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DEVELOPMENT OF PLANT FUNCTION TYPES FOR STUDYING IMPACT OF GREEN HOUSE GASES ON TERRESTRIAL ECOSYSTEMS

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ABSTRACT

Increasing carbon dioxide concentrations and associated climatic changes have pronounced effects on carbon storage in ecosystems. This, in turn, is likely to affect C/N ratios of the plant material with possible effects on decomposition cycles. Hence, it becomes important that at local levels mechanisms of CO_2 interactions with water, light, nutrients and temperature should be investigated, and the effects integrated in order to quantify the cumulative impact of CO_2 increase on biomass production. This article discusses importance of parameter 'G' in connection with maximum increments in plant volume, and provides models for certain important Indian species.

1. INTRODUCTION

Concerns expressed about the effects of global climate change due to increased concentrations of greenhouse gases [1], regional air pollution, and consequent shifts in vegetation cover and biomass density [2] are quite serious in nature. Carbon dioxide has risen significantly from the preindustrial levels to the present level, and there is something of a consensus within the scientific community that global atmospheric gaseous concentrations of concern are likely to rise more rapidly in coming years [3]. While there are many adverse likely climatic implications of this increased concentration, there may be some beneficial consequences too. Continued increases in CO_2 level will inevitably have a significant positive

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effect on photosynthesis, and thereby on growth and development of a wide range of cultivated and native plant species [1, 3].

There also is a growing awareness of impacts of the use of biomass from both forest and agricultural lands as fuel (to supplement or replace dwindling supplies of petroleum). Promising options for reducing those imports include [4]:

1. Planting fast growing trees which can be harvested on short rotation;
2. Proper utilization of limbs and such other parts of trees as are not suitable for either lumber or paper-making;
3. Using pulp wood as a substitute for home-heating and electricity generation;
4. Using agricultural plant and animal wastes to produce methane gas or alcohol which can be substituted as fuel for internal combustion engines.

This amounts to saying that our forest and agroecosystems should be so designed and managed as to convert solar and other natural forms of energy into useful forms with the maximum efficiency.

Many empirical studies of plant growth and development have nonsystematically assembled information from scattered sources. Evaluation of results, more often than not, has in many cases evidenced a quick search for statistical significance with insufficient regard to biological understanding. For example, maximum biomass production capacity, which is the obvious basis for identification and quantification of growth limitations, is still very poorly understood for important plant species [5].

Many regional and global mathematical models have also been developed for assessing and predicting ecosystem processes and quantifying likely environmental impacts. A major shortcoming afflicting most of these models is their being mainly static-budget models. Hence, they do not adequately accommodate mechanistic treatment of processes, and, more often than not, are not driven by site-specific data and boundary conditions [6]. Hence, there is a very strong and obvious need for developing species—specific ecosystem functions or "plant function types" (PFT's) [7]. This article is an attempt in this direction.

Moreover, this article forms an important link in the series of earlier contributions from the authors [8, 9] for developing ecosystem-process models. It discusses importance of parameter 'G' [10] in connection with maximum plant-volume increments, and provides models for certain important Indian species. Relevant ecological issues and a computer code (DIAM) developed for estimating G values for different species also are discussed. The code is written in 'C' and can be run on a personal computer. This facilitates rapid determination of species-specific values of 'G'. Combined with the appropriate PFT's developed in the present research, issues related with biomass measurements and monitoring become easier to tackle, and the estimation of biomass becomes more precise [7].

2. PLANT PRODUCTIVITY IN DIFFERENT ECOSYSTEMS [4]

2.1 Types of Ecosystem

Although aquatic and terrestrial ecosystems have the same basic structure and similar function, biotic composition and size of trophic components, in certain situations, are strikingly different (Tables 1 and 2). The most striking contrast appears in the size of the green plants. The autotrophs of terrestrial ecosystem tend to be fewer but they are very much bigger, both as individuals and as biomass per unit area.

In both, land and aquatic ecosystem, a large part of the solar energy is dissipated in the evaporation of water, and only a very small fraction (approximately 5%) is fixed through photosynthesis. For every gram of CO_2 fixed in a grassland or forest ecosystem, as much as 100 grams of water must be moved from the soil through the plant tissues, and transpired. In contrast, the use of water associated with

Table 1. Comparison of Density (Numbers/m^2) and Biomass (as Grams Dry Weight/m^2 of Organisms in Aquatic and Terrestrial Ecosystems of Comparable and Moderate Productivity

	Open water pond		
Ecologic	Assemblage	No/m^2	Gm Dry Wt/m^2
Producers	Phytoplanktonic algae	10^8-10^{10}	5.0
Consumers in the autotrophic layer	Zooplanktonic crustaceans and rotifers	10^5-10^7	0.5
Consumers in the heterotrophic layer	Benthic insects, mollusks, and crustaceans	10^5-10^6	4.0
Large roving consumers (permeants)	Fish	0.1-0.5	15.0
Microorganism consumers (saprophages)	Bacteria and fungi	10^{13}-10^{14}	1-10***

*Including only small birds (passerines) and small mammals (rodents, shrews, etc.).
**Including two to three cows (or other large herbivorous mammals) per hectare.
***Biomass based on the approximation of 10^{13} bacteria = 1 gram dry weight.
Source: Odum [4].

Table 2. Comparison of Density (Numbers/m^2) and Biomass (as Grams Dry Weight/m^2 of Organisms in Aquatic and Terrestrial Ecosystems of Comparable and Moderate Productivity

	Meadow or Old-Field		
Ecologic	Assemblage	No/m^2	Gm Dry Wt/m^2
Producers	Herbaceousktonic angiosperms (grasses and forbs)	10^2-10^3	500.0
Consumers in the autotrophic layer	Insects and spiders	10^2-10^3	1.0
Consumers in the heterotrophic layer	Soil arthropods, annelids, and nematodes	10^5-10^6	4.0
Large roving consumers (permeants)	Birds and mammals	0.0-0.03	0.3* 15.0**
Microorganism consumers (saprophages)	Bacteria and fungi	10^{14}-10^{15}	0.0-100.0***

*Including only small birds (passerines) and small mammals (rodents, shrews, etc.).
**Including two to three cows (or other large herbivorous mammals) per hectare.
***Biomass based on the approximation of 10^{13} bacteria = 1 gram dry weight.
Source: Odum [4].

production of phytoplankton or other submerged aquatic plants is significantly lower.

Terrestrial and aquatic ecosystems can be categorized under different classes as shown in Table 3. Large amounts of productive energy are dissipated in supporting tissues of terrestrial autotrophs. This supporting tissue has a high content of cellulose and lignin. The rate of metabolism per unit weight of land plants is much lower than that of plants in water. Moreover, plants on land contribute more to the structural matrix of the ecosystem than do plants in water. "Maintenance to structure ration," better known as "Schroedinger's ratio," is the ratio of total community respiration (R) to total community biomass (B). Energy dissipation of solar radiation use has been depicted as percentages in Table 4.

Table 3. Different Classes of Terrestrial and Aquatic Ecosystems

Terrestrial Biome
- a) Tundra: Arctic and alpine
- b) Desert: Herbaceous and shrub
- c) Chaparral: Winter rain-summer drought regions
- d) Boreal coniferous forests
- e) Temperate deciduous forests
- f) Temperate grassland
- g) Tropical grassland and savanna
- h) Semievergreen tropical forest: pronounced wet and dry seasons
- i) Evergreen tropical rain forest

Freshwater Ecosystem Types
- a) Lentic (standing water): lakes, ponds and so on
- b) Lotic (running water): rivers, streams, and so on
- c) Wetlands: marshes and swamp forests

Marine Ecosystem Types
- a) Open ocean (pelagic)
- b) Continental shelf waters (inshore water)
- c) Upwelling regions (fertile areas with productive fisheries)
- d) Estuaries (coastal bags, sounds, river mouths, salt marshes, and so on)

Source: Odum [4].

Table 4. Energy Dissipation of Solar Radiation Use

S. No.	Energy Form	Percent
1.	Reflected	30
2.	Direct conversion to heat	46
3.	Evaporation, precipitation	23
4.	Wind, waves and currents	0.2
5.	Photosynthesis	0.8

Tidal energy — about 0.0017 percent of solar
Terrestrial heat — about 0.5 percent of solar

Source: Odum [4].

2.2 Plant Productivity

A large portion of earth's surface is in the low-production category because of scarcity of water or shortage of nutrients, (the chief limiting factors). On the other hand, areas that receive natural energy subsidies, e.g., river deltas, estuaries, coastal upswelling zones and zones having rich glacial till, wind-transported, or volcanic soils in regions of adequate rainfall, constitute naturally fertile areas.

Table 5 depicts the distribution of primary production and its relation to biomass. Turnover time is the parameter which brings about striking distinctions between terrestrial and aquatic ecosystems. It is of the order of years in case of forests; for sea on the order of days. And if for reasons of convincing comparison, one compares only the terrestrial green leaves (which compose about 1 to 5% of the total forest biomass) with the aquatic phytoplankton, the turnover time would still be longer in the forest.

Total chlorophyll (Table 6) value is found to be highest in stratified communities such as forests. Moreover, it generally has a higher value on land than in water. Concentration of chlorophyll varies widely among shade-adapted plants and light-adapted plants. Shade-adapted plants generally have higher concentrations, and this property enables them to trap and convert more photons. Consequently, light-conversion-efficiency is higher in shaded systems, but the cumulative photosynthetic yield and assimilation are low.

In the aquatic ecosystems, primary production is mainly concentrated in the upper 30 meters or so. In the clearer waters of the open sea, the primary production

Table 5. Distribution of Primary Production and Its Relation to Biomass

S. No.	Biomass	Net Primary Production
Above ground		
1. Trees	6403.0 (g/m^2)	796.0 (gm^{-2} yr^{-1})
2. Shrubs	158.0 (g/m^2)	61.0 (gm^{-2} yr^{-1})
3. Herbs	2.0 (g/m^2)	2.0 (gm^{-2} yr^{-1})
Below ground		
1. Trees	3325.0 (g/m^2)	260.0 (gm^{-2} yr^{-1})
2. Shrubs	305.0 (g/m^2)	73.0 (gm^{-2} yr^{-1})
3. Herbs	1.0 (g/m^2)	4.0 (gm^{-2} yr^{-1})
Aquatic		
1. Offshore waters	2.0 (KCal/m^3)	40.0 (KCal m^{-3} yr^{-1})
2. Inshore waters	1.0 (KCal/m^3)	11.0 (KCal m^{-3} yr^{-1})

Source: Odum [4].

Table 6. Chlorophyll Values

S. No.	Chlorophyll (g per Square Meter)	Assimilation ratio (g O_2 Produced per Hour/g Chlorophyll
1. Forests, stratified grasslands and croplands (stratified)	0.4-3.0	0.4-4.0
2. Winter, underwater or cave communities; lab cultures under low light intensity (shaded)	0.001-0.5	0.1-1.0
3. Phytoplankton in lakes and oceans (mixing)	0.02-1.0	1.0-10.0
4. Thin vegetation, algae mats on rocks; young crops; lab cultures under intense light (side lighted)	0.01-0.60	8.0-40.0

Source: Odum [4].

zone may extend down to 100 meters or more. In all waters, the peak of photosynthesis tends to occur just under the surface because the circulating phytoplankton are "shade-adapted" and are inhibited by full sunlight. In the forest, where the photosynthetic units (the leaves) are permanently fixed in space, tree-top-leaves are sun-adapted, and understory leaves are shade-adapted. In a given light-adapted system, the chlorophyll in the autotrophic zone self-adjusts to nutrients and other limits. Hence, if the assimilation ratio and the available light are known, gross production can be estimated by extracting pigments and then measuring the chlorophyll concentration.

The primary productivity of an ecological system, community, or any part thereof is defined as the rate at which radiant energy is converted by photosynthetic and chemosynthetic activity of producer organisms to organic substances. It is important to distinguish the following successive steps in the production process:

1. Gross primary productivity: the total rate of photosynthesis, including the organic matter used up on respiration during the measurement period. This is also known as "total photosynthesis" or "total assimilation."
2. Net primary productivity: the rate of storage of organic matter in plant tissues exceeding the respiratory use by the plants during the period of

measurement. This is also called "apparent photosynthesis" or "net assimilation."

3. Net community productivity: the rate of storage of organic matter not used by heterotrophs (i.e., net primary production minus heterotrophic consumption) during the period under consideration.

Finally, the rates of energy storage at consumer levels are referred to as secondary productivities.

3. IMPACT OF GREENHOUSE GASES

Increasing CO_2 concentrations and climatic changes have effects on carbon storage in ecosystems. This, in turn, is likely to affect C/N ratios of the plant material with possible effects on decomposition cycles. Hence, it becomes important that at local levels mechanisms of CO_2 interaction with water, light, nutrients and temperature should be investigated, and the effects integrated in order to quantify the cumulative impact of CO_2 increase on biomass production and community composition. This is especially so in view of the fact that the rapid climatic changes likely to result from increasing concentrations of various greenhouse gases may exceed the rate at which the species composition, production and biomass of terrestrial ecosystems can remain in dynamic equilibrium with the environment [1, 2].

Accordingly, there is a growing need for developing site-specific species-specific (plant-function types: PFT's) models as an aid to understanding the underlying ecosystem processes and also as assessment or predictive tools in quantification of environmental impact of greenhouse gases. While developing such models, one important fact which must be borne in mind is that there is a fundamental difference between the development of models for the terrestrial subsystem and the formulation of basic models for the atmospheric and marine subsystems. In the latter case, the transfer due to air or water motions can be defined using basic hydrodynamical principles, and serve as a basis for biophysical and biochemical model formulation. The terrestrial ecosystem, on the other hand, is geographically stationary to a first approximation.

4. DEVELOPMENT OF PFT'S AND ESTIMATION OF PARAMETER 'G'

PFT's have been developed for six Indian species, viz. Neem, Ashok, Badam, Amaltas, Jamun, and Teak in order to find out models for species-specific height and diameter relationships (Table 7). These PFT's have been incorporated appropriately in the model for volume increment [10, 11]. Subsequently, a computer code (DIAM) has been developed for estimating minimum G values for different species. Parameter 'G' and its estimation play a very important role in the

Table 7. Species Specific Models for Height-Diameter Relationships

1. Neem: Height = $15.357026\,(\text{Diameter})^{0.701368}$
2. Ashok: Height = $48.089703\,(\text{Diameter})^{1.585615}$
3. Badam: Height = $19.770260\,(\text{Diameter})^{0.976626}$
4. Amaltas: Height = $17.4418\,(\text{Diameter})^{0.91841}$
5. Jamun: Height = $12.200018\,(\text{Diameter})^{0.544314}$
6. Teak: Height = $16.424248\,(\text{Diameter})^{0.96384}$

equation for volume increment [10, 11]. Its dependence on plant-specific physiological parameters enhances its utility in understanding the underlying ecosystem processes, and also as an assessment or predictive tool in quantification of environmental imapact due to green house gases. The code is written in 'C' and runs on a Personal Computer. Simulation of the computer model points to the following salient features:

1. Minimum value of G is site-specific in the sense that it is dependent on the maximum height of the species under investigation for a given site. For example, minimum values for G (through simulation runs) were found to be 105.0, 52.0, 63.0, 65.0, 131.0 and 54.0 for Neem, Ashok, Badam, Amaltas, Jamun, and Teak, respectively.
2. Model simulation results for changes in diameter (d), height (h) and h/d ratio with respect to changes in parameter G have been presented in Tables 8 through 13. Values of G have varied in steps of 10, starting with the near-minimum value. These results (in the form of sensitivity analysis) have been presented and plotted in Figures 1 through 3.

5. DISCUSSION

The model presented in this article simulates the dynamics of diameter over a time period of one year, and can be used to study the impact of changes in parameter G on diameter (d), height (h) and h/d ratio. Through simulation studies it was found that the Parameter G is strongly dependent on species-specific-values of maximum height and respiration coefficient. Thus, the model is extremely useful in species-specific biomass estimation. Apart from the advantage of using appropriately developed species-specific models based on data collected through field survey, the present software offers a very rapid means of estimating species-specific values of the parameter 'G'.

Biomass, net primary production (NPP), and leaf area are key features of autotrophic ecosystems because they define the standing crop and flux of carbon and nutrients, and set upper limits on water use through transpiration, and on

Table 8. Species: Neem

S. No.	Value of G	Diameter (m)		Height (m)		Height/Diameter	
		After One Month	After Twelve months	After One Month	After Twelve Months	After One Month	After Twelve Months
1.	105.00	0.037	0.003	1.519	0.281	41.123	84.334
2.	115.00	0.039	0.037	1.598	1.507	40.245	41.258
3.	125.00	0.042	0.067	1.669	2.306	39.508	34.429
4.	135.00	0.044	0.095	1.733	2.947	38.876	31.010
5.	145.00	0.046	0.121	1.792	3.494	38.328	28.844

Table 9. Species: Ashok

S. No.	Value of G	Diameter (m)		Height (m)		Height/Diameter	
		After One Month	After Twelve months	After One Month	After Twelve Months	After One Month	After Twelve Months
1.	55	0.039	0.024	0.695	0.435	17.971	17.958
2.	65	0.043	0.085	0.786	1.533	17.975	17.993
3.	75	0.048	0.137	0.865	2.475	17.977	18.006
4.	85	0.052	0.183	0.933	3.299	17.979	18.014
5.	95	0.055	0.223	0.994	4.031	17.981	18.019

Table 10. Species: Badam

S. No.	Value of G	Diameter (m)		Height (m)		Height/Diameter	
		After One Month	After Twelve months	After One Month	After Twelve Months	After One Month	After Twelve Months
1.	65	0.037	0.015	0.809	0.334	21.341	21.797
2.	75	0.042	0.067	0.900	1.423	21.287	21.055
3.	85	0.046	0.113	0.979	2.356	21.244	20.802
4.	95	0.049	0.153	1.049	3.178	21.209	20.654
5.	105	0.052	0.190	1.112	3.913	21.179	20.551

Table 11. Species: Amaltas

S. No.	Value of G	Diameter (m)		Height (m)		Height/Diameter	
		After One Month	After Twelve months	After One Month	After Twelve Months	After One Month	After Twelve Months
1.	65	0.037	0.006	0.848	0.166	22.815	26.363
2.	75	0.041	0.058	0.939	1.287	22.610	21.985
3.	85	0.045	0.104	1.018	2.186	22.449	20.975
4.	95	0.048	0.144	1.087	2.957	22.317	20.419
5.	105	0.051	0.181	1.149	3.636	22.207	20.048

Table 12. Species: Jamun

S. No.	Value of G	Diameter (m)		Height (m)		Height/Diameter	
		After One Month	After Twelve months	After One Month	After Twelve Months	After One Month	After Twelve Months
1.	135	0.037	0.014	2.054	1.229	54.208	83.297
2.	145	0.040	0.041	2.117	2.139	52.848	52.388
3.	155	0.042	0.065	2.175	2.759	51.672	42.337
4.	165	0.044	0.088	2.228	3.249	50.642	36.925
5.	175	0.045	0.109	2.277	3.659	49.730	33.428

Table 13. Species: Teak

S. No.	Value of G	Diameter (m)		Height (m)		Height/Diameter	
		After One Month	After Twelve months	After One Month	After Twelve Months	After One Month	After Twelve Months
1.	55	0.038	0.016	0.702	0.307	18.485	19.066
2.	65	0.043	0.077	0.793	1.389	18.402	18.018
3.	75	0.047	0.129	0.870	2.287	18.338	17.684
4.	85	0.051	0.175	0.937	3.061	18.286	17.492
5.	95	0.054	0.215	0.996	3.743	18.244	17.361

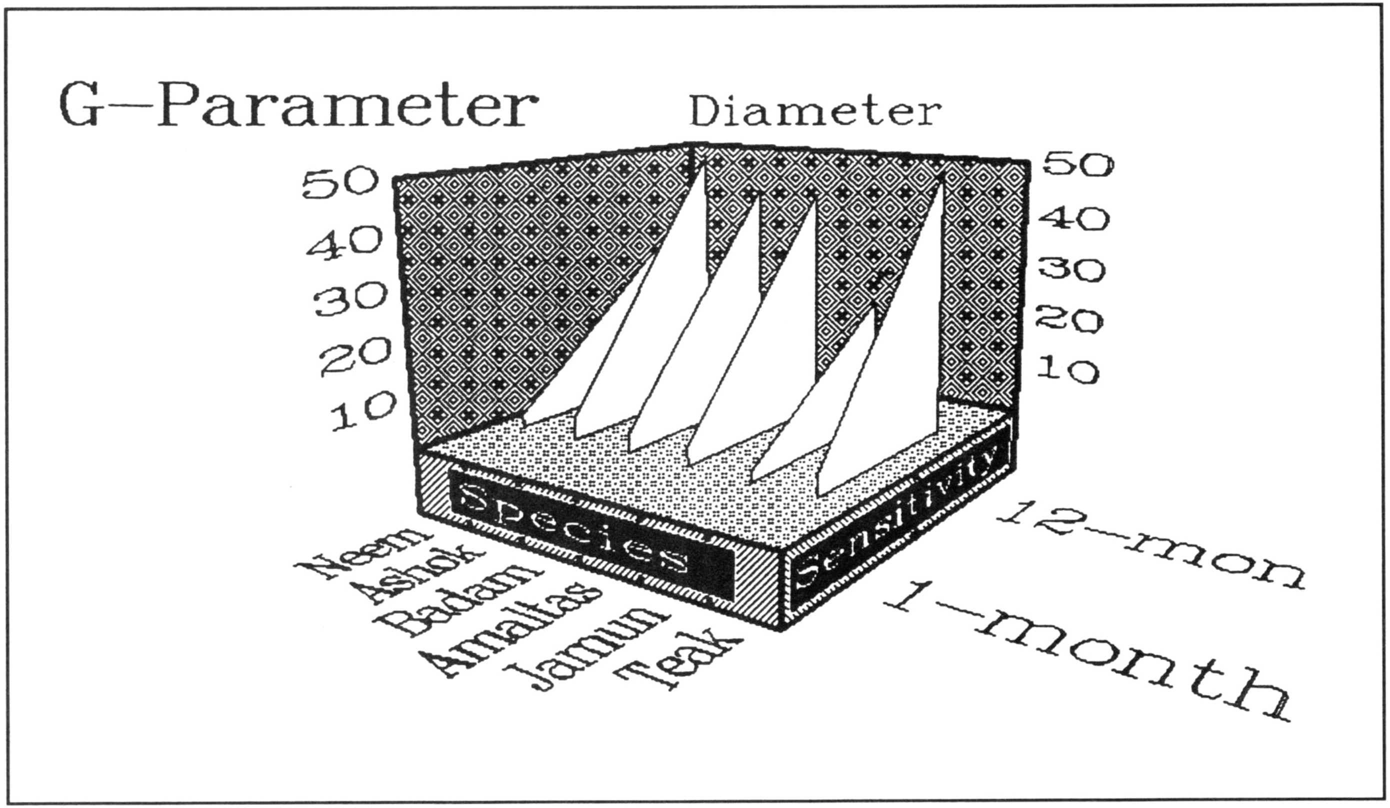
G—Parameter
Diameter
50
40
30
20
10
50
40
30
20
10
Species
Sensitivity
Neem
Ashok
Badam
Amaltas
Jamun
Teak
12—mon
1—month

Figure 1.

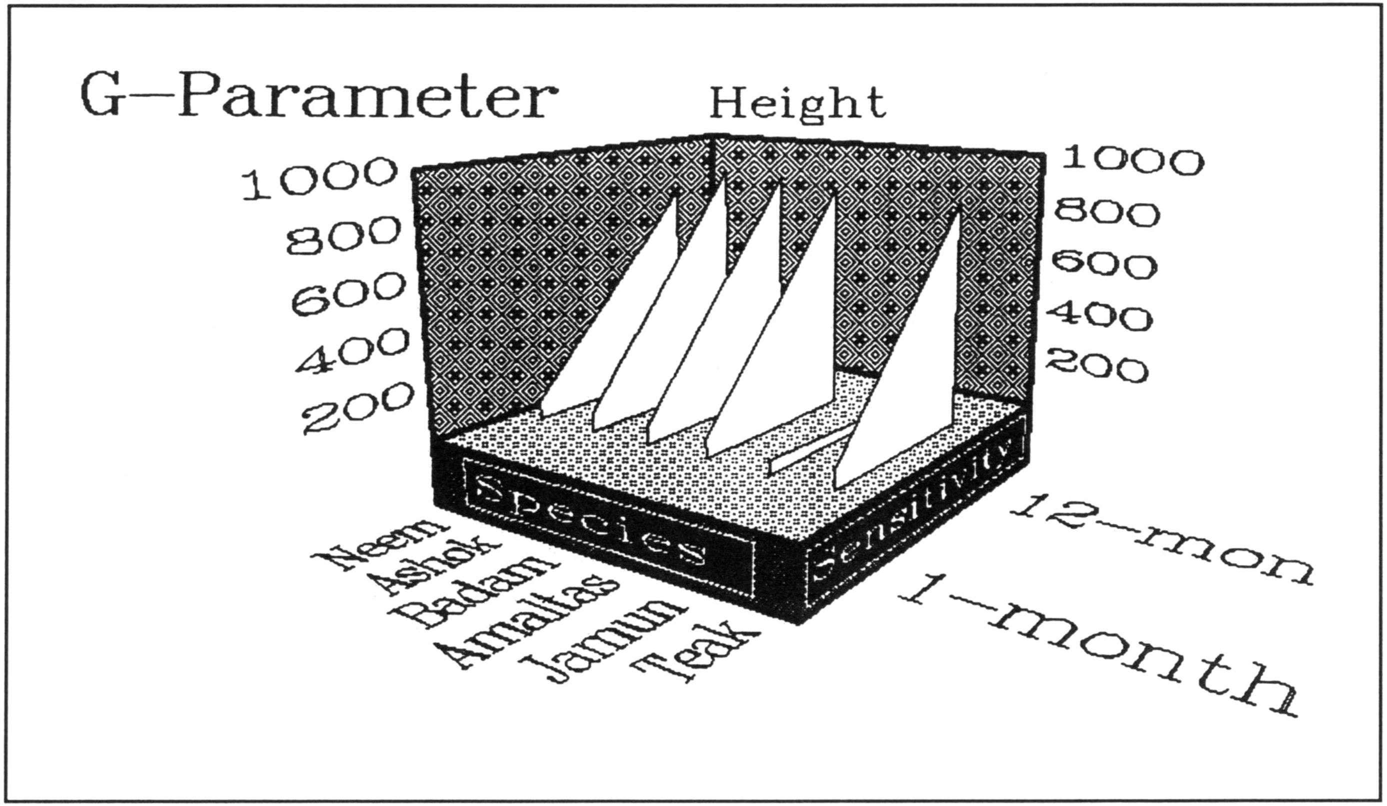
G—Parameter
Height
1000
800
600
400
200
1000
800
600
400
200
Species
Sensitivity
Neem
Ashok
Badam
Amaltas
Jamun
Teak
12—mon
1—month

Figure 2.

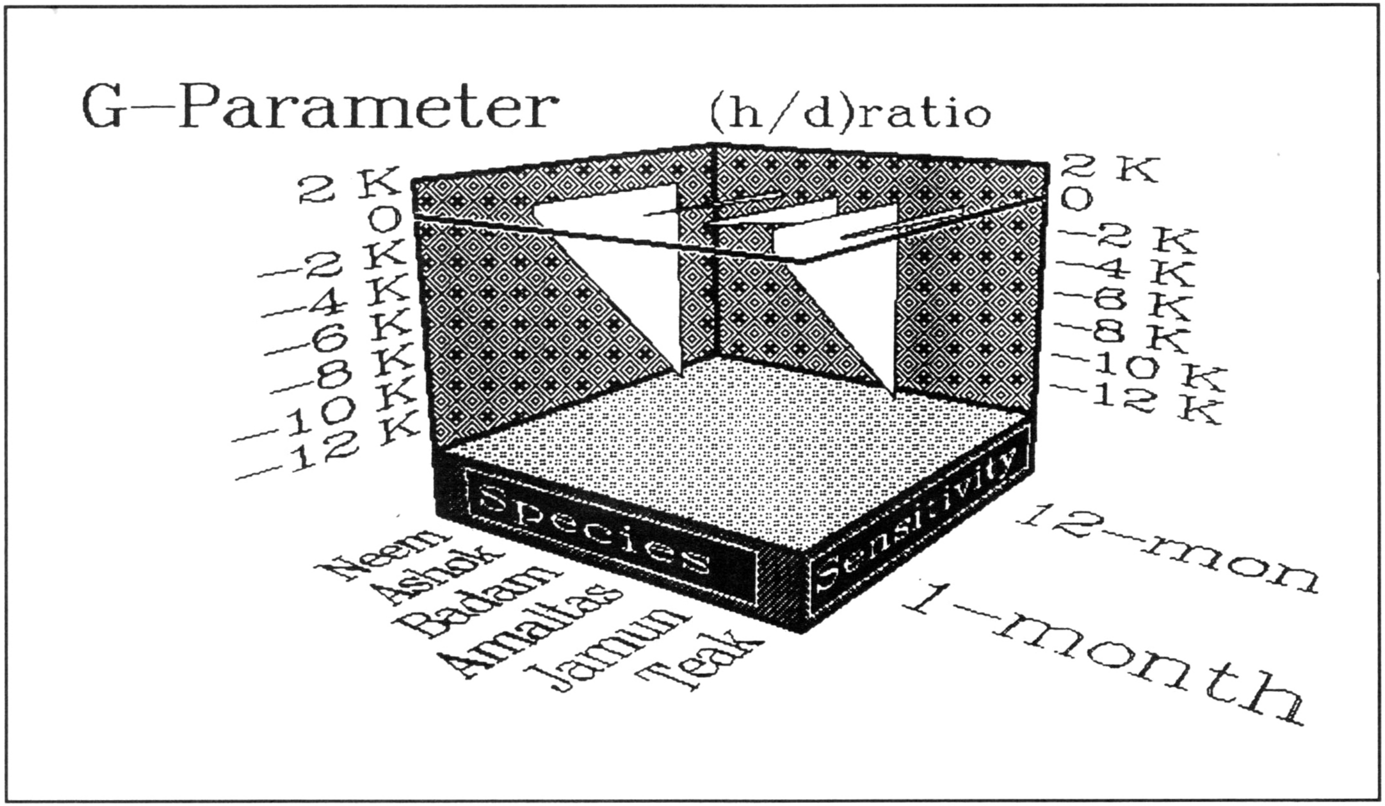
G—Parameter
(h/d)ratio
2 K
0
—2 K
—4 K
—6 K
—8 K
—10 K
—12 K
2 K
0
—2 K
—4 K
—6 K
—8 K
—10 K
—12 K
Species
Sensitivity
Neem
Ashok
Badam
Amaltas
Jamun
Teak
12—mon
1—month

Figure 3.

carbon fixation through photosynthesis [12]. Moreover, relationships between structural features, such as biomass or leaf area, and functional features such as NPP are immensely important. At the same time, direct estimates of NPP or structure for even one stand are very costly and time consuming at regional levels. Hence, estimation should be done through indirect methods [10, 12-16]. The present modeling exercise provides one such useful method.

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