Hydrol. Earth Syst. Sci. Discuss., 3, S1402–S1406, 2006
www.hydrol-earth-syst-sci-discuss.net/3/S1402/2006/

Hydrology and Earth System Sciences Discussions

HESSD

3, S1402–S1406, 2006

Interactive Comment

Interactive comment on "Dynamics of resource production and utilisation in two-component biosphere-human and terrestrial carbon systems" *by* M. R. Raupach

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Received and published: 7 November 2006

I am grateful to both reviewers for their broadly supportive comments on the paper, and for their constructive criticisms. Of these criticisms, two have significant implications and are the focus of this response. The others are helpful for improving the paper (and will be used in that way) but not basically controversial and hence not discussed in detail here.

1. COMMENTS BY VICTOR BROVKIN ON THE "MALTHUSIAN" APPROACH TO POPULATION DYNAMICS, AND TECHNOLOGICAL INFLUENCE ON BIOMASS PRODUCTION

The essence of this comment is: "Suggested model of biosphere-human interactions could be easily criticized for exploring Malthusian approach of direct link between population dynamics and food availability. This simple approach neglects intrinsic society feedbacks, like reduction of population growth in industrial societies. Ě An amount of food (biomass) available for population can be controlled by society, for example, as a result of the Green Revolution. This means that productivity, p, is a function of population, h, and this may lead to a different system behaviour."

This is a fair and valid criticism, if the two-state variable model for biosphere-human interactions is pushed too far from conceptual to predictive. In technologically advanced societies, population is indeed controlled by factors other than the availability of food or most other resources.

There are two responses to this general (and valid) point. The first is to acknowledge that a simple two-state-variable (biosphere-human) model cannot describe this feature of recent human evolution. This is true (and is already stated in the paper at the start of both Sections 3 and 4). One way to incorporate such dynamics predictively would be to include more state variables, as in the paper on the Neolithic transition by Wirtz and Lemmen (2003) (and I am grateful to Victor Brovkin for bringing this paper to my attention). Wirtz and Lemmen use four state variables, one for (human) population and the other three for aspects of human exploitation of natural resources, including technology. As more state variables and phenomenological equations are added, it becomes progressively more difficult to investigate analytically the general response of equilibria and stability to parameter perturbation, which is a principal aim of this paper. The choice made here is to keep the model absolutely minimal by using just two variables, biosphere (b) and humans (h), which provides some analytic insight at the expense of explicit predictive capability.

A second and more creative response, however, is to reinterpret the variables b and h. This is consistent with the broad goal of attempting to capture general features of resource production and utilisation, rather than to predict biomass and human pop-

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ulation in a narrow sense. A possible reinterpretation is to regard b as "renewable natural capital" and h as "human capital". Such an interpretation is at least qualitatively consistent with recent evolution of technologically advanced societies, where increase in human capital continues unchecked though human populations are stabilising or even declining. In the context of farm management, a two-equation model rather similar to the (b,h) model in this paper has been proposed by Fletcher and Miller (2006) "Operationalizing Resilience in Australian and New Zealand Agroecosystems" (http://journals.isss.org/index.php/proceedings50th/article/viewFile/355/133), with the variables b and h interpreted in this way.

A related issue is the means by which h exerts feedback on b. Victor Brovkin suggests including a direct dependence of net primary production (NPP) on h, to account for technological innovation. This is certainly possible, but the route taken in the present analysis is rather to describe the fraction of NPP appropriated by h, for instance with the resource condition index W defined in Equation (15). The human appropriated fraction of resource production or the generation rate of natural capital is W at equilibrium. The critical feedback determining W occurs through the term cbh in the basic model equations (11) and (12), with the effect of human technology development being encapsulated in the parameter c. This view supposes an upper limit at which natural capital can be replenished, independent of h and represented by the production term in Equation (11). In principle, such a cannot capture enhancement of potential production by the green revolution (for example by increasing nutrient supply), but it can capture enhancement of the fraction of production that reaches human consumption (for example by increasing allocation fractions to grain and reducing crop death and decay before harvest).

2. COMMENTS BY ANONYMOUS REFEREE ON TREATMENT OF RANDOM EXTERNAL FORCING

The central point is: "[... In a randomly forced system with two state variables], the system dynamics can be described by a Fokker-Planck equation. If one of the variables

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is assumed to be a slow process then the two equations can be reduced to one. This allows to define a potential U=-grad f for the one-dimensional system dx/dt=f(x). The average residence time in the different domains of attraction can be estimated from the potential U."

As pointed out in the comment, a two-dimensional system can be further reduced to one dimension when one variable is "fast" compared with the other, by statistically averaging the fast variable and solving for the slow variable. However, to analyse the significance of this comment it is useful to consider the general case of a system of arbitrary dimension obeying dx/dt = f(x). If f were a generalised conservative force and x a generalised velocity vector, the physical definition of a potential (V) would be f=-grad(V), rather than U=-div(f) as suggested by the comment (the required vector differentiation operation being div rather than grad because f is a vector). Hence, the meaning of "potential" in the comment cannot be a quantity (V) such that f=-grad(V).

Instead, the comment appears to be alluding to the equation for the probability density function of x(t) in the system configuration space x. Let this PDF be p(x,t), a scalar. For a deterministic system, p(x,t) obeys the Liouville equation

dp/dt=-div(pf).

This appears to be close to meaning of the referee when she or he speaks of "a potential U=-grad(f) for the one-dimensional system dx/dt=f(x)".

If the system is stochastically forced, then the governing equation dx/dt=f(x) (a deterministic ordinary differential equation) is replaced by the stochastic differential equation dx/dt=f(x,Y(t)), where Y(t) is a stochastic random process with specified statistical properties. If Y is a Markovian random process, these statistical properties are fully specified by a transition probability PY(y,t|y0,t0) obeying a master equation

dP/dt=L(P)

where L is a linear operator (for instance L(P) is Kd2P/dy2 for a one-dimensional Gaussian diffusive process with diffusivity K). When the system is stochastic in this way, with a Markovian random forcing Y(t), the above deterministic Liouville equation is replaced by a stochastic Liouville equation (van Kampen 1981)

dp/dt=div(pf)+L(p).

With appropriate restrictions on Y(t) (essentially to a diffusive process), this is the Fokker-Planck equation.

The question of the probability of jumping from one basin of attraction to another (or of the average residence time in different basins, as the referee puts it in the comment) is essentially that of finding p(x). However, p(x) is not determined in any sense (even under a restriction to one dimension) by a "potential" of the form div(f) in more than one dimension (or df/dx in one dimension). Instead, the "gradient" down which the probability density function flows is div(pf), in either the stochastic or deterministic case. The conclusion is that the above comment by the referee raises a significant set of issues, but is in need of clarification.

Reference:

van Kampen NG (1981) Stochastic Processes in Physics and Chemistry (North-Holland, Amsterdam).

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 3, 2279, 2006.