J. ENVIRONMENTAL SYSTEMS, Vol. 28(4) 279-291, 2000-2001

DEVELOPMENT OF A DYNAMIC AND PREDICTIVE MODEL FOR ECOLOGICAL FOOTPRINTING (EF)

J. S. PANDEY

S. KHAN

V. JOSEPH

R. N. SINGH

National Environmental Engineering Research Institute (NEERI)
Nagpur, India

ABSTRACT

Although a very useful tool, Ecological Footprint (EF) analysis has recently been subject to quite a bit of criticism. One of the most important weaknesses that EF suffers from is the fact that it is not a dynamic EF-model. An attempt has, therefore, been made in this article to develop a suitable dynamic EF-model. The dynamic EF-model, thus developed, can be used also for future predictions. A condition for future sustainability has also been derived and tested. Although the model development and analyses have been carried out for the rice-component only, they can likewise be extended for various other components.

INTRODUCTION

The premises on which the EF concept is based can be summarized as follows [1-2]:

a) Every individual, process, activity, and region has an impact on the Earth. And these impacts (due to resource use and waste-generation) can be quantified in terms of biologically productive area.

b) Consumption patterns as well as waste-generation-potentials can be estimated in terms of the land-area needs for different human ecosystems.
c) Estimates for biological productivity of these systems can also be worked out as ecosystems' supportive (resource-utilization) and assimilative (pollution-sink) capacities [3-4].

EF is calculated on the basis of parameters such as production, import, export, and yield; values for the resource under consideration [1-2, 5] and EF-assessments have been applied at various scales: household, municipal, national, and global [1, 6]. Such estimates point out that at the global level, the EF of humanity has far exceeded the biocapacity of the ecosystem supporting it, thus suggesting a very high degree of unsustainability.

There are reports, on the other hand, that argue that because the EF model is a static one, it cannot be used for future predictions [2, 7]. To address this limitation in the present article, we have developed a dynamic EF-model. Human population as well as production, import, export, and yield of rice have been modeled as different functions of time. The resulting model for EF automatically becomes dynamic and can be used not only for present assessment, but also for future predictions. For calibration of different parameters, Indian data from various sources [8-11] has been used. A condition for ecological feasibility has also been derived and tested. Although the model development and analyses have been carried out for the rice-component only, they can likewise be extended for various other components.

ECONOMICS OF INDIAN ENVIRONMENT

In India, environmental degradation has become a very serious concern. This is mainly because most of the urban and fringe rural populations in India live with their wastes and suffer the consequences due to overloading of the neighboring ecosystems [4, 12]. The most obvious danger that faces us today is galloping population growth because food and materials requirements become enormous and, in turn, cause additional problems regarding the management of air, land, and water. To balance the unprecedented rate of human consumption of food, fodder, fiber, fuel, and fertilizer against their production is perhaps the biggest problem confronting our society today. The shortfall between consumption and production, whether because of the need or the greed of mankind, puts undue pressure on planning and management. The sustainability of our future society is directly proportional to the rationality it adopts in the use of natural resources. Therefore, the strongest need of the hour is to evolve a sound understanding of ecology and economy, and to integrate them in such a manner as to ensure sufficient feed-back controls, which finally help ecosystems in enhancing their self-rectifying capacity.

THE DYNAMIC EF-MODEL

Data in regard to Production (kg), Import (kg), Export (kg), and Yield of Rice (kg/ha) for different years were collected from available Indian Statistics [8-11]. Time-dependent models [equations 1 through 4] were thereafter developed for Production, Import, Export, and Yield for the rice. Similarly for population also a temporal quadratic model was developed [equation 5]. For calibration of different parameters, the data-set for the period 1991-95 was used.

$$\text{Production\_Rice (kg)} = (10)^9 \lfloor a_{prod}\,(t\text{-}1991)^2 + b_{prod}\,(t\text{-}1991) + c_{prod} \rfloor \tag{1}$$

$$\text{Import\_Rice (kg)} = (10)^7 \lfloor a_{import}\,(t\text{-}1991)^2 + b_{import}\,(t\text{-}1991) + c_{import} \rfloor \tag{2}$$

$$\text{Export\_Rice (kg)} = (10)^8 \lfloor a_{export}\,(t\text{-}1991)^2 + b_{export}\,(t\text{-}1991) + c_{export} \rfloor \tag{3}$$

$$\text{Yield\_Rice (kg/ha)} = (1.0) \lfloor a_{yield}\,(t\text{-}1991)^2 + b_{yield}\,(t\text{-}1991) + c_{yield} \rfloor \tag{4}$$

$$Population = (10)^6 \lfloor a_{pop}\,(t\text{-}1991)^2 + b_{pop}\,(t\text{-}1991) + c_{pop} \rfloor \tag{5}$$

After substituting equations (1) through (5) in the EF expression of Wackernagel et al. [13], the Rice_Component of the Ecological_Footprint (EFRC) assumes the following form:

$$EFRC \quad \frac{EFRC1}{EFRC2} \tag{6}$$

Where,

$$EFRC1 = A_1 x^2 + B_1 x + C_1 \tag{6.1}$$
$$EFRC2 = A_2 x^4 + B_2 x^3 + C_2 x^2 + D_2 x + E_2 \tag{6.2}$$
$$x = t\text{-}1991 \tag{6.3}$$
$$A_1 = a_1 + a_2 - a_3 \tag{6.4}$$
$$B_1 = b_1 + b_2 - b_3 \tag{6.5}$$
$$C_1 = c_1 + c_2 - c_3 \tag{6.6}$$
$$A_2 = a_4 a_5 \tag{6.7}$$
$$B_2 = a_4 b_5 + b_4 a_5 \tag{6.8}$$
$$C_2 = a_4 c_5 + b_4 b_5 + c_4 a_5 \tag{6.9}$$
$$D_2 = b_4 c_5 + c_4 b_5 \tag{6.10}$$
$$E_2 = c_4 c_5 \tag{6.11}$$

Details of a_1's, b_1's, and c_1's are given in the Appendix. For sustainability, it is essential that EFRC shows temporal stability. Mathematically speaking, this can be represented by assuming that the partial derivative of EFRC with respect to x (i.e., t-1991) is zero. This condition finally leads to the following equation:

$$P_5 x^5 + P_4 x^4 + P_3 x^3 + P_2 x^2 + P_1 x + P_0 = 0.0 \tag{6.12}$$

Where,

$$P_5 = -2A_1A_2 \quad (6.13)$$
$$P_4 = -(A_1B_2 + 3B_1A_2) \quad (6.14)$$
$$P_3 = -2\ (B_{1\delta}B_2 + 3C_1A_2) \quad (6.15)$$
$$P_2 = \mathrm{A}_1D_2 - B_1C_2 - 3C_1B_2 \quad (6.16)$$
$$P_1 = 2A_1E_2 + B_1D_2 - B_1B_2 - 2C_1C_2 \quad (6.17)$$
$$P_0 = B_1E_2 - C_1D_2 \quad (6.18)$$

Differentiating equation (6.12) with respect to x (in a step-wise manner), one finally arrives at the following equation:

$$5P_5x + P_4 = 0.0 \quad (6.19)$$

$$\text{i.e., } x = -(1/5)\ (P_4/P_5) \quad (6.20)$$

For any future time-scale t-1991 > 0.0, i.e., $x > 0.0$. Therefore, from equation (6.20) it follows that (P_4/P_5) should be negative. In other words,

$$(P_4/P_5) < 0.0 \quad (6.21)$$

From equations (6.21), (6.13), and (6.14), one obtains the following condition for future-sustainability:

$$(B_2/A_2 + 3(B_1/A_1) < 0.0 \quad (6.22)$$

A_1's, B_1's, etc. are functions of a_1's, b_1's, and c_1's details of which are given in the Appendix. With these substitutions and multiplication by (10^{-15}) on both the sides equation (6.22) attains the following form:

$$SUST1 < SUST2 \quad (7.23)$$

Where,

$$SUST1 = Sust1 + Sust2 \quad (7.23.1)$$
$$SUST2 = Sust3 + Sust4 \quad (7.23.2)$$
$$Sust1 = (a_{yield}b_{pop} + b_{yield}a_{pop})\ (a_{prod} + b_{prod}) \quad (7.23.3)$$
$$Sust2 = 3(a_{yield}a_{pop}) \lfloor b_{prod} + (b_{import}/100) \rfloor \quad (7.23.4)$$
$$Sust3 = a_{\mathrm{export}}\ ((a_{yield}b_{pop}/10.0)) + (b_{yield}a_{pop}/10.0) \quad (7.23.5)$$
$$Sust4 = 3(a_{yield}a_{pop})\ (b_{\mathrm{export}}/10.0) \quad (7.23.6)$$

RESULTS AND DISCUSSION

Validation of time-dependent models [equations (1) through (5)] has been shown in Figures 1 through 3. Condition for future sustainability (7.23) demands that *SUST*1 should be less than *SUST*2. Thus, it was thought appropriate to study the sensitivity of both these mathematical expressions with respect to the parameters whose functions they are (Figures 4 through 7). The condition of future sustainability is satisfied in almost all the cases except for those cases, which are

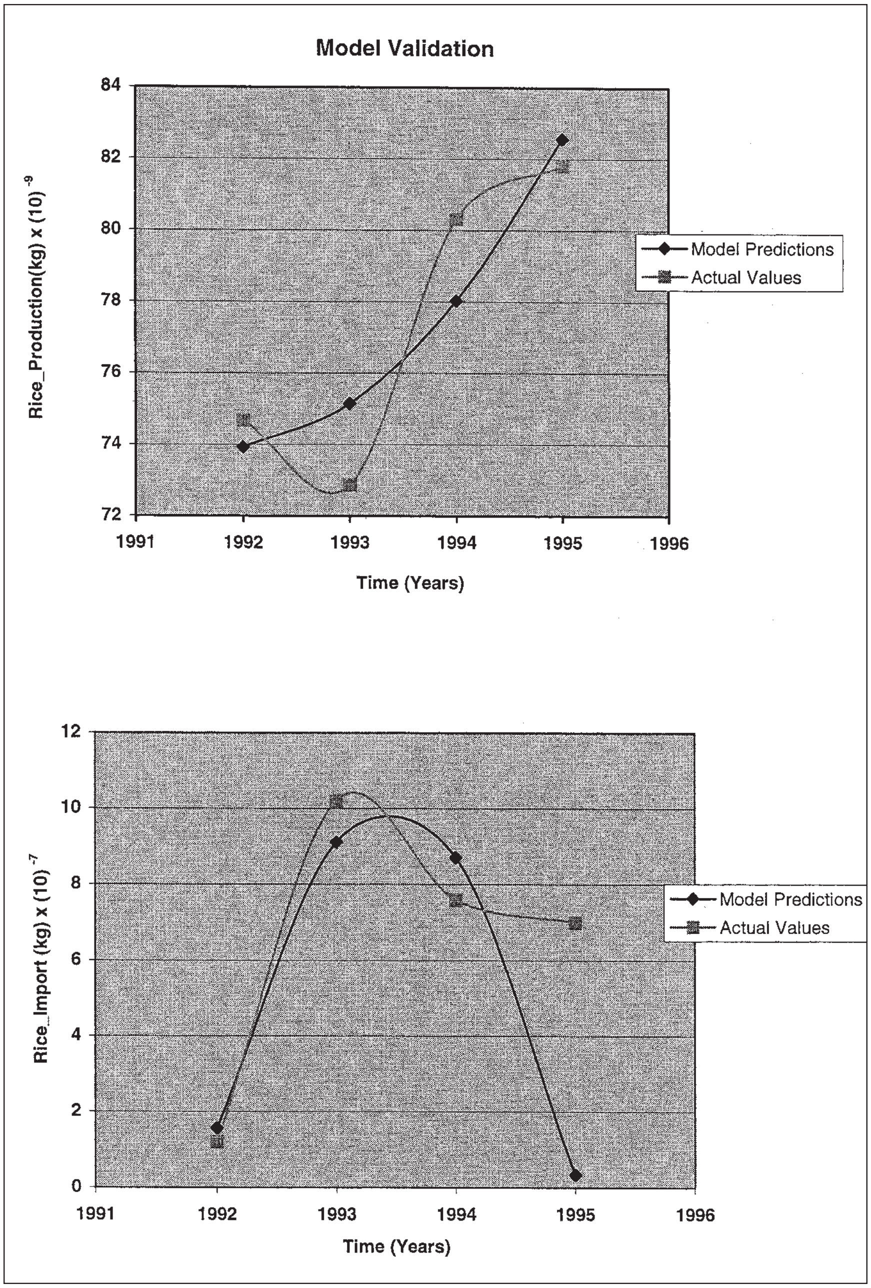

Figure 1. Comparison between model predictions and actual values for Rice_Production (kg) × 10^{-9} and Rice_Import (kg) × 10^{-7}.

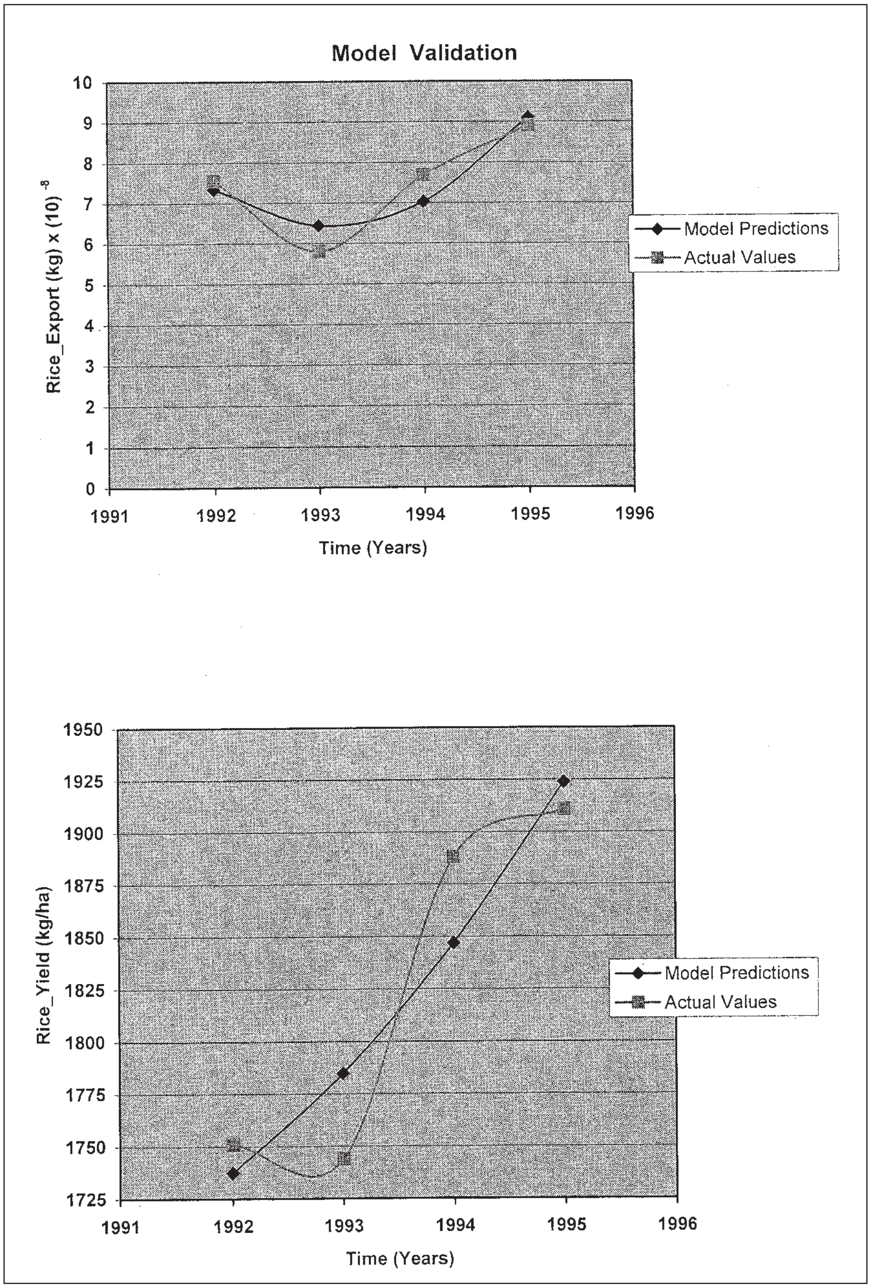

Figure 2. Comparison between model predictions and actual values for Rice_Export (kg) $\times$ 10^{-8} and Rice_Yield (kg/ha).

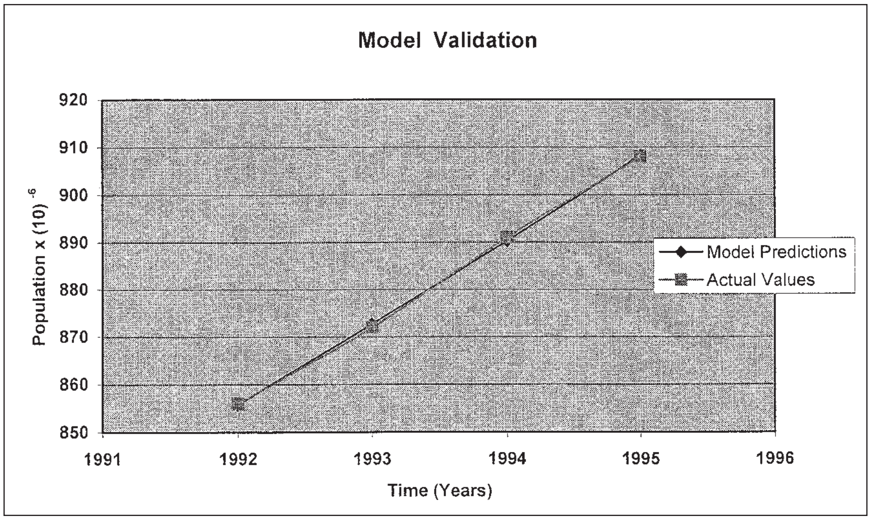

Figure 3. Comparison between model predictions and actual values for Population × 10^{-6}.

shown in Figure 6. Figure 6 shows that there are only limited ranges in which the variations with respect to coefficients a_{prod} and b_{prod} satisfy the desired condition for future sustainability. For a_{prod} this range is from 0.2 to 1.4 and for b_{prod} it is from –1.8 to 1.0. Thus, coefficients a_{prod} and b_{prod} turn out to be the most important coefficients and, therefore, the data on which the relevant model (equation 1) is dependent, becomes all the more important.

The dynamic model developed in this article has been quantified and discussed for the rice-component only, however, it can likewise be quantified for various other EF-components depending upon the objectives of that particular study.

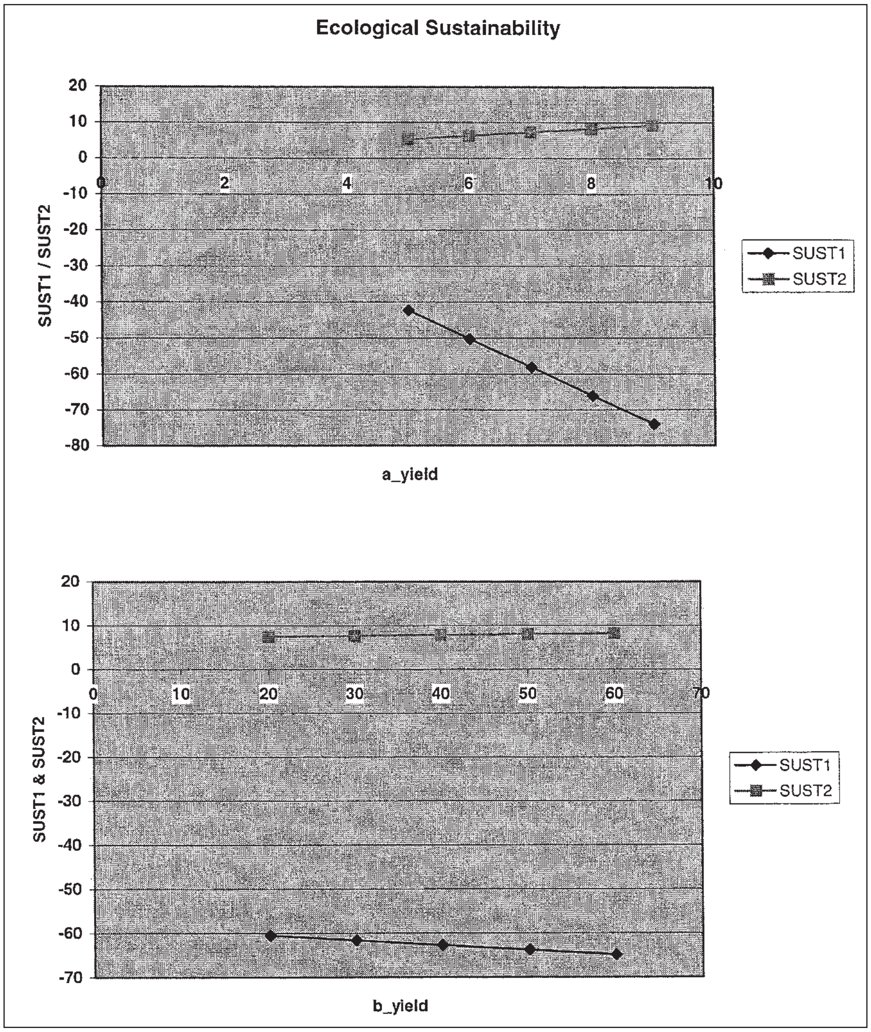

Figure 4. Values for SUST1 and SUST2 plotted w.r.t. a_yield and b_yield.

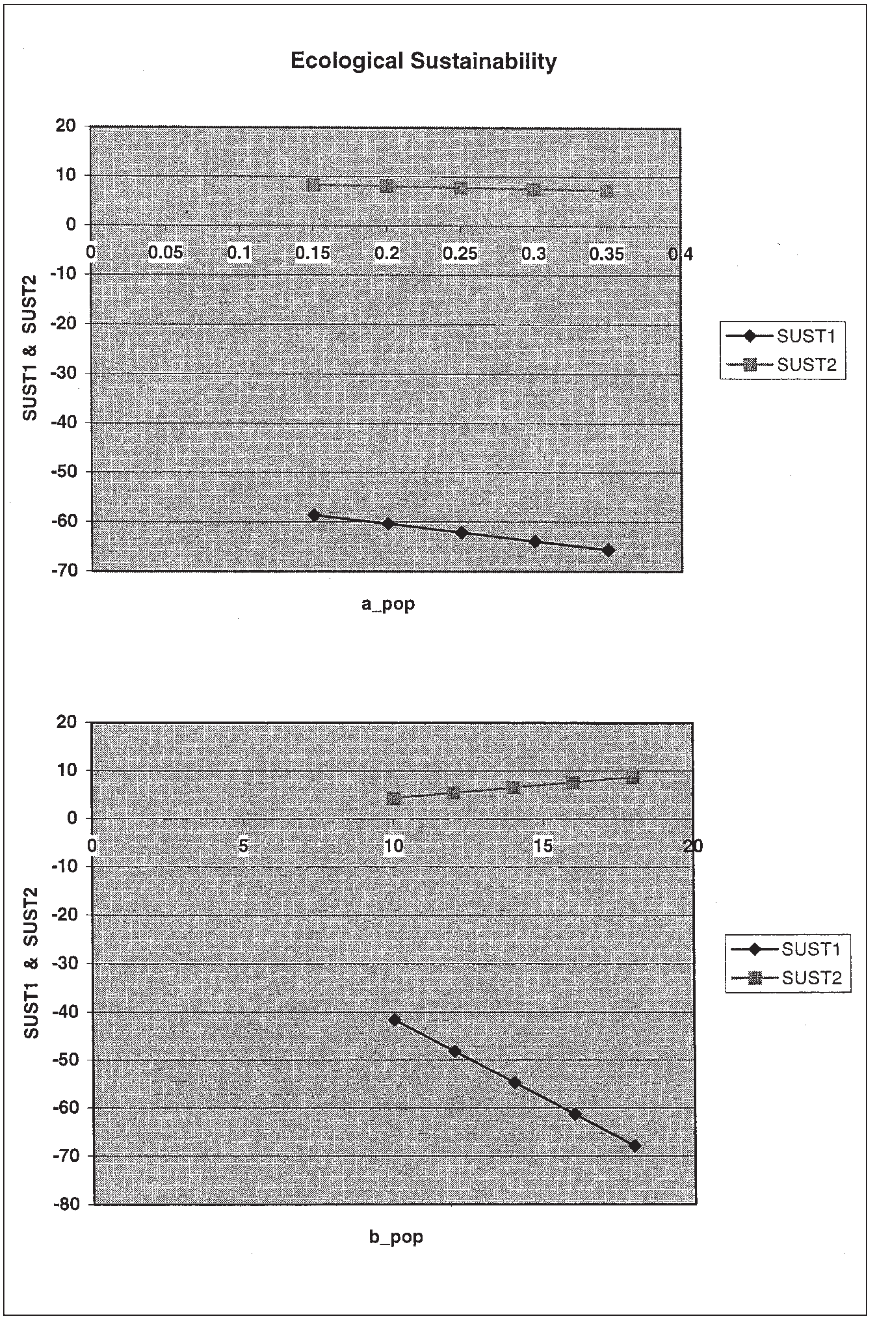

Figure 5. Values for SUST1 and SUST2 plotted w.r.t. a_pop and b_pop.

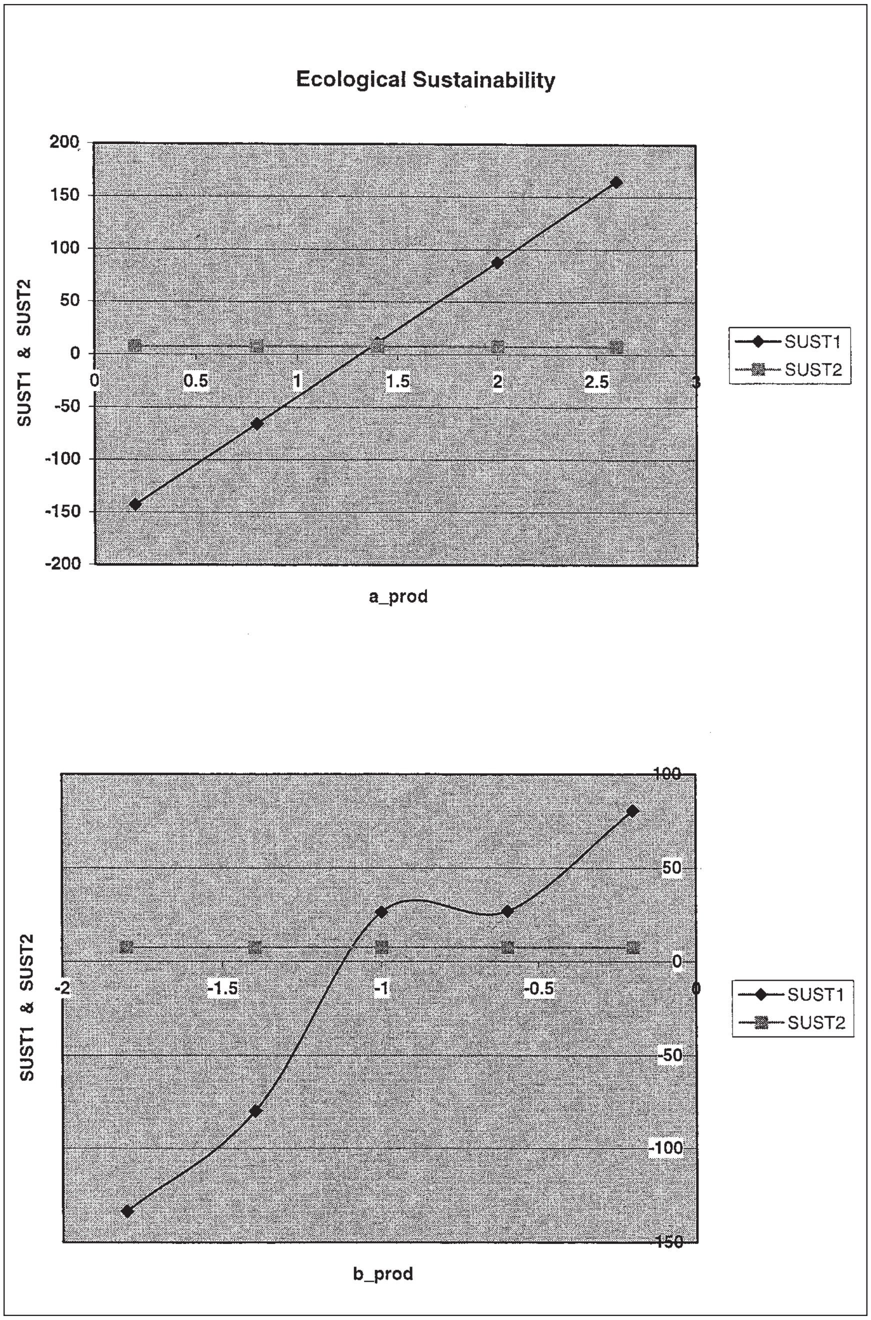

Figure 6. Values for SUST1 and SUST2 plotted w.r.t. a_prod and b_prod.

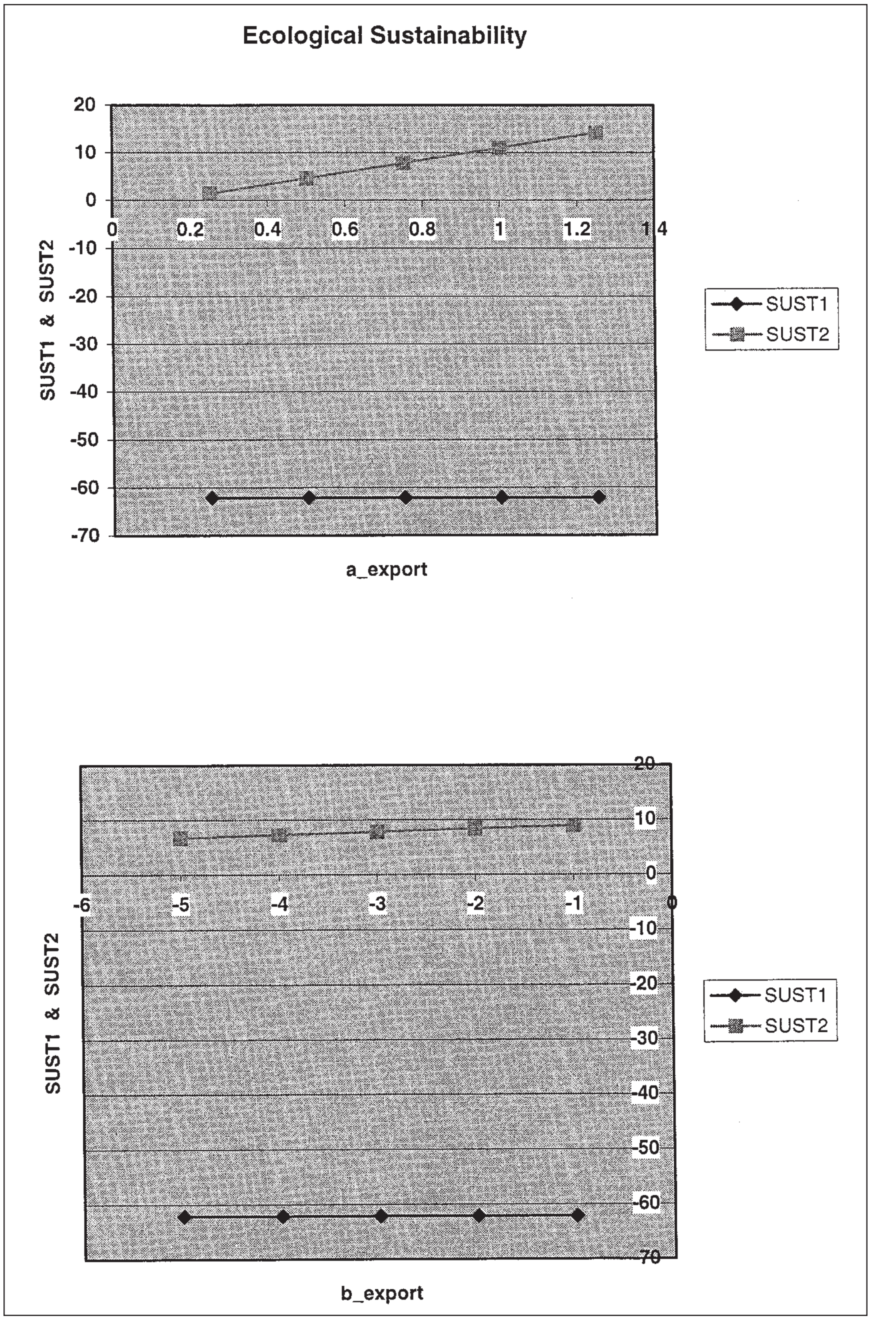

Figure 7. Values for SUST1 and SUST2 plotted w.r.t. a_export and b_export.

APPENDIX
Meanings of Different Terms in Equations (6.1) through (6.23)

S. No	Terms	Actual values	Numerical values
1.	x	t-1991	As 't' changes
2.	a_1	$a_{prod} \times 10^9$	$a_{prod} = 0.829$
3.	b_1	$b_{prod} \times 10^9$	$b_{prod} = -1.267$
4.	c_1	$c_{prod} \times 10^9$	$c_{prod} = 74.359$
5.	a_2	$a_{import} \times 10^7$	$a_{import} = -3.975$
6.	b_2	$b_{import} \times 10^7$	$b_{import} = 19.465$
7.	c_2	$c_{import} \times 10^7$	$c_{import} = -13.925$
8.	a_3	$a_{export} \times 10^8$	$a_{export} = 0.744$
9.	b_3	$b_{export} \times 10^8$	$b_{export} = -3.129$
10.	c_3	$c_{export} \times 10^8$	$c_{export} = 9.720$
11.	a_4	a_{yield}	$a_{yield} = 7.5$
12.	b_4	b_{yield}	$b_{yield} = 24.9$
13.	c_4	c_{yield}	$c_{yield} = 1705.0$
14.	a_5	$a_{pop} \times 10^6$	$a_{pop} = 0.25$
15.	b_5	$b_{pop} \times 10^6$	$b_{pop} = 16.25$
16.	c_5	$c_{pop} \times 10^6$	$c_{pop} = 839.25$

REFERENCES

1. W. E. Rees and M. Wackernagel, Monetary Analysis: Turning a Blind Eye on Sustainability, *Ecological Economics, 29,* pp. 47-52, 1999.
2. W. E. Rees and M. Wackernagel, Urban Ecological Footprints: Why Cities Cannot be Sustainable—and Why They are a Key to Sustainability, *Environmental Impact Assessment Review, 16,* pp. 223-248, 1996.
3. P. Khanna, V. S. Kulkarni, P. S. Dutt, J. S. Pandey, V. Joshi, and A. L. Aggarwal, An Approach to Carrying Capacity Based Developmental Planning Process, *Journal of Indian Association for Environmental Management, 18,* pp. 1-19, 1991.
4. J. S. Pandey, R. Kumar, and V. S. Kulkarni, A Case Study of Terrestrial Ecosystem for Suggesting Modifications in the Carrying Capacity Studies, *Journal of Indian Association for Environmental Management, 27,* pp. 175-177, 2000.
5. M. Wackernagel and W. E. Rees, Conceptual and Structural Barriers to Investing in Natural Capital: Economics from an Ecological Footprint Perspective, *Ecological Economics, 20,* pp. 3-24, 1997.

6. C. Folke, A. Jansson, J. Larson, and R. Costanza, Ecosystem Appropriation by Cities, *Ambio, 26,* pp. 167-172, 1997.
7. J. C. J. M. van den Bergh and H. Verbruggen, Spatial Sustainability Trade and Indicators: An Evaluation of the 'Ecological Footprint,' *Ecological Economics, 29,* pp. 61-72, 1999.
8. *Economic Intelligence Service, Monthly Review of Indian Economics,* Foreign Trade Statistics of India, CMIE, Centre for Monitoring Indian Economy, pp. 1-141, 1996.
9. *Economic Intelligence Service, Monthly Review of Indian Economics,* Foreign Trade Statistics of India, CMIE (Centre for Monitoring Indian Economy), p. 4, 1999.
10. *Statistical Abstract of India, Central Statistical Organization,* Department of Statistics and Programme Implementation, Government of India, New Delhi, 1998.
11. V. Singhal, *Indian Agriculture,* Indian Economic Data Research Centre, New Delhi, India, pp. 60-83, 1999.
12. P. Khanna, J. S. Pandey, S. Khan, and F. J. Abidi, Regional Carrying Capacity Based Integrated Planning for Sustainable Development of Urban and Fringe Rural Areas in Sensitive Terrestrial Ecosystems, *Journal of Rural Development, 17*:3, pp. 495-509, 1998.
13. M. Wackernagel, L. Onisto, P. Bello, A. C. Linares, I. S. L. Falfan, J. M. Garcia, A. I. S. Gerrero, M. G. S. Guerrero, National Natural Capital Accounting with the Ecological Footprint Concept, *Ecological Economics, 29,* pp. 375-390, 1999.

Direct reprint requests to:

Dr. J. S. Pandey
National Environmental Engineering Research Institute (NEERI)
Nehru Marg
NAGPUR – 440 020, India