable. Equations: $G = A + B + C + D$; $F = TA - G$; $R = J/(1 + k_0G)$; $dA/dt = k_4F - k_{10}AR$; $dB/dt = k_5FU \cancel{+} k_{11}BR$; $dC/dt = k_1U - k_{12}CR$; $dD/dt = k_6FH_1 - k_{13}DR$; $dU/dt = k_7W + k_8WU^2 - k_9U$; $dW/dt = k_{14}FW - k_2W - k_3WU^2$. Equation pairs used as outside oscillating driving functions: $dQ/dt = k_{20}M - k_{21}Q - \boxed{k_{22}QH_1^2;}$ $dH/dt = k_{21}Q + k_{22}QH^2 - k_{23}H$; $dQ_1/dt = k_{20}M - k_{21}Q_1 - \boxed{k_{22}QH_1^2;}$ $dH_1/dt = k_{21}Q + \boxed{k_{22}Q_1H_1^2} - k_{23}H_1$. (b) Simulation of GAPS to show growth and pulsing with time; (c) results of simulation with GAPS plotted on a graph of quantity and position in the hierarchy.

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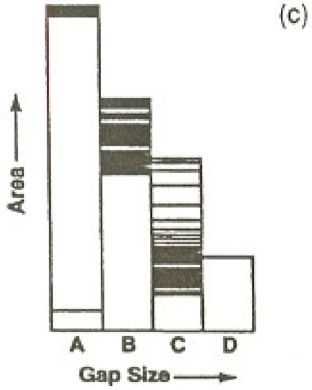

Figure 14.11. *(continued)*

The program may also be set to show bar graphs of the area for each gap-size class (Fig. 14.11c). Bars are in hierarchical order from small gaps (A) at the left to large gaps (D) at the right. During a run, the bars are continuously graphed by the program, thus simulating the gap hierarchical pattern occurring in nature. As the simulation runs, the bars are shown at different levels going up and down with the oscillations. The program keeps the old positions on the screen for a time, clearing the screen at intervals. The pattern in Fig. 14.11c is typical, with more small gaps (A) being maintained than larger gaps (D). Brokaw (1990) found a hierarchical bar graph distribution of gap area at El Verde not unlike that in Fig. 14.11c.

The configuration of W and U in Fig. 14.11 is the classic predator–prey pathway with linear pathways added. It has the same configuration (linear and autocatalytic pathways from W to U with recycle) used for the external pulse generators (H and H_1). In temperate forests, such biotic internal oscillations that generate gaps are well known, such as the spruce budworm epidemics. However, the extent of internal biotic gap generators in tropical forests is not clear yet. Benedict (1976) studied herbivory and holes in leaves in tropical forests of Puerto Rico and found a wide range of rates. For the El Verde forest, there may be other mechanisms generating the medium-sized gaps. In many lectures, Ariel Lugo has described the interlaced growth of tree roots in rough topography so that groups of trees fall rather than single trees (see Chapter 4, this volume).

The self-organization idea is that whichever gap mechanisms get started become reinforced by improved gross production. The gap-generating mechanism is the means, but the large-scale causal reason is the greater performance achieved with hierarchical gap structure. If there is a natural pattern of gap generation and restoration that gives sustained production and maintenance of information and diversity, it may be desirable in planning economic-use patterns to control size and times of human disturbance to follow the same graph (Figs. 14.3 and 14.11c).

Individual Tree Model of Forest Hierarchy

Doyle (1981) and Weinstein and Shugart (1983) adapted an individual tree summation model used earlier in the Appalachians to the tropical forest at El Verde. This class of model identifies each tree and has it growing according to its species characteristics and the local conditions of space-proportional light and nutrients. Tree mortalities were applied by species, and the gaps created were started with new trees according to propensities for reproduction of the surrounding stand. This approach allows application of growth characteristics of each of the species included in the model while restricting growth according to crowding and available resources.

The authors published a graph of dominance and diversity generated by the model. Plot dominance (basal area) was graphed as a function of rank order starting with the dominant tabonuco. Such rank-order curves have been interpreted by some to be a result of random influences in dividing up the resources available to the different species. The result of fractal divisions is hierarchical. I have suggested that the rank order represents hierarchical influences by which some more abundant dominants are at the base of the network supporting the complex web of the ecosystem. The Weinstein–Shugart (1983) simulation shows that the tendencies of the individual species generate a hierarchy. These are not incompatible statements, because there have to be mechanisms for generating the hierarchies that are necessary properties of successful organization. The individual-tree method uses the autecology of the species and interactions, such as light sharing among adjacent trees, to generate observed patterns. Apparently, the fitting together of species with somewhat different growth characteristics by dividing up a resource is inherently hierarchical, which may be why the evolution of a forest species has retained the genetic mechanisms for this kind of self-organization.

Optimal Use for Maximum Forest Contribution

A model, MATCHUSE, in Fig. 14.12a was simulated to illustrate the principles of optimum forest use. This is a quantitative expression of Fig. 14.2. Forest products (Q) are developed by environmental work. Economic use develops the interface with assets (A), which delivers products and/or services and receives money. The money received from sales and from outside investments is used to purchase necessary inputs (goods, services, fuels, etc.). Because the sales price was held constant, the detail on sales was omitted from the diagram to make it simpler for showing points about EMERGY and reinforcement. Representative simulations in Figs. 14.12 to 14.14, showing the effects of competition and economic reinforcement of preferred forest products, are discussed in the following paragraphs.

As it runs, the program for the model calculates the solar EMERGY exchange between the forest system and the outside economy. Flows are multiplied by the solar transformity in solar emjoules/joule (TJ, TF, TY, etc.; see Table 14.2) to obtain solar EMERGY flows (EI, EF, EY, EV, EVC). The total solar EMERGY (ET) that goes from the forest to the economy is the sum of the paid-for yield (EY) and

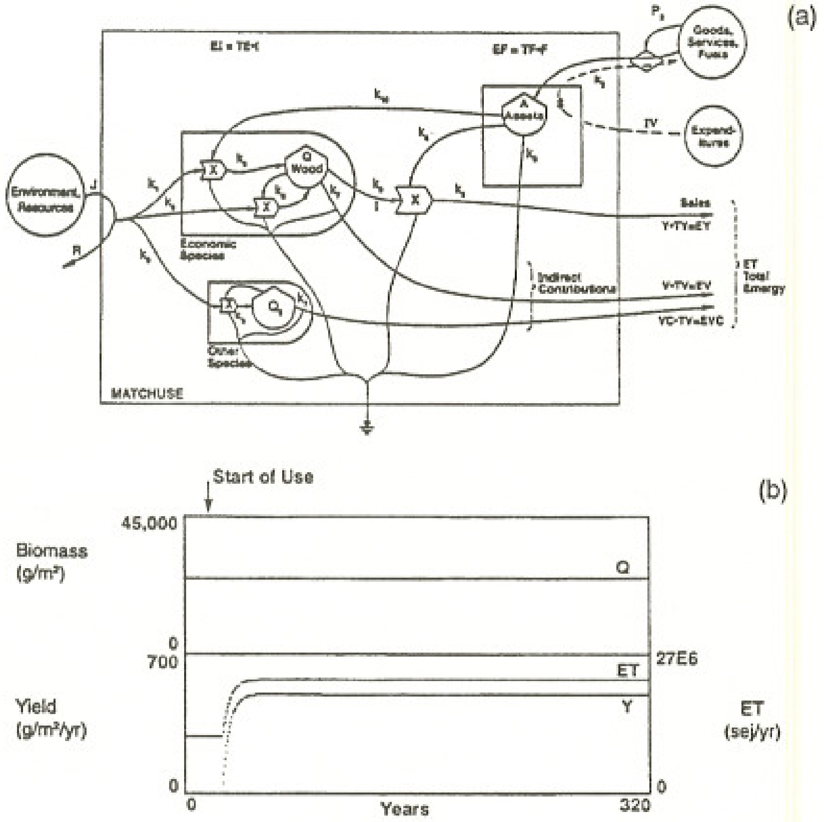

Figure 14.12. Model of EMERGY contributions and economic use of a tropical forest, MATCHUSE. Abbreviations: Q, wood of commercial species; Q_2, biomass of forest competitors; A, economic assets of forest user; P_2, price of assets purchased; Y, sales yielded; V, intangible contributions of the commercial stands to the economy; VC, intangible contributions of competing species to the economy; ET, total EMERGY derived from the forest; EF, EMERGY purchased; EI, free EMERGY contribution to commercial production from environment; R, resource remainder; J, resource inflow; I, environment resource used; F, flow of fuel, etc; TE, TF, TY, TV, transformities of environmental resource, fuels, etc. yield, and indirect value; EI, EVC, EF, EY, EV, flows of EMERGY in inflow, indirect values, fuels, etc. and yield; k, transfer coefficients; X, multiplication; P, price; Z, on/off switch; M, money. (a) System diagram with equations: $R = J/(1 + k_0Q + Zk_1A + k_0Q_2)$; $Y = k_5QA$; $dQ/dt = k_6RQ + Zk_8RA - k_7Q - k_9QA$; $dQ_2/dt = k_8RQ_2 - k_7Q_2$; $dM/dt = P_1Y - k_2M + IV$; $dA/dt = IV/P_2 - k_3A - k_4QA - k_{10}RA$. (b–d) Simulation of forest properties over time with economic use beginning after 10 years; (b) simulation of Q without competitors Q_2 and without reinforcing feedback pathway k_{10}; (c) simulation with economic species Q and noneconomic competitors Q_2 but without feedback pathway k_{10}; (d) simulation with both Q and Q_2 and with feedback reinforcement by economic users k_{10}.

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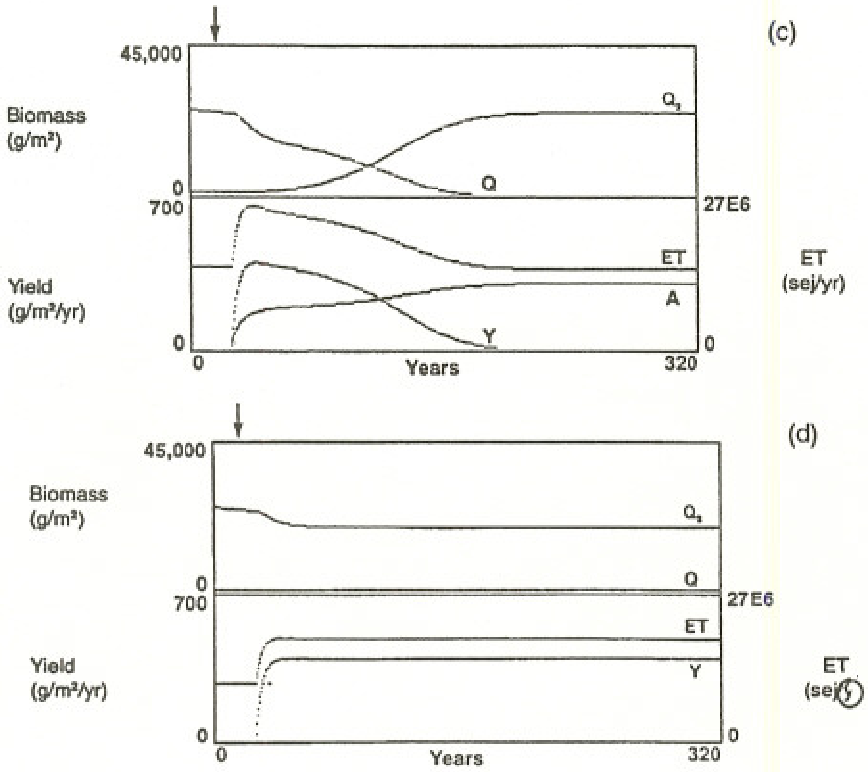

Figure 14.12. *(continued)*

the indirect flows (EV, EVC) that are not recognized as paid sales or services. The feedback to the forest system from the outside economy is EF.

In addition to time simulations, the program MATCHUSE generates graphs of the steady-state outputs of the forest as a function of the intensity of economic purchases (feedback flow, F). This kind of graph makes it easy to locate the maxima of various flows and storages as the intensity of purchased inputs is increased from zero to high values with diminishing returns. Although a user might seek maximum yield, maximum sales, or maximum EMERGY drawn from a forest, a larger-scale view for public policy decisions would seek maximum sustainable EMERGY contribution from the forest and the purchased resources. The theory is that self-organization, by mutual reinforcement, eventually maximizes EMERGY production and use, which is the primary reason for managing for this result. For maximum performance, the EMERGY of the purchased part of the inputs (EF in Fig. 14.12a) should achieve as much environmental matching (forest production, EI) as the alternative use of these resources typical of that region.

The simulations are made in three stages, each with a larger view of ecological economics (Fig. 14.12b,c,d): first, considering yield (Y) of one producing species

(Q) alone; next, considering the yield when there are other species (Q_2); and finally, considering the way feedback reinforcement (k_{10}) can make a sustainable yield in the face of competition by the other species.

Forest Product Evaluation without Competing Species Considered. Consider a harvest system as if it were isolated and did not have alternative competing species pathways. Figure 14.12b shows the startup of a forest-yield system that goes into a renewable steady state. In other words, the area included is large enough so that the cutting of separate stands averages out.

Figure 14.13a,b shows the steady states for successive runs of the model in Fig. 14.12 with an increasing component of purchased inputs (F). Compare the maxima of the graphs for ET and Y. The maximum EMERGY contribution to the

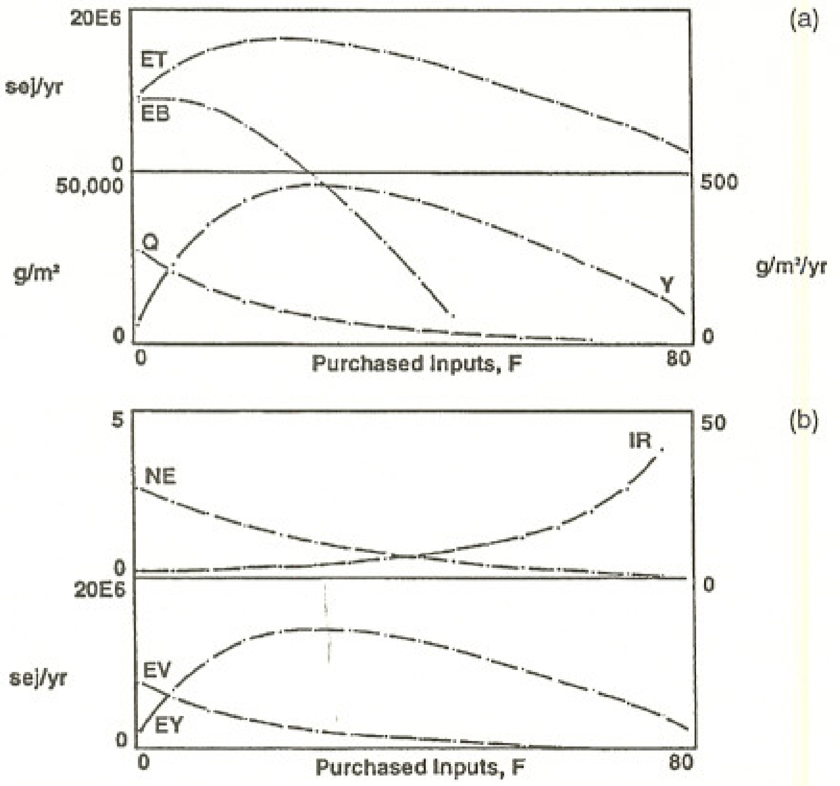

Figure 14.13. Results of simulating the model MATCHUSE in Fig. 14.12 without competitors Q_2 and without feedback reinforcement k_{10}. Graphs of steady-state forest properties and contributions as a function of the intensity of purchased inputs (*F*). (a) Abbreviations: *ET*, total EMERGY contribution; *EB*, EMERGY yield in excess of alternative investment with 7/1 investment ratio = (*EF* + *EF*/7); *Y*, yield; *Q*, useful stock. (b) Abbreviations: *NE*, net EMERGY ratio = *EY*/*EF*; *IR*, EMERGY investment ratio = *EF*/*EI*; *EY*, EMERGY in yield; *EV*, EMERGY of intangible contributions from commercial species.

whole economy (ET) occurs at less development than does the maximum yield (Y) or sales. The intensity of economic development that represents the best overall use of purchased resources is less developed than that for maximum yield.

This single-product analysis is very incomplete and is presented here only to show how misleading the results are in representing population yields in ecosystems. Most fisheries and some forests have been managed as if there were an optimum yield estimable from the single species population alone. Without appropriate reinforcement, such management is an invitation to loss of the resource. (See the next simulation.)

Forest Production with Competing Species Considered. The representative time simulation in Fig. 14.12c includes a competing alternative species that has the same coefficients as the usable production process. As soon as some harvesting is started, the desired species (Q) is driven out and replaced by the species not being harvested (Q_2). Yield goes to zero. Figure 14.14a,b shows the contribution versus intensity of economic inputs (F). The production system (Q) is not sustainable as the swap of species occurs (Figs. 14.12c and 14.14).

The program counts the EMERGY contribution of the unusable species as part of the indirect contribution to public value because its functions are usable for maintaining soil-, water-, and air-regulating processes. However, without feedback of the EMERGY of the purchased inputs, the total EMERGY contribution of the forest is less than its potential. Most public fisheries of the world fit this case and have proven to be unsustainable. All the optimum-catch models were irrelevant because they did not include the whole ecosystem web.

Economic-Based Feedback Reinforcement. In contrast to fisheries in public waters, forest practices have often reinforced the food chains that are the basis for economic interfaces. Note the feedback pathway (k_{10}) from A to amplify and reinforce the desired production pathway in Fig. 14.12a. In Figs. 14.12d and 14.15a,b, simulations are made with the same procedure as before, but with the reinforcement pathway included. The effect of the reinforcement counterbalances the negative effect of harvest, and the desired species (Q) maintains its competitive position (Fig. 14.12c).

Figures 14.13 through 14.15 overview the matching of the environmental contribution of EMERGY with the inputs from the use interface. The simulation generates EMERGY and transformity values. There is growth as available resources from outside are drawn into system development. The graph in Fig. 14.15b shows the EMERGY contributions as a function of increased use and increased inputs from outside. A plateau on the right develops with higher intensities of use because increases of inputs from use begin to cancel out the contributions from the environment. Also, the combined values of environment and use require the matching of lower- and higher-quality inputs. As uses become excessive, there is a diminishing return because the environmental inputs are source limited. Maximum contribution is not found in the range of energy investments given.

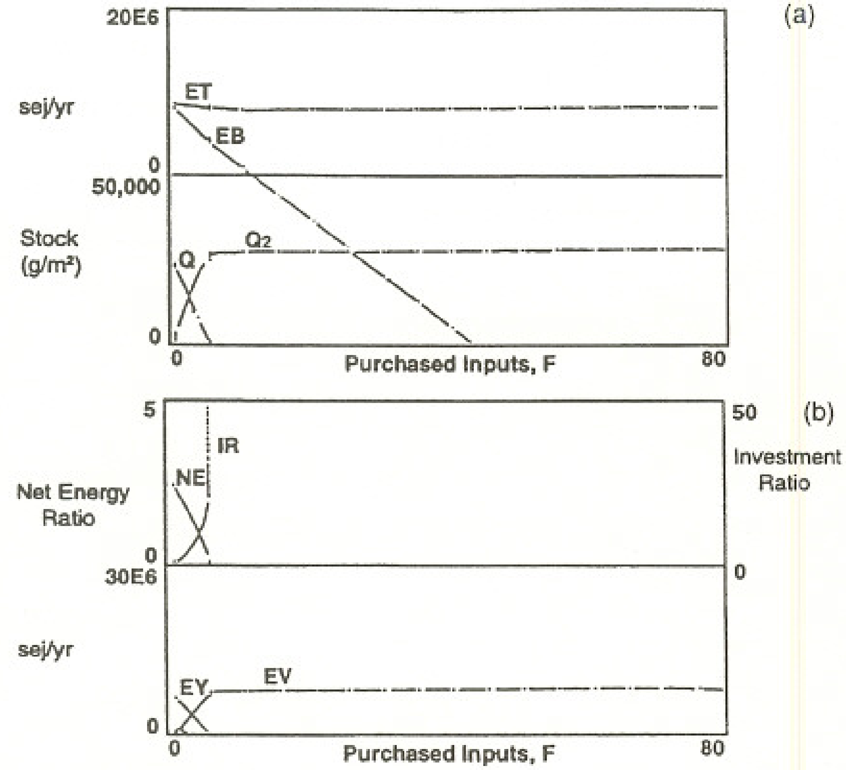

Figure 14.14. Results of simulating the model in Fig. 14.12a with competitors Q_2 and no feedback reinforcement from users. Graphs of steady-state forest properties and contributions as a function of the intensity of purchased inputs. (a) Abbreviations: *ET*, total EMERGY contribution; *EB*, EMERGY yield in excess of alternative investment with 7/1 investment ratio = $(EF + EF/7)$; Q, useful stock; Q_2, competitors. (b) Abbreviations: *NE*, net EMERGY ratio = EY/EF; *IR*, EMERGY investment ratio = EF/EI; *EY*, EMERGY in yield; *EV*, EMERGY of intangible contributions from commercial species.

Ecological Economic Indices. Figures 14.13 to 14.15 plot indices as part of the output of the simulations of the model in Fig. 14.12. Net EMERGY-yield ratio (NE) is the yield EMERGY (EY) divided by the EMERGY feedback from the economy (EF). This ratio is useful for considering whether a source is a primary source capable of supporting more of the economy than itself. In recent years, nonrenewable fuels, such as coal, oil, and natural gas, yielded six times more EMERGY than was required for their mining. When forests were harvested without any effort at replanting, very high net EMERGY-yield ratios were obtained—as high as or higher than those of the fossil fuels. Greater net EMERGY yields require longer growing cycles relative to replanting effort. In the simulations, as in previous EMERGY analysis calculations, the more intensive the forest production efforts (more pur-

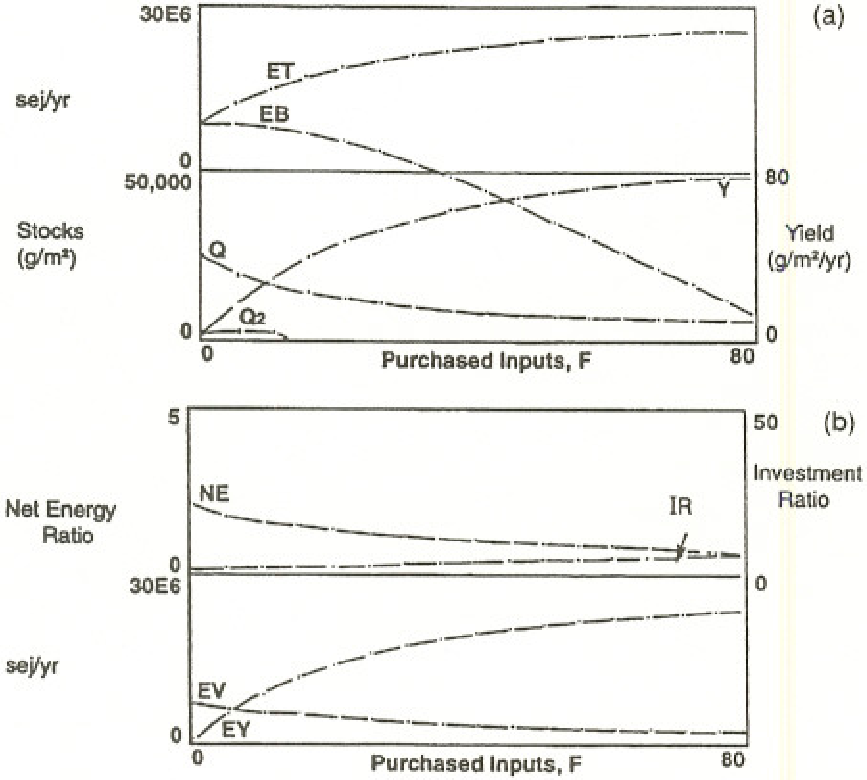

Figure 14.15. Results of simulating the model MATCHUSE in Fig. 14.12a with competitors Q_2 and feedback reinforcement from economic users k_{10}. Graphs show steady-state forest properties and contributions as a function of the intensity of purchased inputs (*F*). (a) Abbreviations: ET, total EMERGY contribution; *Y*, yield; *EB*, EMERGY yield in excess of alternative investment with 7/1 investment ratio = (*EF* + *EF/7*); Q, useful stock; Q_2, competitors. (b) Abbreviations: *NE*, net EMERGY ratio = *EY*/*EF*; *IR*, *F*, feedback from assets; EMERGY investment ratio = *EF*/*EI*; *EY*, EMERGY in yield; *EV*, EMERGY of intangible contributions from commercial species.

chased inputs, F), the lower the net EMERGY-yield ratio (NE decreasing in Figs. 14.13b, 14.14b, and 14.15b).

The EMERGY investment ratio (IR) is the purchased EMERGY (EF) divided by the environmental EMERGY contribution to that use (EI). It is a measure of intensity of silvicultural forest effort; investment ratio increases to the right with increasing purchased inputs (F) in the simulation graphs (Figs. 14.13b, 14.14b, and 14.15b). A process is economically competitive when its investment ratio is the same as or smaller than other economic activities in the same economy. For example, short-rotation forestry with large costs for frequent fertilizing, thinning, and transporting might have too high an EMERGY investment ratio to be economical in a resource-rich area where better matching of environmental EMERGY is being obtained with alternative investments (lower investment ratio).

Also shown in the simulation graphs are the intangible EMERGY contributions (EV and EVC in Fig. 14.12a), which may be compared with the yield contribution (EY). Intangible EMERGY contributions include the work of the natural processes to maintain watersheds, water quality, air quality, greenbelt esthetics, and wildlife.

Intangible Uses, Recreational Forests, and Wildernesses. The model and simulations of economic use (Figs. 14.12 to 14.15) were discussed in terms of a forest product such as wood-harvest yield, but the model applies to any economic use, such as hunting, fishing, or esthetic appreciation by visitors. Recreational use of tropical forests, such as that in the Luquillo Forest in Puerto Rico, illustrates the matching of environmental contributions with contributions from the human users that was shown in Fig. 14.1.

The dual sources of EMERGY flux, one from the environment and that from economic use, tend to prevail because more EMPOWER results (maximum-EMPOWER principle, Lotka 1922, 1925, Odum 1971). Efforts to save complex tropical forests from economic uses are largely unsuccessful unless some reinforcement can be arranged such as watershed protection and tourist appreciation.

Wilderness plots, which are managed without human interface, generate less EMPOWER and may be vulnerable to being reassigned. Nondestructive human uses to maintain public support may include direct use by hikers or indirect use through development of programs for education and television.

More complex than Fig. 14.12 but similar in principle were evaluations of the contribution of mangrove forests as environments for housing and condominium development in southwest Florida. Sell (1977) studied housing developments in coastal zones of Florida, where mangrove ecosystems were contributing from the environment with housing construction and use supplied from the main economy. Other examples of optimum development for maximum economic vitality were evaluated with energy calculations and simulations by Odum et al. (1972), Browder (1976), DeBellevue (1976), Steller (1976), and Littlejohn (1977). The sales promotions emphasized environmental amenities while the housing density was low. Later, however, densities and investment ratios were high, overloading environmental resources and limiting economic values as well.

Tropical Forests in International Trade

The worldwide deforestation of tropical forests driven by overpopulation, autocatalytic money processing in the money centers of the world, the pressure to pay back loans, and other factors (Fearnside 1987) raises important questions about the way international relationships may be contributing to deforestation as well as to inequity in uses of other resources such as shrimp (Odum and Arding 1991). I will consider the ecological economics of the present system of international forest use and ways to correct its evils.

Net EMERGY *Benefits of Local Use Compared with Foreign Sales*

Recommendations for developing underdeveloped tropical forest areas have been to generate an export product and then to use the money received to pay for further development and economic growth. A simulation version of the interface model (Fig. 14.2) was used to consider the alternative of sales abroad versus development of local industries, tourist trades, and domestic use of forests.

The simulation model INTSALE (Fig. 14.16) generates forest products and services using the environmental work (I) inflowing from the left and utilizing assets of the home economy (A), which are developed partly from imports (IM) and partly from the use of homegrown products (P). Part of the production is shown as sales (S) going abroad in the lower right. The rest is used to develop assets domestically (pathway k_2). The fraction of production (P) used domestically is (U); ($I - U$) is the fraction of production sold abroad.

The home-use fraction (U) was varied to see the effect on the flows of money and on the EMERGY indices of value, which are a comprehensive measure of contribution to public welfare. The feedback necessary to maintain a sustained yield considered in Fig. 14.12 is aggregated with the rest of the local economy within the autocatalytic feedback loop (F).

The model uses solar transformities of the inputs to calculate the solar EMERGY of the products, imports, sales, and net benefits. The net benefit to the home country is the total EMERGY per year used at home. The net benefit to outside purchasers and users is the difference between product received and that delivered. The circulation of money involved in international trade is shown by dashed lines; it measures the benefit to the financial sector of the foreign users but not to the public of either economy. Money being paid to people only measures the services involved in a product or service. The contribution of the product as a whole is evaluated by the solar EMERGY.

When the simulation model is run, the graphs of assets and money circulation grow from the starting condition, leveling off as the system becomes limited by the environmental resource base (J in Fig. 14.16). The nature of the products bought and sold is set by the value of solar transformity used. Whether there is benefit or loss also depends on the differences in the EMERGY/\$ ratio of the domestic economy compared to that of the outside market economy.

Simulations were made in which these properties and the fraction of forest product used domestically (U) were varied. The graphs shown in Figs. 14.16b,c,d are not graphs with time but computer plots of dependent variables at steady states on the y-axis versus different values of independent variables on the x-axis. The simulation with time shows as a vertical bar for assets (A) on these graphs.

Increasing the Fraction Used Locally. For the base situation in which the wood product has a moderate transformity and the EMERGY/\$ ratio of the home country is large, increasing the fraction of wood used domestically (U) rather than sold increases the benefit to the home country. In Fig. 14.16b, home assets (A) increase, with decreasing benefit to the purchasing country. Note that the money flow (JM) passes through a maximum. To operate at this maximum is to hurt the

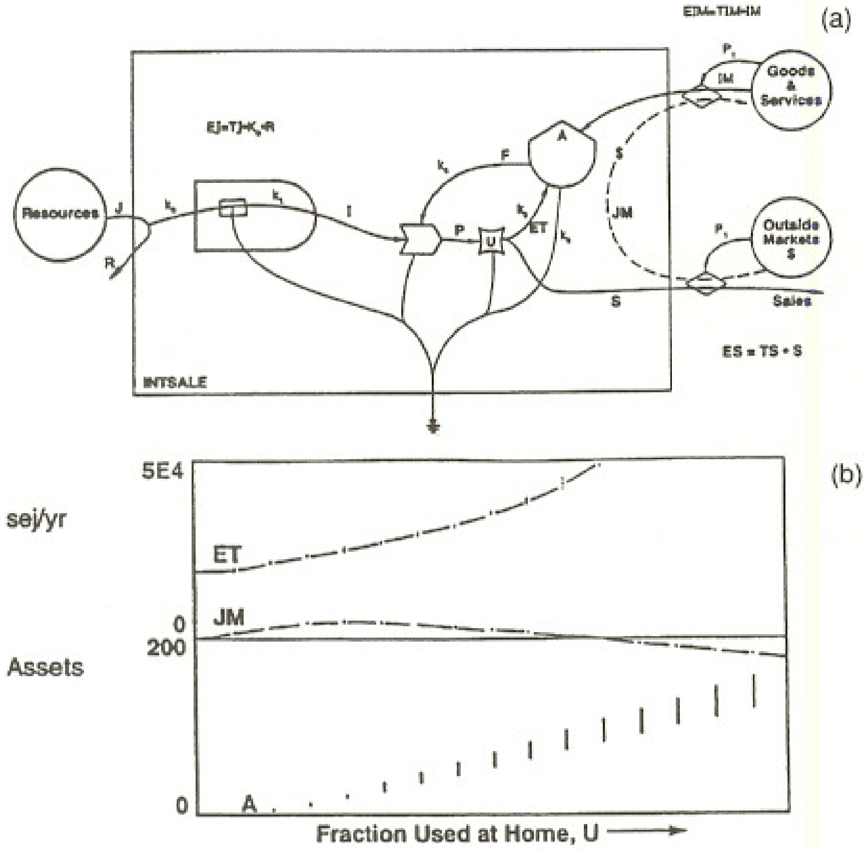

Figure 14.16. Model INTSALE for comparing net EMERGY benefit of domestic versus export sales. Abbreviations: *A*, economic assets; *JM*, money flow; *ET*, EMERGY to assets; P_1, price of sales; P_2, price of imports; *P*, production; *IM*, imports; *TIM*, solar transformity of purchased imports; *EIM*, EMERGY of imports; *S*, products sold; *TS*, solar transformity of products sold; *ES*, EMERGY of products sold; *ED*, EMERGY/$ ratio of the nation's economy; *EDIM*, EMERGY/$ ratio of country supplying imports; *U*, fraction of production used in home country; *I*, environmental contributions to production; *EJ*, EMERGY of resource inflow; *P*, products; *R*, light remaining; *J*, flow of available environmental resources; *TJ*, solar transformity of environmental resources used. (a) Simplified systems diagram; *EA* is an EMERGY storage in the computer program (available from the author) but is not shown in the diagram. $R = J/(1 + k_0A)$; $DA = Uk_2RA - k_4RA - k_3A + JM/P_2$; $dEA/dt = U{*}EP + EIM - EF$; $S = (1 - U)k_2RA$; $P_1 = TS/ED$; $P_2 = TIM/EDIM$; $TI = EJ/I$; $JM = P_1S$. (b) Simulation of characteristics as a function of the fraction of production used at home (*U*); (c) same as b but with much ~~higher~~ EMERGY/$ ratio in selling country than in outside markets; (d) simulation of characteristics as a function of increasing solar transformity of imports.

Lower ES

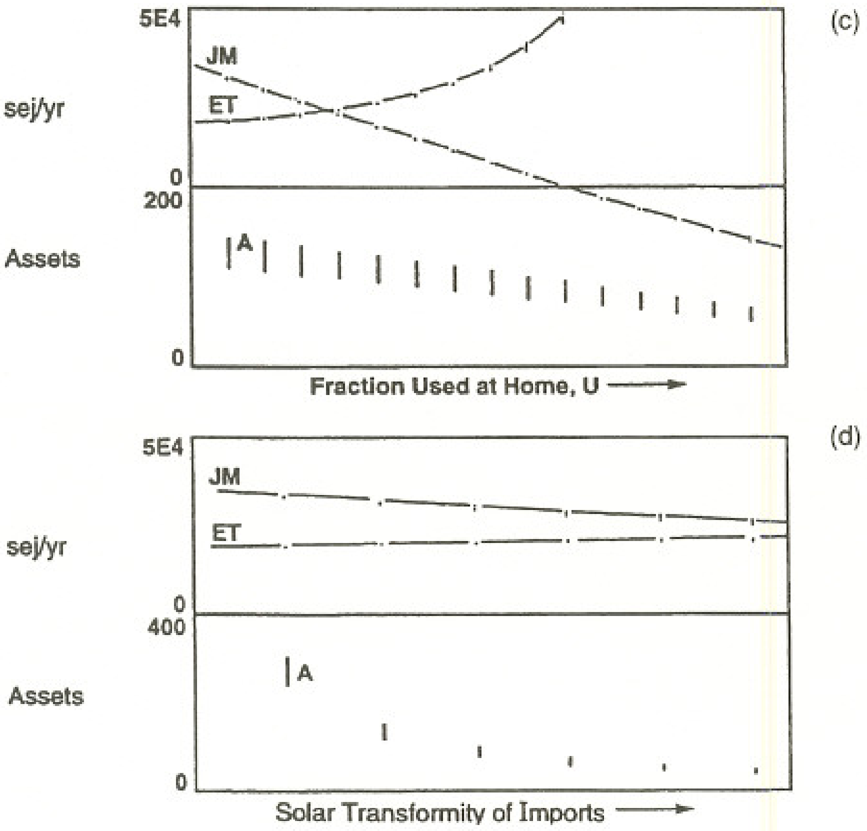

Figure 14.16. *(continued)*

home country and help the purchasers. A situation that would help the domestic economy would be to use the money from foreign sales of wood to purchase something with an even higher EMERGY per unit cost, such as oil.

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Considering Trade with Differences in EMERGY/\$ Ratio. Underdeveloped countries supply more real value directly to their people without money being involved. For example, where wood is still abundant, it is mostly free, or the cost is very low. Consequently, the ratio of total EMERGY used to the money circulation (gross economic product) is higher, with values of 4 trillion sej/\$ or larger. Developed countries have values 0.7 to 3.0 trillion sej/\$. The effect of the differential, other things being equal, is that the country buying on the international market gets a buying-power edge inverse to the ratio of its EMERGY/\$ ratio. Part of the economic crisis in underdeveloped countries is the imbalance of trade using world markets that ignore this difference. The model has its prices calculated according to the EMERGY/\$ ratios and transformities (EMERGY/unit energy) of the products according to equation 1.

$$\text{Price} = (\text{EMERGY/energy}) / (\text{EMERGY/\$}) = \text{\$/energy} \quad (1)$$

The units are:

$$(\text{solar emjoules/joule})/(\text{solar emjoules/\$}) = \text{\$/Joule} = \text{\$/J}$$

As long as the export transformity is large, increasing internal use (U) benefits the domestic economy (Fig. 14.16b). This is the case where the main export is wood. The larger the EMERGY/$ ratio compared to the market countries, the more benefit the home country gains from domestic use of its raw products. If the EMERGY/$ ratio of the sale product is very low, and the EMERGY/$ ratio of the purchased items is large, then the effect is reversed. The home country is benefited by increased sales and less use at home (Fig. 14.16c).

EMERGY Exchange and Trade Transformities. In Fig. 14.16d, the transformity of the purchased imports was varied. Increasing the transformity was tantamount to substituting a higher-quality import for a lower-quality import. With everything else remaining the same, the price was affected, and the EMERGY contribution to the economy from imports was reduced.

Policy for Foreign Aid Projects Involving Tropical Forests

Because tropical forest products have much higher EMERGY than that in the money received for services, exports drain EMERGY that would produce much larger contributions to economic growth and the standard of living if used domestically. Thus, EMERGY evaluations lead to different recommendations for management of tropical forests for local benefit. This confirms the intuitions of many resource managers. Foreign aid institutions have operated on false premises by assuming that increasing money circulation was good for both countries, theirs and the underdeveloped country. EMERGY evaluation of trade raises the unpopular question of which country foreign development projects are intended to aid.

A foreign aid program that develops wood sales can be made mutualistic by providing prices in terms of an EMERGY-based international dollar (EMdollar, Scienceman 1987), or some kind of compensatory feedback of a different nature can be included in the trade arrangements, which are evaluated using the transformities of that aid.

Maximum EMPOWER Tendencies

More sensible policies of tropical forest trade may not generally be made because of the priority that self-organizing systems give to the larger system over the smaller one. Pulling the forest products into the world market is the enormous need to get environmental matching for investment, in other words, to find a raw resource that can support enough economic growth to pay interest at a time when the developed countries no longer possess the natural resources for growth. However, the type of imbalance that results leaves half the world in economic poverty because of the EMERGY imbalance of the trade. To have half of the world's economy in poverty is inefficient in the long run, and I predict a more stable equity to follow as nations develop better exchange policies. This discussion is part of the process of showing the way.

Tropical Forests and the World Carbon Cycle

The autocatalytic stripping of the world's stored resources affects the global homeostasis of the atmosphere and oceans. Hutchinson (1948) raised the question of whether forest cutting could have as great an effect on carbon dioxide levels as fossil fuel combustion. Evaluation of carbon dioxide contributed to the atmosphere from cutting and burning was made by Houghton et al. (1980), with the estimates reduced by later papers such as that by Detwiler and Hall (1988). The controversy concerned the quantity of net release or uptake of carbon dioxide where many lands, after clearing, produced net carbon dioxide uptake as part of agricultural forestry production or successional restoration. Many efforts now under way by others to simulate the effect of carbon dioxide on climatic change integrate more details than one can visualize easily (Houghton et al. 1980, Broecker and Peng 1987, Detwiler and Hall 1988). King et al. (1989) used ecosystem models of main classes of biomes (tundra, coniferous forest, etc.) and areas of these biomes to evaluate the contribution of the net primary production of those forests to the reduction of atmospheric carbon dioxide. The minimodel (Fig. 14.17) performs a similar process holistically aggregated. In simulations that follow, gross productive capacity to respond to carbon dioxide change is found to be more important in the long run than net carbon dioxide release calculated from clearing the forest.

Simpler simulation minimodels may be helpful in putting the magnitude of tropical forest processes in perspective. For overview thinking, the models should match in complexity human thinking about causes. Rather than trying to predict what will happen with all processes, minimodels can be used as controlled experiments to see what happens with alternatives when everything else is held constant. For example, how do the main features of a tropical forest respond to changes in the amount of coverage.

Terrestrial Production and Consumption without the Sea

First, the production and consumption of terrestrial ecosystems as they bind and release carbon dioxide was considered. Figure 14.17a is the same minimodel that was used earlier (Odum et al. 1970) to simulate forest microcosms, duplicating the daily rise and fall of carbon dioxide. Although each microcosm developed a homeostatic balance of production and respiration, it was found that different biota produced different mean levels of carbon dioxide and was suggested that evolution and ecological organization control climate.

The same minimodel (Fig. 14.17a) was recalibrated with balanced production and consumption and the present carbon dioxide level. The small, seasonal, winter increases in carbon dioxide stimulated increased photosynthesis and full-light utilization in the summer, maintaining a steady pattern from year to year. When the

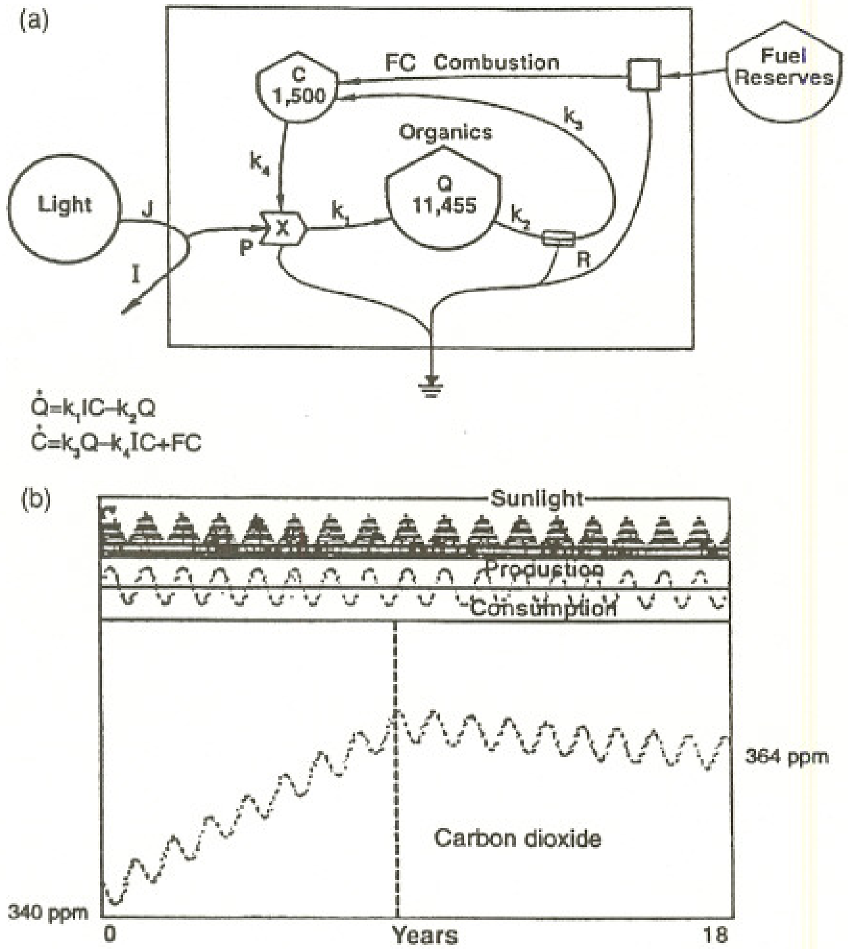

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Figure 14.17. Minimodel LANDCO2 of terrestrial processes and atmospheric carbon dioxide without the sea. (a) Energy system diagram. Abbreviations: C, carbon dioxide concentration; Q, organic storage; R, respiration; X, multiplication; J, solar energy inflow; I, remaining energy; k_x transfer coefficients; P, production; FC, fuel combustion. Equations: $I = J/(1 + k_0C)$; $dC/dt = R + FC - P$; $dQ/dt = P - R$, where $P = k_1IC$, $k_1 = k_4$, $R = k_2Q$, and $k_2 = k_3$. (b) Simulation of carbon dioxide resulting from production, consumption, and current fossil fuel use (FC). Fuel use was turned off after 8 years.

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world's approximate fossil fuel consumption was added, a sharply rising graph resulted (Fig. 14.17b). This pattern is not unlike that observed in the atmosphere (Bolin and Keeling 1963). This calculation is the reverse of that made by Hall et al. (1975), who subtracted the fossil fuel to show a nearly seasonal balance of biospheric production and consumption in the short run.

During the high rate of carbon dioxide addition, the model behaves almost as a ramp. The effect was even greater when the reduction in the area of available terrestrial production was simulated by reducing insolation (J). When the fuel combustion was removed, the minimodel system did not promptly return to original carbon dioxide levels (Fig. 14.17b). The addition of fuel-generated carbon dioxide was so large relative to the light limitation in the minimodel that there was not enough increase in photosynthesis for rapid homeostasis.

Fortunately, the planetary system is buffered by the calcium carbonate equilibrium in the sea and wherever limestones and calcareous soils are interacting with the biosphere. Next, the model was revised to add aquatic production and the bicarbonate system.

World Carbon Dioxide Minimodel Including the Sea

A world carbon dioxide minimodel in Fig. 14.18a has net primary production of the world aggregated into that of terrestrial areas and that of the aquatic ecosystems including the sea. The carbon dioxide production in hard waters precipitates limestone along with generation of organic matter, and, conversely, the carbon dioxide released from living and nonliving oxidation of organic matter dissolves limestone. The model links the terrestrial and aquatic components. Increased consumption of biomass or fuels adds carbon dioxide to the atmosphere in the short run. Carbon dioxide binding on the land has a limited capacity, but there is a longer-run, larger-capacity binding by the sea. Having summarized new data on the effect of higher carbon dioxide concentrations increasing forest photosynthesis and decreasing respiration, Idao (1991) asked how high the global carbon dioxide would go as a result of global homeostasis.

Whereas the land vegetation uses carbon dioxide and generates organic matter, the photosynthetic production in hard waters (including sea water) utilizes bicarbonate to generate organic matter, at the same time raising the pH and shifting the carbonate equilibrium so as to make it easy for tropical cocoliths, calcareous algae, and reef animals to deposit limestone. Consumption of the organic matter on land and in the water generates carbon dioxide, but much of the carbon dioxide interacts with the limestone to generate bicarbonate. More detailed models, such as that by Broecker and Peng (1987), attempt to consider this system more

Figure 14.18. Overview minimodel WORLDCO2 of world carbon dioxide processing including terrestrial and aquatic metabolism. (a) Energy system diagram. Abbreviations: C, atmospheric carbon dioxide concentration; TC, total carbon; Q, total organic matter accessible to biospheric metabolism; L, limestone reserve; B, bicarbonate concentration in the sea; FC, rate of fuel consumption; CT, combustion from clearing vegetation; ALJ, solar insolation over land; IL, unused solar insolation on land; AWJ, solar insolation over water; IW, unused solar insolation at sea; k's, transfer coefficients; X, multiplication. Equations: $IL = ALJ/(1 + k_1C)$; $IW = AWJ/(I + k_wB)$; $TC = B + C + Q + L + FC$; $dQ/dt = k_1I_LC + k_8J_WB - k_2Q - CT$; $dB/dt = k_6CL - k_7I_WB$; $dL/dt = k_9J_WB - k_{10}CL$; $dC/dt = CT + FC + k_3Q - k_4I_LC - k_5LC$. (b) Ten-year simulation of the effect of forest clearing on atmospheric carbon dioxide. Upper curve with forest clearing and combustion (pathway CT); lower curve without forest clearing and combustion.

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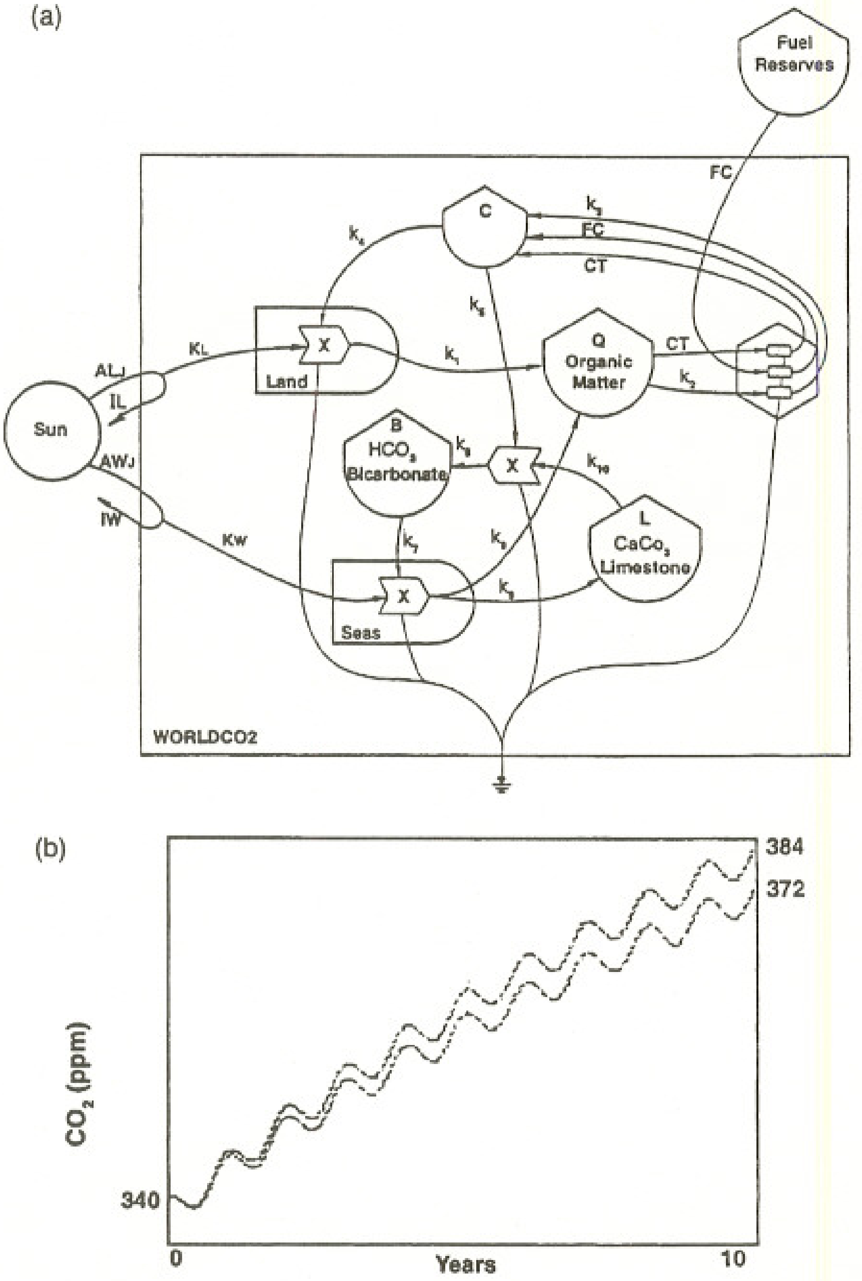
(a)
Fuel Reserves
FC
k_3
FC
CT
C
k_4
k_6
X
Land
K_L
k_1
Q
Organic Matter
CT
k_2
AL_J
IL
Sun
AW_J
IW
B
HCO_3
Bicarbonate
k_8
X
k_{10}
L
$CaCo_3$
Limestone
Kw
k_7
k_5
X
k_9
Seas
WORLDCO2
(b)
384
372
CO_2 (ppm)
340
0
Years
10

accurately with separate compartments for the separate oceans and depth zones, but the simplicity of Fig. 14.17a may represent the principles and order of magnitudes so they can be understood. The coefficients were calibrated for present conditions. This simulation can be used to evaluate the role of tropical forests in the aggregate.

In Fig. 14.18b the model produced the lower curve when simulated 10 years into the future. The short-range pattern is similar to the terrestrial model (Fig. 14.17b), because much of the rapid seasonal change in carbon dioxide metabolism is by the terrestrial vegetation.

Over a longer time period, this minimodel is homeostatic, as shown in Fig. 14.19a. Note the slow rise in bicarbonate. Even with the present rate of fuel consumption continuing and a 20% further reduction in forest area (Fig. 14.19a), carbon dioxide concentration reaches a peak and begins to return to a lower level after 50 years, but the high concentration attained might have major climatic implications involving temperature and icecaps. These are not included in the minimodel. A model by Sergin (1980) does include some of these properties and finds sharply pulsing oscillations of temperature and global ice on a long-period cycle, representing Pleistocenon phenomenon very well.

Effect of Consuming the Stored Biomass in Clearing the Tropical Forests. The pathway CT in Fig. 14.18a is the estimated rate of organic-matter consumption from present clearing of the stored biomass in tropical forests. Adding this consumption generates the upper curve in Fig. 14.18b, increasing carbon dioxide 4 ppm in 10 years. To isolate the consumption effect, the coefficient of primary production on land (k_1) was held constant (as if the forest clearing did not long reduce gross photosynthetic production).

Effect of a Reduced Area of Tropical Forests. Whereas the effect of oxidizing organic matter in a forest clearing was temporary, the effect of permanently changing the photosynthetic capacity of the vegetation was greater (Fig. 14.19a). An increase in forest production capacity (k_1) of 20% was enough to eliminate a further increase in atmospheric carbon dioxide even with present continued fuel consumption (Fig. 14.19b). Here, the distinction is made between the effect of increased consumption of stored biomass and increased forest capacity to produce.

Effect of Reduced Fossil-Fuel Consumption. The worst-case run in Fig. 14.19a included a continuation of present rates of fossil-fuel consumption with 20% more

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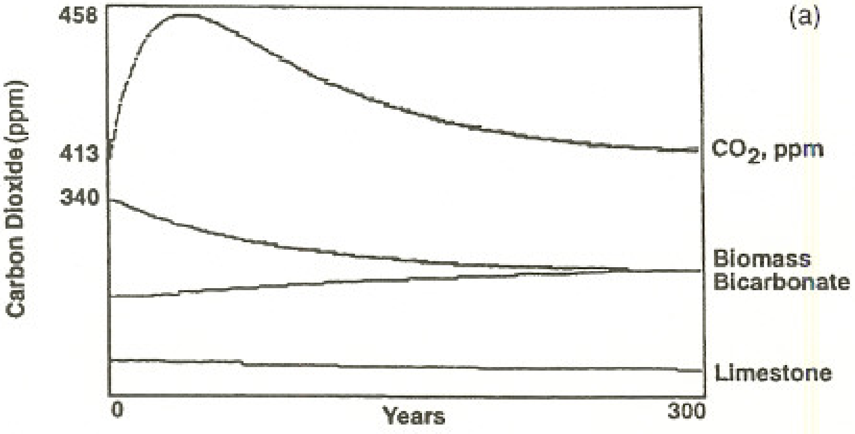
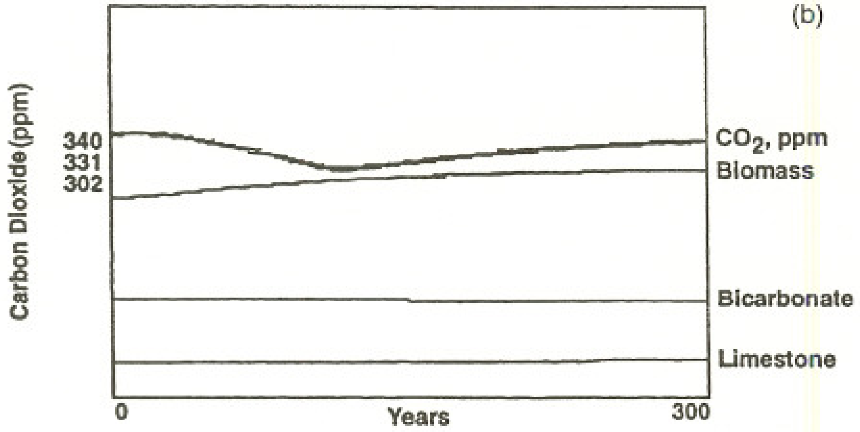
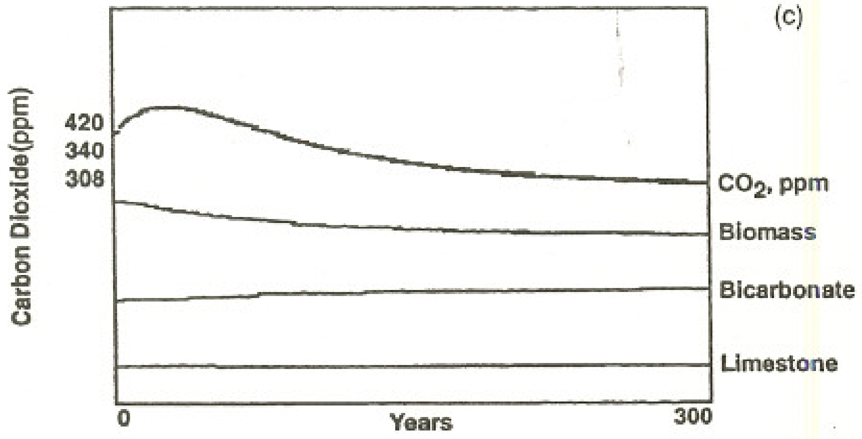
Figure 14.19. Representative 300-year simulations of the world carbon dioxide minimodel in Fig. 14.18a. Parts per million of carbon dioxide by volume are indicated for some beginning, ending, high, and low points of the curves. (a) Simulation with a 20% reduction in production of land vegetation (k_1 in Fig. 14.18a) and with fuel consumption (*FC*) continuing at the present rate; (b) with a 20% increase in land production and with fuel consumption decreasing by an annual increment that is 1% of the present rate; (c) with present forest productivity, with no fuel consumption, and with a 10% reduction in global insolation (*ALJ* and *AWJ* in Fig. 14.18a).


(a)
Carbon Dioxide (ppm)
458
413
340
CO2, ppm
Biomass
Bicarbonate
Limestone
0
Years
300


(b)
Carbon Dioxide (ppm)
340
331
302
CO2, ppm
Biomass
Bicarbonate
Limestone
0
Years
300


(c)
Carbon Dioxide (ppm)
420
340
308
CO2, ppm
Biomass
Bicarbonate
Limestone
0
Years
300

forest reduction. A run with present forest production and fossil fuels declining with an increment of 1% of the present consumption per year crests at 375 ppm in 20 years and returns to present levels in 100 years. This scenario may be realistic as fuel availability decreases and prices rise. Runs with calibration conditions and without fossil-fuel consumption hold present carbon dioxide levels about constant (not shown).

A Preferred Scenario? The effect of increasing tropical forests was as great as that of eliminating fossil-fuel consumption. A possible combination scenario (Fig. 14.19b) combines incrementally decreasing fossil-fuel consumption (1% of present level per year) with a 20% restoration of terrestrial productivity. The combined effect draws carbon dioxide levels back to values that prevailed early in the century. The minimodel suggests opportunities for global human management for restoration of terrestrial productivity.

Restoration of primary production means eliminating areas that are chronically bare or below their potential vegetation cover. Adapted mature forests, such as those useful for maintaining watershed integrity, maximize the gross production in the sense of this discussion. Some forestry-yield practices that maintain good substory cover and immediate reforestation after cutting may approach the mature forest in maintaining the carbon dioxide homeostasis capacity (high production and consumption). However, many agricultural practices and some forestry management rotations keep the landscape underproductive. High economic values to the public of maintaining the green cover is measurable through the EMERGY calculations (see Tables 14.2 and 14.3).

Effect of Reduced Solar Insolation. Some of the ice-age theories involve changes in solar insolation absorbed. For example, Milankovitch's theories (Ruddiman and McIntyre 1981) suggest a change in solar energy received on a 23,000-year cycle. Increased carbon dioxide, causing greenhouse heating of the tropical seas, increases the vapor and clouds in the upper latitudes, increasing albedo and reducing the insolation used by the Earth. There are, apparently, cycles in the insolation caused by oscillations within the sun as well.

When the world carbon dioxide minimodel in Fig. 14.18a is given reduced solar insolation, there is a temporary increase in carbon dioxide followed by a decrease (Fig. 14.19c). This is the pattern found in the cores of Antarctic ice through the last glacial period (Lorius et al. 1988). In the simulation, the carbon dioxide was high at the start but declined through the glacial period as oceanic binding and decreased organic respiration caught up with decreased production. With increased insolation, there was an initial reduction in carbon dioxide followed by an increase as the initial increase in organic matter generated a later pulse of increased carbon dioxide.

Long-Range Homeostasis

Regardless of the treatment given this model, after several hundred years, it returns carbon dioxide to lower levels as the homeostasis of the ocean buffering catches up with the initial effects of change (Fig. 14.19). As others have suggested, the global system is better organized in the long run against accelerating change. Efforts to eliminate wasteful and luxury fuel consumption can help reduce carbon dioxide, but attempts beyond these efforts to force reduction of fuel consumption violate the maximum EMPOWER principle, diminishing economic production and the influence of this policy. For better homeostasis in the short run, reforestation and other restoration of green cover seem to offer the best opportunity for worldwide cooperative action. This is also the best plan for transition to an agrarian world with a decline of fossil fuels—toward a prosperous way down from the present system.

Discussion

Running overview simulation models suggests trends and public policy for the world's tropical forests. Production, biomass, diversity, and hierarchy can be represented in overview at the same level of aggregation as public-policy thinking. The hundreds of details about structure and process discovered by forest science may exist because they are consistent with the aggregate performance as controlled and reinforced at a larger scale. Species that perform best are reinforced, and the genetic information for the contributors is replicated when they reproduce. A set of genetic information carries the means for effective ecosystem self-organization. Thus, minimodels that deal with higher-level, aggregated performance can represent what the many small components are constrained to perform. Minimodels at the stand level aggregate the physiology and autecology; minimodels at the regional scale aggregate the ecologic–economic coupling; and minimodels of the globe aggregate world production, economic carnivory, and the atmospheric gases.

As its fuel base declines, the frenzied pulse of the world economy, based on the fuels, biomass, and other resources, subsides, returning the system to a more moderate part of the pulse cycle. For now, however, the availability of international capital may force the remaining tropical forests to support its own excess unless checked with better public policy. The perception that expanding the amount of money in circulation in financial centers helps the underdeveloped countries needs to be replaced with the concept of maximizing EMERGY use in each region.

The EMERGY measurements and model simulations suggest a better pattern for the economy of the underdeveloped countries of the world and, in the long run, for the entire world. Human use and management need to be consistent with the hierarchy of international, national, regional, and within-forest stands and gaps. It is time now to start a sustainable rotation of forest regeneration and use that will maximize total EMERGY production and use. Development and use should match the local resources with imported EMERGY, but on an EMERGY-equity basis, with more domestic use. Some decentralization of the world's economic information hierarchy can lead to a better international mosaic of forest production and use.

Restoring forest cover also brings carbon dioxide and its climatic effects under control. The availability of many species that are part of tropical forest systems is the most critical factor in the minimodels. The models suggest economic reasons for maintaining high diversity in gene pool plots everywhere, not only for preservation objectives but as the most efficient way to use automatic forest rotation to work for the general economy. A sustainable landscape needs its forest users to maintain the hierarchy of species, size of trees, and size of gaps as a known way to maintain high performance in the long run.

The following comments summarize these points:

1. Tropical forest restoration is a world priority for sustainable economies, stabilized atmospheric carbon dioxide, and preparation for a prosperous way down from the present system. The world economic–environmental pattern can be prosperous during a time of declining use of fossil fuels provided we make a smooth transition from high-intensity, fuel-based systems to those with a greater role for environmental production.
2. Simple overview models are able to generate some of the special features of tropical forests such as seasonal changes, differences in island forests, patterns of succession, nutrient conservation, roles of seeding, and gap-generating oscillations.
3. For more equity in developing tropical forests, products should be used in the home country or exchanged for products with equal EMERGY.
4. Intensity of tropical forest utilization systems that are appropriate now are indicated by EMERGY investment ratios of 7.0 in developed countries, 2.5 on the average for the world, and less than 1.0 in rural tropical forest areas.
5. Lower-intensity versions of various tropical forest utilization systems will become prevalent as the EMERGY-investment ratios of the world decline again as fuels and other minerals become relatively less net yielding.
6. In the lower-energy future, products will draw a higher percentage of EMERGY from the environment and less from purchased fuels, goods, and services. The yields and costs will be less, and efficiency greater.
7. Maximum long-range production may require rotation of lands following the natural hierarchical pattern generated by steady production and pulsed consumption.
8. Preservation of high-diversity gene pools in complex forests is a major need for maximizing economic contributions, especially as the fossil fuels decrease.
9. Utilization, as much as possible, of the natural cycles and homeostasis prevents nutrient limitations and maximizes production potentials.
10. Natural patterns of hierarchy are represented by timber-age distribution and by the distribution of gaps.
11. Patterns of tropical forest management may retain the hierarchical structure by adapting size and frequency of cutting to the hierarchical gap distribution found in nature.
12. Coupled pulsing of production and consumption models can generate spatial hierarchy where time between pulses is proportional to the area of the gaps generated.

13. Photosynthesis of tropical forests may be stimulated by the increase of carbon dioxide from the consumption of fossil fuels, but the minimodel suggests that the area of vegetation must be restored to return carbon dioxide to lower levels.
14. A reasonable management of world tropical forests requires their use to be organized in sustainable cycles to maximize the EMERGY use of national and regional systems in which they are embedded, contributing more to the world economy in the long run than when left to the excess of market economies.

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AU: Really? Not spelled thus anywhere else in chapter.

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