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MODELING FOREST DYNAMICS OF THE SUNDARBANS

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ABSTRACT
This paper presents a system dynamics model to simulate the growth of mangrove forest of the Sundarbans. The model is individual based and the trees of same diameter class are designated as one cohort. The model consists of two sub-models and these are: present forest growth and recruited forest growth. Two main state variables in each of the sub-models are tree biomass and number of trees. The tree biomass is computed from the physiological process of photosynthesis and respiration. Number of trees is increased by recruitment and decreased by mortality and harvesting. The parameters of the model are determined from field data and research reports. The model is validated both quantitatively and qualitatively. Some simulation results of the mangrove forest (Sundri and Gewa) of the Sundarbans are discussed.

1. INTRODUCTION

Industrialization, population growth and depletion of natural resources are threatening ecosystems all over the world. Climate change is one of the results of this development. But forests can play an important role in maintaining the global system in balance and these forests are also the largest carbon sink above the soil. Furthermore, about 70 to 90 % of the global biodiversity are found in this ecosystem.

The Sundarbans is the largest contiguous patch of mangrove forest in the world. It is located in the south-west of Bangladesh. The forest covers an area of 577,000 ha, of which 401,600 ha is land and the remaining 175,600 ha is water bodies. The Sundarbans constitutes 51% of the total reserved forest of Bangladesh. It plays a vital role in the economy of Bangladesh and provides raw materials for industries, fuelwood for cooking and inputs to flourishing aquacultural industries. The present endowment of the Sundarbans is much reduced from the past levels and unplanned harvesting of forest in the past has already created an ecological imbalance. This has created an upsurge of interest in the proper management of the forest resources of the Sundarbans. Recently, it has been declared as WORLD HERITAGE by UNICEF.

The Sundarbans is a complex ecosystem containing biological, technological, environmental, socio-economic and political components and modeling of such a complex system is a formidable challenge. Forrester's system dynamics methodology provides a foundation for constructing computer models to do what human mind can not do – rationally analyze the structure, the interactions and mode of behaviour of complex socio-economic, technological, biological and political systems. System dynamics is the most appropriate technique for modeling and simulation of dynamic systems through models [1].

For proper management and understanding of the forest ecosystem, it must be modeled and simulated. Growth models of forests can assist in many ways. Some important uses of growth models are: its ability to predict the future yields; it provides an efficient way to resource forecasts; it can be used to prepare harvesting schedules for sustainable development. It can also provide a better understanding and greater insights into forest dynamics.

In the modeling of forest dynamics individual based model has been used for over 20 years [4], [10], [5]. Köhler [8] applied cohort structure to simulate individual based model for tropical rainforests for analysis of logging and fragmentation. Kubo and Ida [9] applied Monte Carlo method to operate individual based model for analysis of forest dynamics.

The need of more reliable assessment of natural forest growth dynamics prompted Bossel and Krieger [3] to develop a vertically and spatially structured dynamic simulation model of a natural forest development. The model accounts spatially for biomass and tree numbers in five distinct layers (seedlings, saplings, poles, main canopy, emergent). Energy accounting for assimilation and dissimilation rates leads to biomass, diameter, and height growth. Huth and Ditzer [6] developed a new model (FORMIX3) for simulation of the growth of tropical rain forest. The model describes growth, mortality, recruitment of trees and competition between trees. The calculation of tree growth is based on carbon balance.

Oikawa and Ito [10] developed a new ecosystem model (Sim-CYCLE) and this ecosystem model was based on the production theory established by Monsi and Saeki. This model provides a reliable estimate of carbon stock, gross primary productivity (GPP), net primary productivity (NPP), and net ecosystem productivity (NEP). This model was applied to study carbon dynamics of terrestrial ecosystem in monsoon Asia. Ito and Oikawa [7] applied this model to study of carbon dynamics of varies terrestrial ecosystems and also estimating the response to global climate change.

The purpose of this research is to develop a system dynamics individual based forest growth model of the mangrove forest of the Sundarbans to predict the dynamics of forest growth for analyzing the strategies for sustainable development of the mangrove forest of the Sundarbans.

2. MODELING OF FOREST GROWTH

Individual based model of forest growth based on system dynamics approach has been developed. The main components of the model are: growth (diameter increment from photosynthesis and respiration), mortality and recruitment.

The forest growth model described here consists of two sub-models and these are: present forest growth sub-model and recruited forest growth sub-model. Trees in each of these sub-models are classified into three diameter classes and these are termed as cohort. Hence the number of cohort is fixed for the present forest growth sub-model, but it increases by one for each recruiting year for the recruited growth submodel. This applies to the mangrove forest of both Sundri and Gewa. Hence each cohort is to be represented by an array to model the forest growth.

Again, in each sub-model two main state variables are tree biomass and number of tree. Tree biomass is computed from the physiological process of photosynthesis and respiration. Tree growth rate computed from photosynthesis and respiration is the potential growth rate. For a time step dt the changes in biomass B_i,n of an individual tree in the cohort i and plot n is computed as:

$$\frac{dB_{i,n}}{dt} = P_{i,n} - R_{i,n} \qquad (1)$$

Where $P_{i,n}$ = actual photo production
$R_{i,n}$ = losses of dead wood and respiration

The maximum photosynthetic production rate $P\max_i$ is computed as:

$$P\max_i = \frac{PM_j}{k} \ln\left[\frac{1 + \frac{\alpha_j}{PM_j} I_o}{1 + \frac{\alpha_j}{PM_j} I_o . e^{-k.LAI}}\right] \qquad (2)$$

Where I_o = incident solar radiation
LAI = maximum leaf area index
k = light extinction coefficient
α_j = initial slope of light response curve
PM_j = maximum gross biomass production

The actual growth rate is computed from potential growth rate and growth multiplier which takes into account of light competition indirectly through cumulative basal area of the trees larger than trees in the concerned cohort.

The changes in the tree number $N_{i,n}$ is given by

$$\frac{dN_{i,n}}{dt} = -M_{i,n} \qquad (3)$$

Where $M_{i,n}$ = mortality

The number of trees in the recruited forest is increased by recruitment and decreased by mortality. Fig. 1 shows the STELLA flow diagram of the forest growth model.

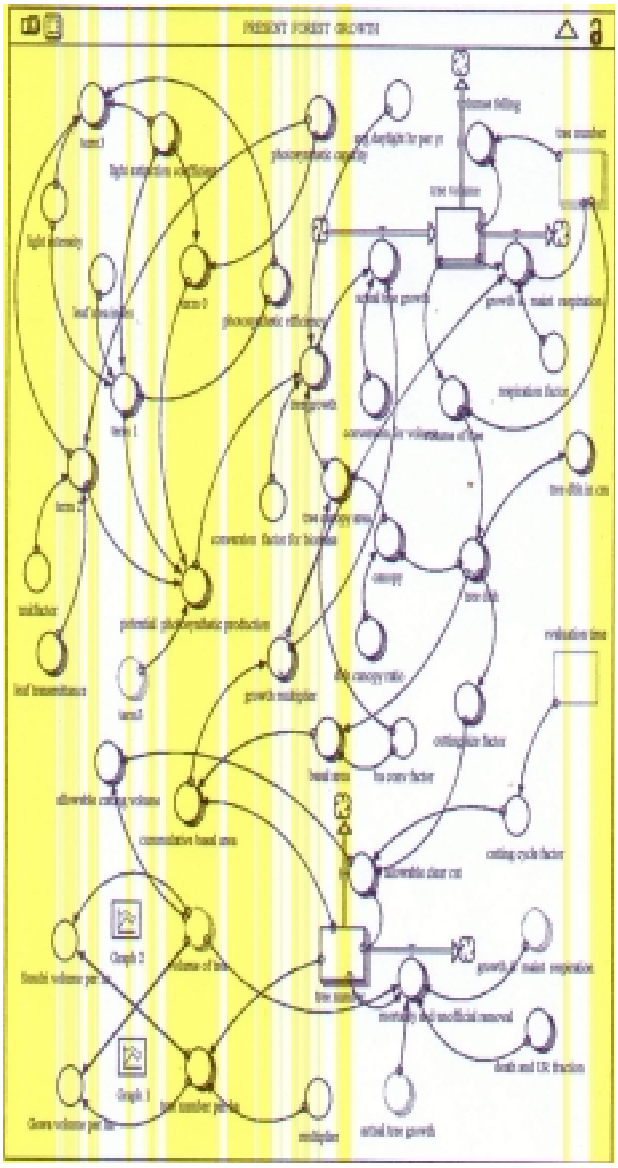

Fig. 1(a) STELLA flow diagram of the present forest growth.

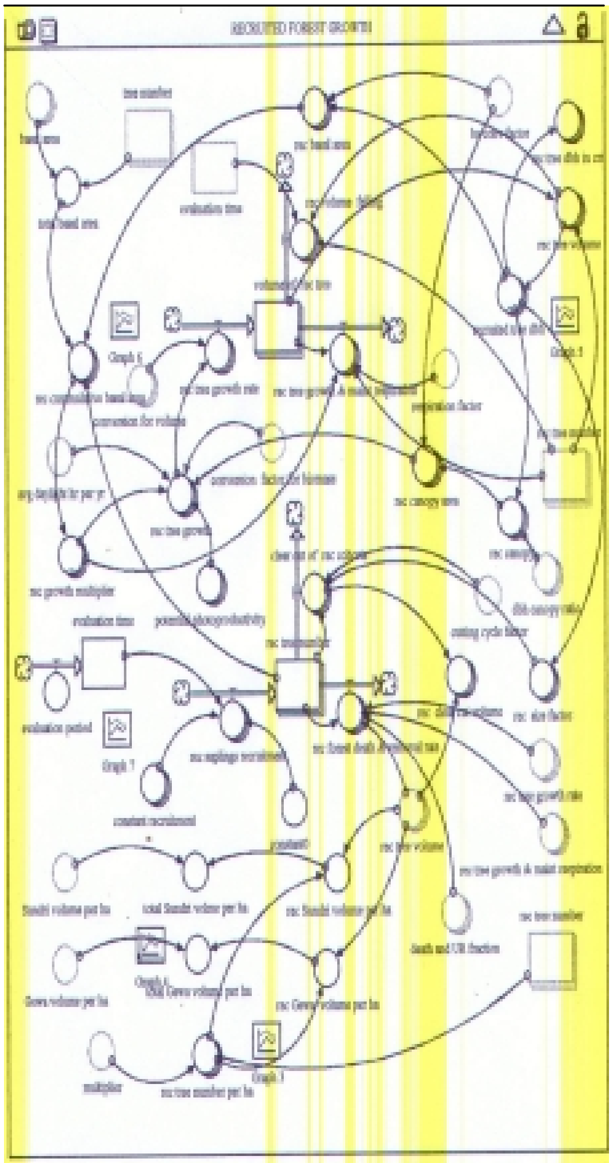

Fig. 1(b) STELLA flow diagram of the recruited forest growth.

3. RESULTS AND DISCUSSIONS

The system dynamics model of forest growth was applied to the mangrove forest (Sundri and Gewa) of the Sundarbans to predict the forest growth in terms of diameter at breast height (dbh) and volume of the biomass and also to determine the number of the trees. The initial values of the stock variables and the values of the parameters were taken from the secondary data obtained from the Department of Forestry and published reports. To build up confidence in the model the simulated diameter at breast height of mangrove forest of Sundri and Gewa was compared with the observed data reported in the literature and the agreement was excellent. Fig.2 shows the comparison between the simulated results and observed values. The model also generates plausible behaviour.

The model was applied to project the diameter at the breast height for both Sundri and Gewa and the model generated plausible behaviour. The diameters at breast height of the Sundri in three cohorts of the present forest increased from 10 cm, 15 cm, and 20 cm to 11.92 cm,

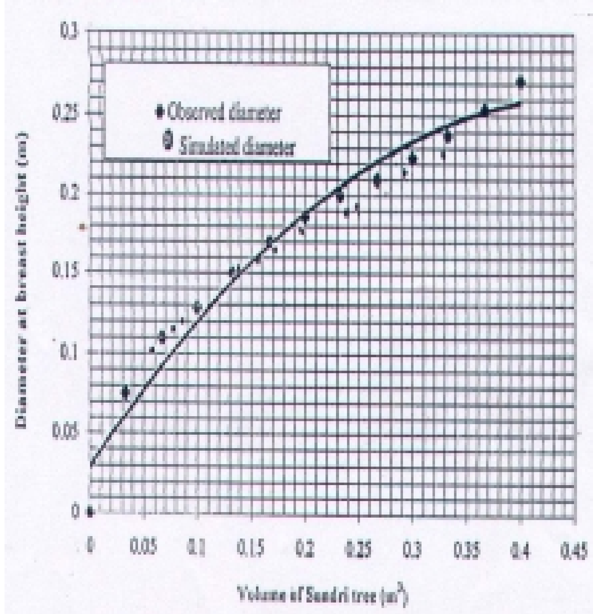

Fig.2 Comparison between the simulated diameter at breast height (dbh) and the observed values.

18.56 cm and 23.77 cm within the simulation period of 12 years. The simulated growth rate of the diameter at the breast height was very close to the growth rate reported in the literature. The diameters at breast height of Sundri and Gewa in the first two cohorts in the recruited forest reached the average values of 12.08 cm and 13.15 cm respectively starting from 10 cm in 11 years.

The simulated volumes of biomass of Sundri and Gewa in the present forest were 38.89 m^3/ha and 139.63 m^3/ha starting from 36.87 m^3/ha and 81.03 m^3/ha respectively. Fig.3 shows simulated volume of biomass of Sundri and Gewa in the first two cohorts of present forest for a simulation period of 12 years. The volume of biomass of Sundri at the end of simulation period was less than that of Gewa because of the fact that Sundri was affected by top dying disease. The volume of biomass of Sundri and Gewa in the recruited forest were 97.25 m^3/ha and 28.29 m^3/ha respectively at the end of 12 years of simulation period with generation of one cohort in each year.

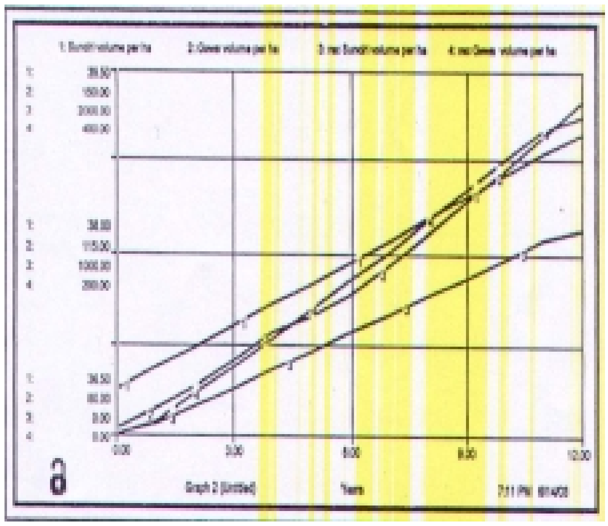

Fig.3 Simulated volume of biomass for both Sundri and Gewa.

The number of trees in the present three diameter classes of 8-12, 13-17, and 18^{+}cm (cohorts) of the Sundri falls to133/ha, 78/ha and 37/ha from 185/ha, 110/ha and 50/ha respectively after a simulation period of 12 years while the number of trees in the present three diameter classes of 8-12, 13-17, and 18^{+}cm (cohorts) of the Gewa in the plot falls to 424/ha, 229/ha and 1/ha from 650/ha, 485/ha and 25/ha, respectively after a simulation period of 12 years. Fig.4 shows the simulated number of trees in the first two cohorts of the present forest of the Sundri and Gewa in the plot under consideration.

The diameters at breast height of the Sundri and the Gewa considered for recruitment was 8 cm and larger and the recruitment was done annually at a constant rate of 350/ha and 650/ha of Sundri and Gewa respectively. The number of trees in the cohort 1 and cohort 2 of the recruited Sundri reached 280/ha and 287/ha after a simulation period of 12 years with diameter of 12.08 cm and 11.90 cm respectively while the number of trees in the cohort 1 and cohort 2 of the recruited Gewa reached 548/ha and 561/ha after a simulation period of 12 years with diameters of 13.15 cm and 12.84 cm respectively. Fig. 5 shows the simulated number of trees in the first two recruited cohorts of the Sundri and Gewa with a reduced level of mortality and unofficial removal. The simulated number of trees follows the behaviour reported in the literature but no data was available for direct comparison.

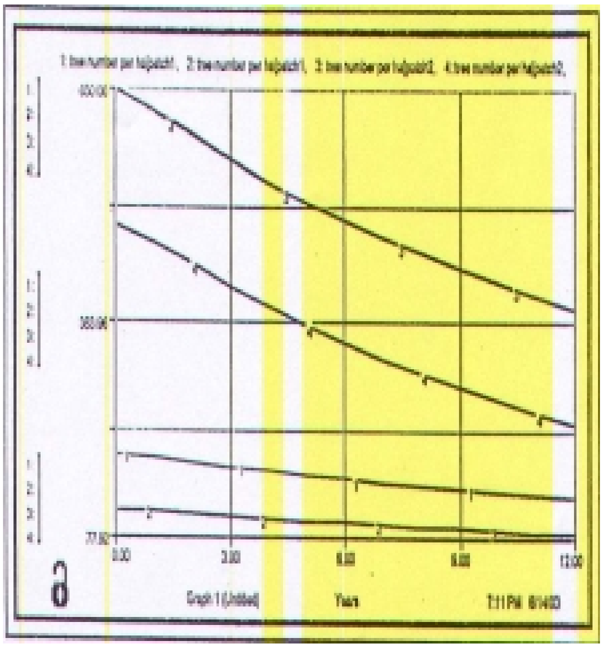

Fig. 4 Simulated numbers of trees

Fig.6 shows the simulated total volume of the biomass in all the cohorts of Sundri and Gewa in the plot for a period of 12 years. Although the total volume of biomass in all the cohorts of the Sundri is much higher than that of the Gewa, the volume growth rate of the biomass is almost identical. The model was also simulated to determine the harvesting schedule for a period of 12 years. No cutting cycle was predicted for a period of 12 years. For predicting the growth and harvest scheduling and climate change impacts, further refinement of the model and updating of data are under study.

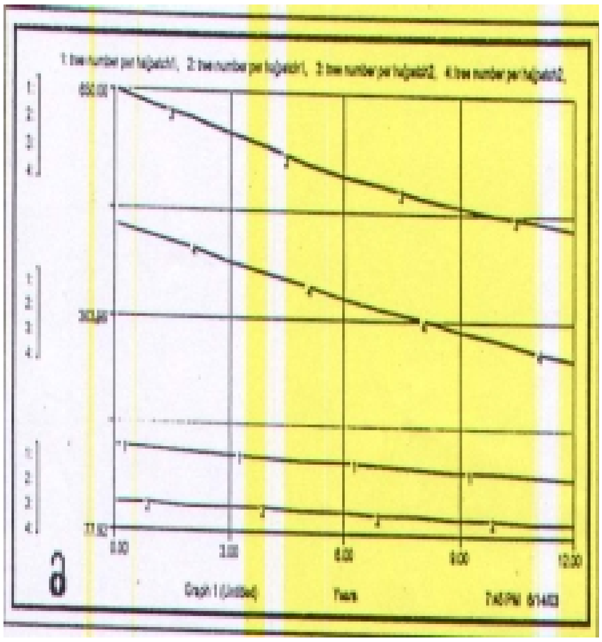

Fig. 5 Simulated number of trees in the first two recruited cohorts of the Sundri and Gewa with a reduced level of mortality and unofficial removal.

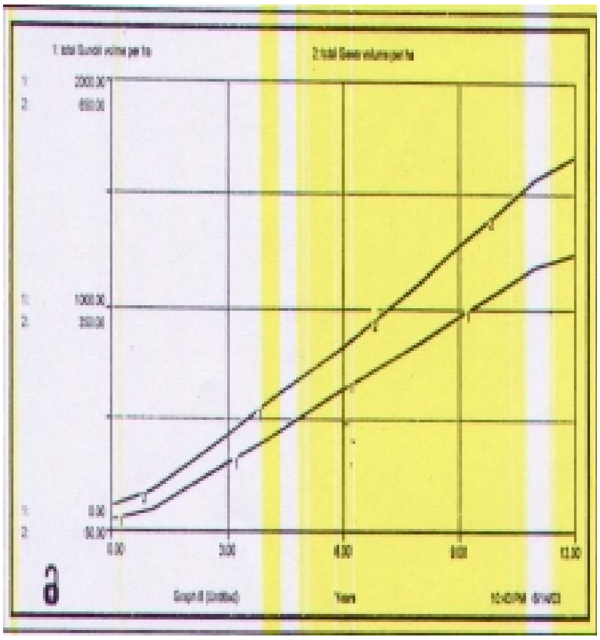

Fig.6 Simulated total volume of Sundri and Gewa**.**

4. CONCLUSIONS

A process based system dynamics model of forest growth is presented. This model has been applied to the Sundarbans in Bangladesh as a case study and the model predicts the forest growth with reasonable accuracy. Further refinement of the model and updating of the data are needed to apply this model to determine the harvesting schedule for sustainable development and also for analyzing the forest management strategies such as climate change impacts on forest dynamics of Sundarbans in Bangladesh.

6. REFERENCES

1. Bala, B.K., 1999, *Principles of System Dynamics,* Agrotech Publishing Academy, Udaipur, India.

2. Bala, B.K. 2002. "Modeling of Forest Ecosystem of the Sundarbans". Department of Farm Power and Machinery, Bangladesh Agricultural University, Mymensingh, Bangladesh.

3. Bossel, H. and Krieger, H., 1991. "Simulation Model of Natural Tropical Forest Dynamics". Ecological Modeling, 59:37–71.

4. Botkin, D.B., Janak, J.F. and Wallis, J.R., 1972, "Some Ecological Consequences of a Computer Model of Forest Growth", Ecology, 60: 849-872.

5. Horn, H.S., Shugart, H.H. and Urban, D.L., 1989, "Simulators as Models of Forest Dynamics". *In: Roughgarden, J., May, R.M. and Levin, S.A. (Eds.), Perspectives in Ecological Theory*. Princeton University Press, Princeton :257-267.

6. Huth, A. and Ditzer, T., 2000, "Simulation of the Growth of a Lowland Dipterocarp Rain Forest with FORMIX3". Ecological Modeling, 134:1-25.

7. Ito, A. and Oikawa, T., 2002, "A Simulation Model of the Carbon Cycle in Land Ecosystems (Sim-CYCLE): a Description Based on Dry-matter Production Theory and Plot-scale Validation". Ecological Modeling, 151:143-176**.**

8. Kohler, P., 2000, "Modeling anthropogenic impacts on the growth of tropical rain forests using an individual-oriented forest growth model for analyses of logging and fragmentation in three case studies", Ph.D Thesis, University of Kassel, Germany.

9. Kubo, T. and Ida, H., 1998, "Sustainability of an Isolated Beech-dwarf Bamboo Stand: Analysis of Forest Dynamics with Individual Based Model", Ecological Modeling, 111:223-235.
10. Oikawa, T. and Ito, A., 2001, "Modeling Carbon Dynamics of Terrestrial Ecosystem in Monsoon Asia". *Present and Future of Modeling Global Environmental Change: Toward Integrated Modeling*, Eds., T. Matsuno and H. Kida, 207-209.

11. Shugart, H.H., 1984, *A Theory of Forest Dynamics*, Springer Verlag, New York.

7. NOMENCLATURE

Symbol	Meaning	Unit
B	Biomass	g
P	Actual photoproduction	MgCO2 /(dm^2.h)
R	Losses of dead wood and respiration	No.
Pmax	Max. Photoproduction rate	$mgCO^2$/ (dm^2.h)
k	Light extinction coefficient	No.
I_0	Incident solar radiation	W/m^2
LAI	Max. leaf area index	No.
α	Initial slope of light response curve	$mgCO^2$. m^2/(dm^2 .h.W)
P_M	Max. gross biomass production	$MgCO^2$/ (dm^2.h)
M	Mortality	No.