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DISCUSSION

Importance of Tightly Coupled Equations in Modelling Grassland Ecological Economics

A response to "Modelling the Economics of Grassland Degradation in Banni, India, using System Dynamics" (Mihir Mathur and Kabir Sharma, *EES*, July 2018)

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The research reported by Mathur and Sharma (2018), referred hereafter as M&S, analyses the interactions between ecology and economy of the Banni grassland, located in the district of Kachchh, Gujarat, through a system dynamic model factoring in area covered by the invasive mesquite *Prosopis juliflora* (mesquite-covered area, hereafter MCA, A_p in M&S) and the incomes from livestock and mesquite. M&S has, however, overlooked the previous work on economy-ecology linkages of the region (Geevan *et al* 2003, 2005). Certain selections from the Geevan et al study, the discussion on system dynamics modelling framework, were published by INSEE as a book chapter (Sengupta and Bandyopadhyay 2005). While M&S has cited Geevan *et al* (2003) several times, its system dynamics model, which is central to the work, was overlooked. This oversight seems to have led to several flawed formulations in M&S. We briefly point out these.

Our study (Geevan *et al* 2003) had adapted certain concepts of grassland resource dynamics modelling from the work of Perrings[1] (Perrings 1994,

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[1] Discussed with Charles Perrings during the Sixth INSEE Biennial Conference and later through correspondence.

1997; Perrings and Walker 1995; Perrings and Stern 2000). Perrings integrated an ecological model of rangeland resource dynamics into an economic analysis framework. It is important to recognize that the challenge in such studies is to model the variables as a tightly interdependent system; the separate uncoupled equations fail to provide insights into the interesting features

The system dynamic model presented in our work is very briefly described here for quick reference. It incorporates three state variables X, K, and W, where X is the livestock numbers expressed in Adult Cattle Units[2] (ACU), K is grazing potential per ha of the grassland, and W woody area invaded by mesquite. The terms, Q_1, Q_2, Q_3 and Q_4 represent control variables –off-take with negative values representing infusion. Q_1 is the off-take of livestock in ACU, Q_2 is the grazing potential removed for milk production, Q_3 is the woody cover from which charcoal is produced resulting in a temporary reduction of the woody cover through coppicing and Q_4 is the area from which woody cover is reduced by uprooting every year. Additionally, there is a discrete parameter θ or switch representing the control of the mesquite re-invasion which takes the value 0 or 1; 0 with re-invasion and 1 without re-invasion (i.e. with adequate measures). It is important to note that a) biomass harvest without uprooting the mesquite (e.g., coppicing to make wood charcoal) does not significantly slow down the spatial spread and b) mesquite will reinvade areas from which it has been completely removed in the absence of measures to stop the spread.

In contrast to the coupled equations employed by us to concurrently compute livestock number, grazing potential and MCA (X, K, and W), M&S use a standalone approach separately for the MCA and the livestock sector. For the former, they employed a single variable equation without any explicit dependency on the livestock sector. They invoke the dependency on livestock by employing a 'graphical function' for E, a livestock dependent multiplier of the rate of spatial spread.

The following comments pertain to certain specifics of the model presented by M&S:

1. M&S use a parameter called 'normal spread rate'(n), the annual increment in MCA. It has been assigned a value of 8.5% per year, which is a very large value for 'normal' (i.e., unassisted) spread. MCA will nearly double in about eight years with such a large compound annual growth rate in the absence of any controlling factors. Note that in the formulation of M&S, parameter 'n' is also multiplied by another

[2] Expressing livestock numbers in Adult Cattle Units (ACU) is a standard practice to account for livestock across different types.

parameter E ($1 \leq E \leq 2$), which means the effective rate of spatial spread in the model ranges from 8.5% to 17% per year, which is much higher than the observed spatial spread. The rate of spatial spread in the absence of animal vectors or any other additional dispersal mechanism will be much lower. In our work, we assigned a nominal value several orders of magnitude less for the parameter representing the natural rate of spatial spread (α_3) based on inferences drawn from our own analysis of the satellite imagery data of different periods and literature.

2. M&S cite the work of Vaibhav *et al* (2012), the preliminary results presented at a conference, as the source for the value of 'normal spread rate' referred to earlier. Curiously, this study is not on the spatial spread of mesquite, but on biomass regeneration under coppicing. Vaibhav *et al* (2012) uses single satellite imagery of 2011 — a period when the Banni region was invaded by mesquite and livestock presence was high. The estimated rate of spatial spread of mesquite in Banni reported in a recent study was 2.1% per year (Pasha *et al* 2014), arrived at after examining satellite imagery datasets of 1977, 1990, 1999, 2005 and 2011. Since livestock vectors are present in large numbers in this landscape, the value is the livestock-mediated rate, i.e., the enhanced value, not the 'normal' or 'natural' rate. There are no historical records of any period for the Banni region without large numbers of livestock. Consequently, there are no known studies providing estimates of the natural rate of spread in the region in the absence of livestock.

3. M&S use a graphical representation of E, the multiplier of the 'normal' rate (n). In our work, we had characterized the multiplier effect on the natural rate, $\alpha_3(1+\varepsilon X)$ with ε as the parameter representing the enhanced rate of spatial spread of woody cover per thousand ACU due to the presence of livestock (X) expressed in terms of ACU. The device of a simple graphical lookup function, akin to a function lookup table, employed by M&S is inadequate to simulate a tightly interconnected system as it cannot concurrently generate the values of the livestock sector.

4. Further, in our view, there is a major error in the way M&S have formulated the equation for the change in MCA by making the rate of change proportional to the current area. Our work considered this as a rather non-intuitive aspect (Geevan *et al* 2003, 2005). It is tempting to assume that the change in area will be proportional to the current area as is usually done, e.g., the future population as proportional to the current value. However, the primary driver of an increase in the mesquite area is the livestock transporting seeds from the periphery of the mesquite-covered patches. They do not graze inside the thick woody growth.

Therefore, in our work, we expressed the increase in mesquite-cover as proportional to the square root of the area (i.e., a proxy for the length of the periphery) as a more realistic formulation representing the spatial spread of mesquite. We recognize there are challenges in characterizing this process as realistically as possible.

5. There are also several deficiencies in the second standalone model of livestock dynamics, which we shall not discuss in detail. It will suffice to state that the equations for the dynamics of the stock of adults, B and calves, C, maturing into adults at age T_m, do not seem to adequately represent the dynamics in a consistent manner.

The aim of this comment is to draw attention to the nuances of developing a system dynamics model of economic activity dependent on an open access resource subject to mesquite invasion.

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