POWER AND A PULSING PRODUCTION MODEL[1]

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Abstract--Simulation studies were made of the power utilization characteristics of a model with production, a self-pulsing consumer, energy constraints, and recycle. An optimum frequency for maximum power existed over part of the range of coefficients; nonpulsing behavior occurred at low and very high energies. Pulses were more intense with longer periods of production. When calibrated with biomass, soils and woods, the interpulse period ranged from 200-300 years. Pulses may represent surges of animal or human activity.

INTRODUCTION

In recent years, many ecosystems have been observed to alternate between long periods of net production followed by consumption and recycle occurring during intensive pulses. Sprugel and Borman (1981) reported on moving waves in balsam fir forests. Odum (1979) suggested that pulsed consumption may help to maximize energy use and give a competitive advantage to systems that pulse. While some oscillating models of populations have been studied for a long time, they have not been very relevant to ecosystems. More recently, models including constraints of energy sources, recycling of materials and nutrients, and parallel alternate pathways by which self organization can feed back consumer control actions have been used to study pulsing systems. In this paper, a pulsing model of production and consumption with the previously mentioned general ecosystem properties was simulated and the relation of maximum energy usage and pulsing behavior studied.

Verhoff and Smith (1971) simulated producer-consumer chains without energy constraints, but with recycling of materials and found unstable oscillations. Quinlan and Paynter (1976) included Michaelis-Menten modules and found more regular oscillations. Odum (1976, 1981a) and Bayley and Odum (1976) studied ecosystems with threshold controlled pulsing consumer actions, in which frequencies were internally determined by energy controlled rates of growth rather than by frequency of external inputs. Alexander (1978) found that consumer unit models with a combination of linear and non-linear input pathways had pulsing properties that were self induced and did not require switching actions. Ludwig, Jones, and Holling (1978) simulated spruce-budworm ecosystems with a three stage ecosystem model that had self pulsing consumption. In chemical systems, Pacault (1977), Noyes (1979), Haken (1978), and Prigogine (1980) have found pulsing models associated with the development of spatial structures. These models have relationships that are expressed by combinations of linear and non-linear pathway. Catastrophe theory has provided an analytical method for examining models with higher order equations to show the sharp transitions from one type of behavior to another. Poston and Stewart (1978) examined the spruce-budworm behavior using this technique.

From these studies, a hypothetical concept emerges that natural systems may self organize pulsing behavior to maximize energy and/or material utilization. The natural frequencies are self generated and may or may not be entrained to outside controlling frequencies. Pulsing may help maximize total resource use by maintaining materials in readiness for production to best capture available energy, by minimizing the time that production is interrupted and by using surges of high quality energies as controlling feedback in the system. Further review and discussion of the pulsing concept is given in another paper at this conference (Odum 1981b).

METHODS

The model was calibrated with appropriate values and simulated to obtain families of curves for various parameters. The models were

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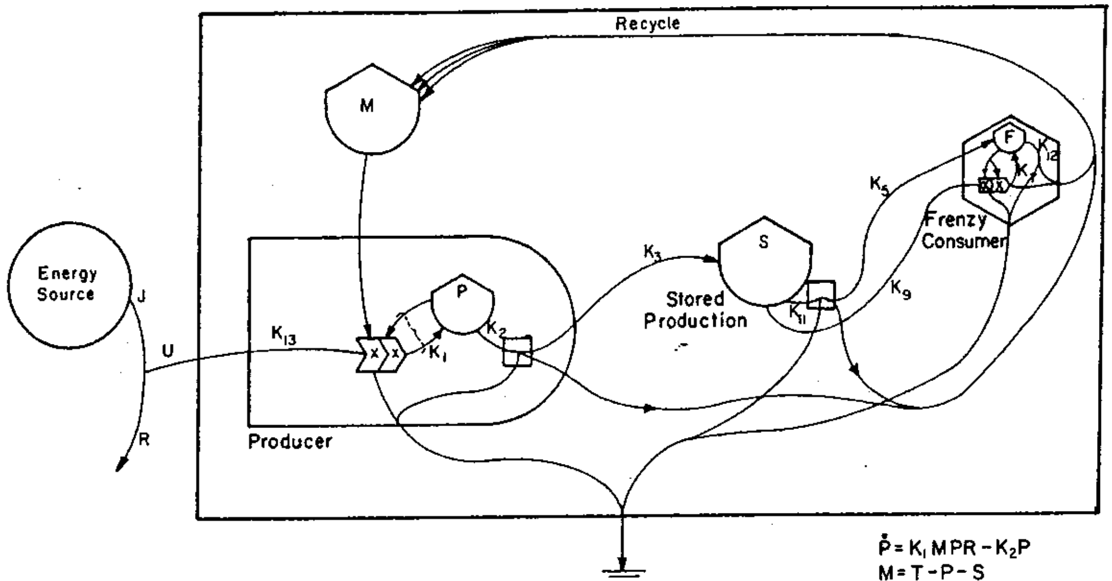

$$\dot{P} = K_1 MPR - K_2 P$$
$$M = T - P - S$$
$$\dot{S} = K_3 P - K_{11} S - K_9 SF^2$$
$$\dot{F} = K_5 S + K_7 SF^2 - K_{12} F$$
$$R = J - K_{13} MPR$$

Figure 1. Energy circuit diagram and differential equations.

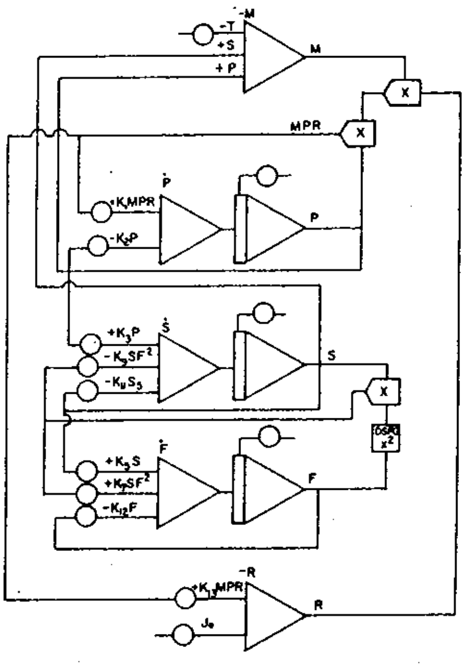

Figure 2. Analog computer diagram of model.

simulated on an EAI 2000/PDP 11 hybrid computer. Using the hybrid computer it is possible to make many runs of the model while altering various coefficients by a set amount for each run and plotting the results on an XY plotter. The rate of energy flow through the system was measured for each run and could be compared with the behavior of the model.

After the model was scaled with values appropriate to the real ecosystems, exploratory experiments were made on the following aspects:

Effect of varying the energy flow.
Effect of varying the initial conditions.
Effect of changing time constant of the consumer storages.
Effect of changing the ratio of linear to nonlinear flows.
Effect of varying the time constant of the producer storages.

The Model

The model studied is given in figure 1 as a set of differential equations and in the energy circuit language. The analog diagram is given in figure 2. It is similar to the one used by Alexander (1978) to describe catastrophes such as earthquakes and floods except that a quadratic autocatalytic feedback is part of this consumer unit. The model is similar to the Brusselator chemical reaction model of Nicolis and Prigogine (1977) except that the model in figure 1 has a

Table 1--Initial conditions and initial flow rates for world ecosystem model.

P = 1000 g Carbon/m^2
S = 4000 g Carbon/m^2
F = 50 g Carbon/m^2
M = 35600 g Carbon/m^2

R1 = 500 g C/m^2/yr
R2 = 500 g C/m^2/yr
R3 = 50 g C/m^2/yr
R5 = 1 g C/m^2/yr
R7 = 100 g C/m^2/yr
R9 = 1000 g C/m^2/yr
R11 = 10 g C/m^2/yr
R12 = 2.5 g C/m^2/yr
R13 = .99 solar units

Source: Bolin 1970, Ryabchikov 1975, Whittaker 1975.

linear pathway from the producer to the consumer instead of an outside linear source as in the Brusselator.

The model was used to simulate two different time scales in the biosphere. First, the model was given values (table 1) of storage and flows that were appropriate for terrestrial ecosystems that develop soil and wood biomass which is then consumed in a rapid pulse by a consumer such as fire, epidemic disease or human use.

Second, the model was given values for fossil fuel reserves for the world as they are built up in the geologic process (table 2). The pulsing consumer in this time frame is our current human civilization.

Table 2--Initial conditions and initial flow rates for world fossil fuel-assets.

P = 24800 g Carbon/m^2
S = 40000 g Carbon/m^2
F = \$.671 /m^2
M = 40000 g Carbon/m^2

R1 = 145 g C/m^2/yr
R2 = 145 g C/m^2/yr
R3 = .0376 g C/m^2/yr
R5 = 3.75E-5 C/m^2/yr
R7 = \$.0671 /m^2/yr
R9 = 51 g C/m^2/yr
R11 = .0376 g C/m^2/yr
R12 = \$.0335 /m^2/yr
R13 = .99 solar units

Source: Bolin 1970, Ryabchikov 1975, United Nations 1980, Whittaker 1975.

RESULTS

Ecosystem Scale

Effect of Varying Energy

The result of varying the energy flow to the model with ecosystem values is shown in figure 3. The input energy was varied from 120% (bottom of graph) to 80% (top of graph) of the normal input energy. The plot is of the pulsing consumer (F), over time. The plots show a transition from a single pulse with dampened oscillation steady state at high energy values through a pulsing phase to a steady state system with no pulsing at lower energy levels. At energy levels in the range which pulsing is seen, the frequency of pulsing changed from low frequency to higher frequency as the energy level was increased until the system transitioned to the single pulse with

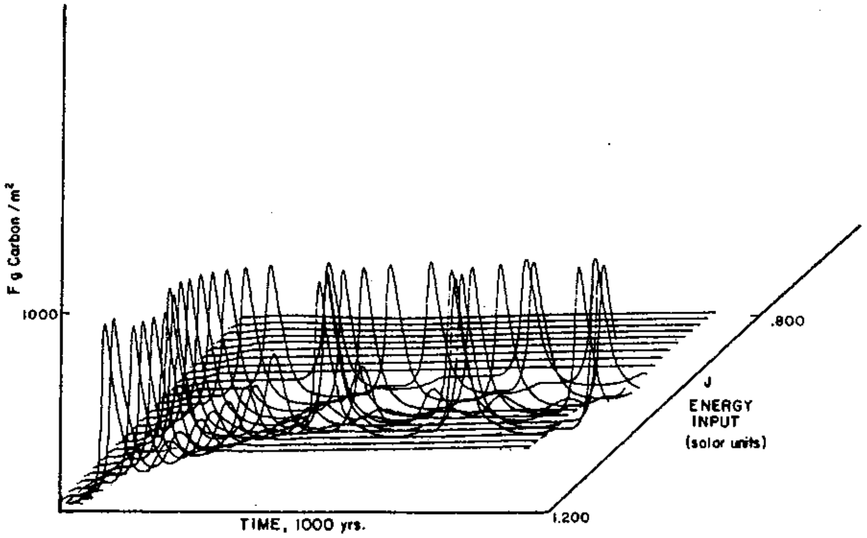

Figure 3. Results of varying energy flow. Pulsing consumer (F) graphed.

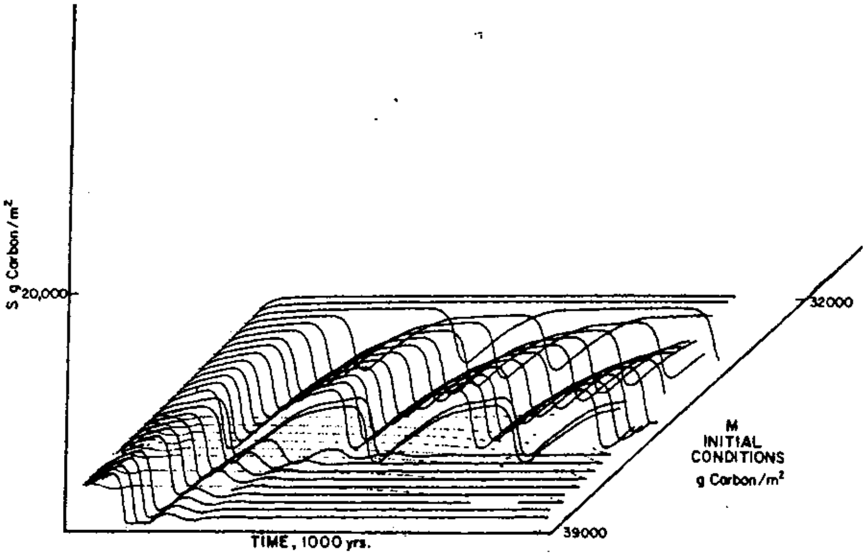

Figure 4. Results of varying initial conditions of total system carbon. Stored carbon (S) graphed.

dampened oscillation steady state. Pulsing was seen to occur at levels of energy flow that are similar to natural systems.

Effect of Varying Initial Storages

Figure 4 is a plot of the stored consumer (S) for different initial conditions on the total system carbon (M). When the initial conditions were varied on the producer (P), consumer storage (S), or the pulsing consumer (F), the only change

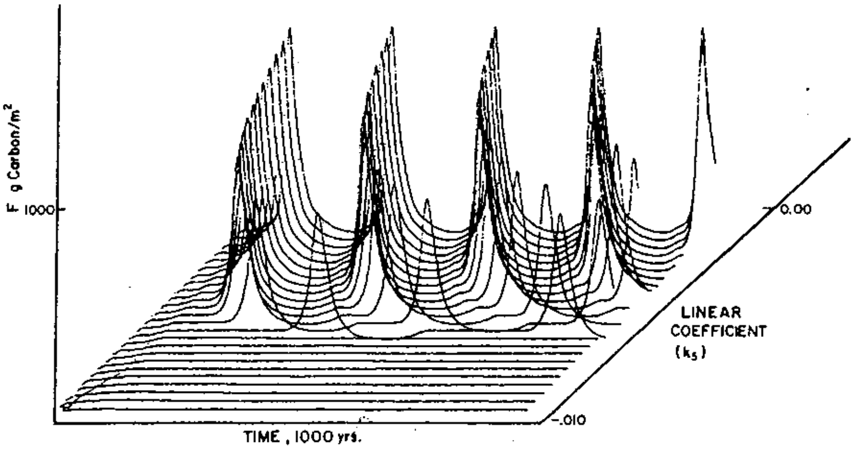

Figure 5. Results of varying linear flow K5 (K11 varied proportionately). Pulsing consumer (F) graphed.

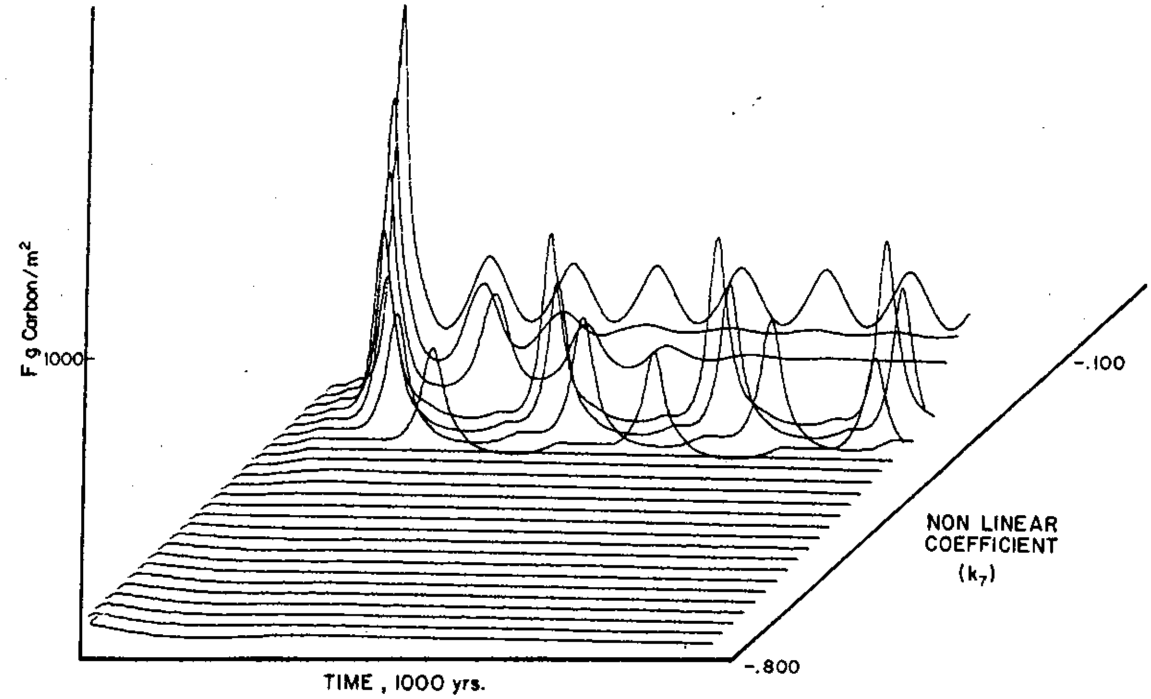

Figure 6. Results of varying non-linear flow K7 (K9 varied proportionately). Pulsing consumer (F) graphed.

seen as a phase shift in the pulsing, with no changes in the pulsing frequency or transitions to other behavior. When the initial conditions were varied on the total carbon in the system, there was a change similar to the one seen when the energy input was varied. At 10% higher than normal levels (bottom of figure 4) the stored reserve of carbon (S) was consumed down by an initial pulse then remained at a lower steady state level. At the same time the pulsing consumer was at a high steady state level. In the middle part of the curve the frequency of pulsing decreased until it finally showed no pulsed consumption but the storage remained at a high steady state level. The pulsing consumer remained low at these values. Measurement of total power in the system showed a maximum value when the initial condition was close to the standard value.

Effect of Varying Consumer Time Constant

The effect of changing the coefficient of the linear pathway from the consumer storage to the pulsing consumer is seen in figure 5. This represents the variation of the time constant of the consumer storage. The graph depicts changing the time constant from two times the normal turnover time at the bottom of the graph to no linear flow at the top of the graph. With higher turnover time there was no pulsing behavior. The higher linear flow set up conditions where the pulsing consumer existed at a low steady state condition but the stored biomass remained at a high steady state level. With very low or no linear flow between the two there was a pulsing behavior that was entirely dependant on the non-linear pathway. The frequency did not change after the initial transition phase.

Figure 6 shows the results of varying the nonlinear pathway coefficients. The transition here was from a low value steady state at high flow rates through a pulsing phase to a single pulse with dampened oscillation to a steady state. Finally at one half normal values a single pulse was observed with a continuous oscillation at a higher frequency than the pulsing behavior.

Effect of Varying Producer Time Constant

When the turnover time of the producer was varied, the result was similar to figure 5 with pulsing at turnover times higher than the standard run and a single pulse steady state at lower turnover times.

World Fossil Fuel Reserves-Assets

Simulation of the model with world fossil fuels-assets are given in figure 7. The producer (P) here represents the world biomass system, the

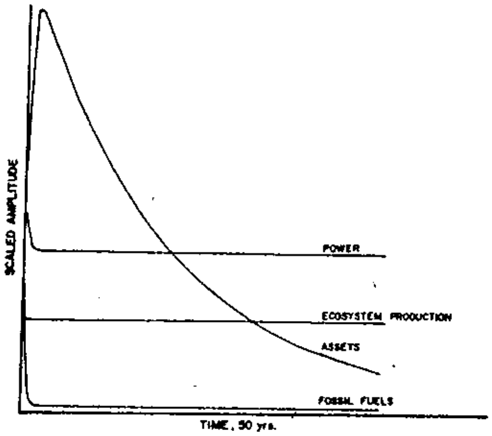

Figure 7. World fossil fuel reserves-assets. Standard model run.

stored reserves (S) represent the accumulated fossil fuels, and the pulsing consumer (F) represents the accumulated assets of the world. The standard run shown in figure 7 had a continuous increase in assets, giving a peak in 5 to 10 years followed by a decline as fossil fuels were exhausted. Various runs were made altering the coefficients and initial conditions of the model with only small changes seen in the output of the model. Because the differences in turnover times in the model are so great, realistic variations in the model show very little change in its basic behavior. If the rate of fossil fuel production were increased by a factor of 50,000 the system then goes into a pulsing behavior with peaks approximately 300 years apart.

DISCUSSION

The existence of parallel linear and nonlinear pathways in this model leads to several different types of behavior of the model. These various behaviors are determined by energy constraints, nutrient constraints and turnover times of the various compartments in the model. The rapid turnover time of the producer section of the model gives a very steady output. The slow turnover time of the stored production makes it available for a rapidly growing consumer to utilize the storage in a frenzy of consumption.

Linear Pathway

The low order, diffusion pathway, between the production storage and the consumer unit is dependent only on the production storage (S). This flow tends to stabilize the consumer part of the system. If the linear flow is very low then there is a tendancy to generate large pulses in the system. If the flow is large enough, then the consumer will maintain itself in a steady state condition with the producer. The pulses tend to be dampened out and the system is maintained in a steady state condition.

Since the linear pathway is source dependent, the exploitation of this resource will reduce this flow. It may be best to design human systems to be receivers of this energy and to interact with it in such a way not to degrade it.

High Order Pathway

In order to grow rapidly, the consumer side of this model also has a third order autocatalytic pathway. This represents spending (or using) some of the stored structure interacting with itself to increase the flow of resources. In actuality this function may have several levels of order. Systems may use higher order feedbacks to increase energy flows and maximize their power flow. High order feedbacks may be able to process energy at higher levels while lower order pathways may be needed to process energy at lower power levels. A fundamental nature of these higher order interactions is that storages are consumed rapidly and recycled back into the resource nutrient pool thus allowing a system to diverge resources back to lower levels of the system for better use.

Maximum Power

When the energy source was held constant and the total amount of carbon was varied (figure 4), there was a change in the total power used in the system. As the carbon was increased in successive runs, the power went through a maximum in the area where pulsing was present and then power use declined as the carbon was no longer limiting. At the point where the top consumer flipped to a high level steady state, the power began to rise again. Whether or not this last transition maximizes power depends on other constraints in the model.

Perspectives

We may use the behavior of this model for insights that may apply to ecosystems and to the system of our current civilization. Perhaps pulsing may be a property of some range of energies and there may be a selection for a particular pulsing period that maximizes energy use. The question may be raised over what period is power maximized? The concept of alternation of production and pulsed consumption with a frequency that is most competitive may supply the answer.

While we deplore the excessively wasteful consumption of our natural resources by our current economic systems, it may be in the order of things that the rapid pulse of consumption returns the materials to a state of readiness for a long period of restoration and net production.

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