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FINAL REPORT FOR

NASA GRANT NO. NAG 5-516

"Comparison of Simulation Modeling and Satellite Techniques for Monitoring Ecological Processes"

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The original focus of this research involved very basic questions, such as:

- What does the AVHRR "greenness index" (Normalized Difference Vegetation Index, NDVI) actually represent?
- How do annual and monthly NDVI values compare with measured and modeled biosphere phenomena such as primary productivity and standing biomass?
- What sort of fieldwork is needed? What other data?
- How can satellite data and modeling approaches be made mutually compatible and complementary?

Some more advanced questions were also posed, for example:

- Can above-ground, satellite-sensed values be combined with modeling results to estimate non-green and/or below-ground biomass components?
- How can satellite data and modeling techniques be combined for better, perhaps self-correcting, more real-world estimates of biosphere patterns (including changes in vegetation, carbon-balance components, etc.)?

Work was hampered by two unexpected problems at the University of Georgia:

1. an increase in teaching loads during the first two years of the grant (1985-1987), to seven courses per year; and
2. a two-year collapse (on one month notice) in the ability to store large data-sets on the UGa mainframe computer system (autumn 1985 to summer 1987).

These problems resulted in funding for only two years instead of three, with 1986 funding carried over through 1987. Nevertheless, there were some accomplishments, as described in the following sections.

Progress during 1985

First-year efforts (before the storage collapse) produced the following results:

- a much improved world climatic data-base for modeling and predictive mapping (more sites, better physiographic representation, etc.); from this a larger, improved simulation of terrestrial biospheric carbon balance (natural vegetation) was produced, for comparison with satellite data (Box 1986). This data-base comprises 1600 sites (cf Box 1981).
- improvements in the individual process models (primary productivity, decomposition, etc.) and the overall carbon-balance model (cf previous item; see also Box 1978 and Box, in press).
- much improved interface software for mapping the simulation results, conversion to NASA formats for color display at NASA-Goddard, and for mapping at NASA-Goddard.

In addition, satellite data were combined with the global climatic and simulation data to provide a first global data-base. Statistical analysis of this data-base was begun, involving relationships between NDVI greenness values and corresponding biomass, productivity, bioclimatic, and other carbon balance data. Production of an initial series of monthly predictive maps was precluded by the loss of computer storage space at Georgia.

Progress during 1986

As a result of the computing problems, mapping was shifted to NASA-Goddard in 1986 and the initial approach involving pattern comparisons was modified to a more statistical approach, involving geostatistical analysis within a framework of bioclimatic-ecological regionalization. A major accomplishment in 1986 was the expansion and improvement (re-evaluation of data, standardization, etc.) of a global data-base of measurements of biomass and primary production, to complement the simulation data. Once the unuseable NDVI sites were removed (due to mixed pixels, coastal/island situations, etc.), these data-bases involved about 100 valid measurement sites (with above-ground and below-ground biomass and production) and 1021 simulation sites. Initial statistical results and scattergrams suggested strongest NDVI relationships to net and gross primary productivity and relatively little relationship to standing biomass amounts (due to the lack of a temporal component in biomass comparable to annual/monthly sums of production). The initial statistical results suggested that the accuracy of models which might be developed for primary productivity, based on the NDVI, would be about as accurate as the climate-based earlier models (r = about 0.80 for global models). Since climate predicts the potential functions of a "natural" biosphere and satellite data indicate functions of the vegetation cover actually there, there seemed to be good potential for combining these approaches for improved estimation of biosphere phenomena.

Progress during 1987

The main accomplishments during 1987 included the following:

- production of a new master tape with all environmental and satellite data (annual and monthly) and model results for the 1600 sites, for use in mapping and pattern comparison at NASA-Goddard. This represented the newest version of the simulation model, as published (Box, in press).
- development of a complete mapping system as Goddard: base maps, projection software, color and contouring schemes for the individual phenomena, data-bases in Goddard formats, improvements in spatial interpolations, etc. This was used for initial color maps comparing annual and monthly patterns of the NDVI, actual evapotranspiration, net primary productivity, gross primary productivity, and net ecosystem production (i.e. net CO_2 flux between vegetation and atmosphere, cf. Tucker et al. 1986, Fung et al. 1987).

- collection of still more biosphere measurements for eventual improvement of the biological models.
- development of some initial monthly models for primary productivity, based on satellite data.

In addition, effects of different vegetation structures on model results were studied (Box 1987), and several presentations of results were made (see list of presentations, below). An initial summarizing manuscript was drafted and submitted in early 1988 (Box et al., in review). Actual results and implications are discussed below.

Results

One difference between the biosphere carbon-balance model used here (Gillete and Box 1986; Box, in press) and other biosphere models involved the question of significant CO_2 flux seasonality in the tropics (e.g. Houghton 1987b). The simulated carbon balance for a tropical wet-dry site is shown in Figure 1 and appears to be typical of a large area of so-called tropical summer-rain climates (or Köppen's Aw climates). This simulation result, with gross production (photosynthesis) essentially shutting down during the long dry season (deciduous vegetation), with respiration and decomposition continuing (at least somewhat), clearly indicates a strong seasonal reversal in the net CO_2 flux which has not been predicted by others' models. Such a strong seasonal change in productivity was clearly evident on the African savanna imagery of Tucker et al. (1985).

Another question in carbon-balance modeling involved the somewhat unexpected model result showing a northward moving wave of net CO_2 release in springtime in the northern temperate zone, preceding the establishment of strong growing-season CO_2 sinks in these areas (see Figure 2). It was feared that this might be a modeling artifact, since the balance of separately simulated processes could be rather sensitive mathematically. Houghton (1987a, 1987b), however, has recently published results from just such a situation (Brookhaven forest, on Long Island) which show an even larger "spring puff" effect of CO_2 release than in the biosphere model. This fortuitous publication of data strengthened confidence in the model by showing that it is producing reasonable results even in a situation which predictably might be one of the most sensitive.

As for the NDVI, initial correlation results suggested good relationships to primary productivity but also to actual evapotranspiration (AET). Since AET is more "basic" than primary production (often being used as a predictor of production), AET was used as the basis for an initial global trend relationship with which to evaluate deviations caused by topography, land use, vegetation effects, etc. (see Figure 3). In looking at the sites in Figure 3, however, one can imagine easily that there may be at least two distinct populations of points in the global data, one in the tropics and one outside the tropics. This result was suggested also by the deviations in different regions (see Box et al., in review). This problem cannot be resolved at this time and requires further study.

Both the measurement and simulation data-bases were equipped (during 1987) with site codes describing the local topography, altitudinal belt, and land use as well as vegetation structure, type, and seasonality (see Tables 1 and 2). These codes were used to study deviations from the global trend and also appear on scattergrams, as a means of regionalizing the results. The final relationship between the current GVI-product NDVI (Tarpley et al. 1984), as composited for this work by Brent Holben (NASA Goddard), and site measurements of net primary production (both on an annual basis) is shown in Figure 4, with vegetation symbolism derived from the site codes.

One can see that there is a relatively good fit but with some scatter, quite comparable to that on earlier scattergrams of net production versus AET or other climatic variables (e.g. Lieth and Box 1972, Lieth 1975). The vegetation symbolism, though, suggests one problem, namely that evergreen needle-leaved forests and woodlands tend to show consistently higher greenness levels than might be expected from the productivity values. This predictable result (Box 1984), however, seems to be the only case of consistent bias based on vegetation structure in the current global data-base. Simulated net primary productivity is plotted against NDVI (annual levels) in Figure 5, which shows a similar relationship between the two variables (but for 947 sites instead of 95). Annual gross primary productivity, as estimated by a climate-based model (Lieth and Box 1977), showed a similar saturation-like relationship to annual NDVI.

Correlation coefficients of the various biosphere variables versus annually integrated NDVI are summarized in Table 3. As one can see, there is little promising relationship between either biomass amounts or shoot-root ratios on the one hand and annual NDVI on the other. (Monthly NDVI values may show better relationships, but more biological data are needed in order to test this.) A scattergram of total standing biomass (above and below ground) versus annual NDVI, with vegetation symbolism, is shown in Figure 6.

Correlations between monthly values of AET, net productivity, and net CO_2 flux, on the one hand, versus monthly NDVI, are shown in Table 4. AET and net productivity maintain some relationship to NDVI throughout the year, but net CO_2 flux does not seem to be related to the NDVI in any consistent geographic way. Even productive vegetation (e.g. late summer in a dry or drying situation) can be green but be a net CO_2 source (i.e. have respiration plus decomposition exceeding gross production). This was illustrated by a color plate of North America (AET, NPP, CO_2 flux, and NDVI for September) in Box et al. (in review) but cannot be reproduced here.

Conclusions

1. NDVI values based on the current GVI product are not reliable in areas of complex terrain (mixed pixels, such as high mountains or coastal areas), at the low end of the NDVI scale (extreme deserts or winter snow covers), or in irrigated areas in dry climates (artificial or natural, e.g. river valleys). Current NDVI data seem to be reliable elsewhere, at least for annually integrated totals. Use in irrigated areas may become possible but requires separate calibration with the appropriate data.
2. Relative to the general global pattern (represented by a global NDVI-AET "trend" curve), montane (not alpine) and temperate mesic wooded sites tend to show higher annual NDVI values than comparable lowland and tropical sites; non-wooded sites (except tropical savannas) generally show elevated NDVI values relative to the global trend.
3. The NDVI seems most closely related to primary production (or productivity), both net and gross, with a predictive accuracy for annual NPP comparable to that of climate-based NPP models. The NDVI-productivity relationship appears to be consistent worldwide.
4. The NDVI is also closely related to actual evapotranspiration (AET), corroborating earlier AET-based models of primary productivity. (Annual NDVI seems statistically closer to AET-based estimates of annual NPP, though, than to annual AET itself.)
5. There seems to be little reliable relationship between annually integrated NDVI and biomass structure across different biomes.

6. Tall evergreen conifer forests do appear to have anomalously high NDVI values in many cases. No other structure-based bias was consistently evident. The apparent tropical/extra-tropical bias cannot be explained at this time.

7. The high-latitude "terminator effect," due to low sun angles in winter, does not seem to invalidate boreal and polar values of annually integrated NDVI, which correspond to annual NPP and AET as well as do NDVI totals from other biomes. Monthly NDVI values in high latitudes (except well within the summer growing season) are less reliable, including a one-month springtime disappearance at some sites which seems to be unrelated to the terminator effect and which currently precludes NDVI application to study springtime phenology in high latitudes.

8. Monthly NDVI, AET, and NPP do not appear to maintain constant proportional relationships to each other from month to month over a year, suggesting that monthly NDVI may improve current bioclimatic methods for estimating seasonal production variations.

9. There seems to be little reliable relationship across different biomes between NDVI and net ecosystem production (CO_2 flux), either annually or monthly, due to seasonality effects and the sensitivity of the net CO_2 balance (equation 4).

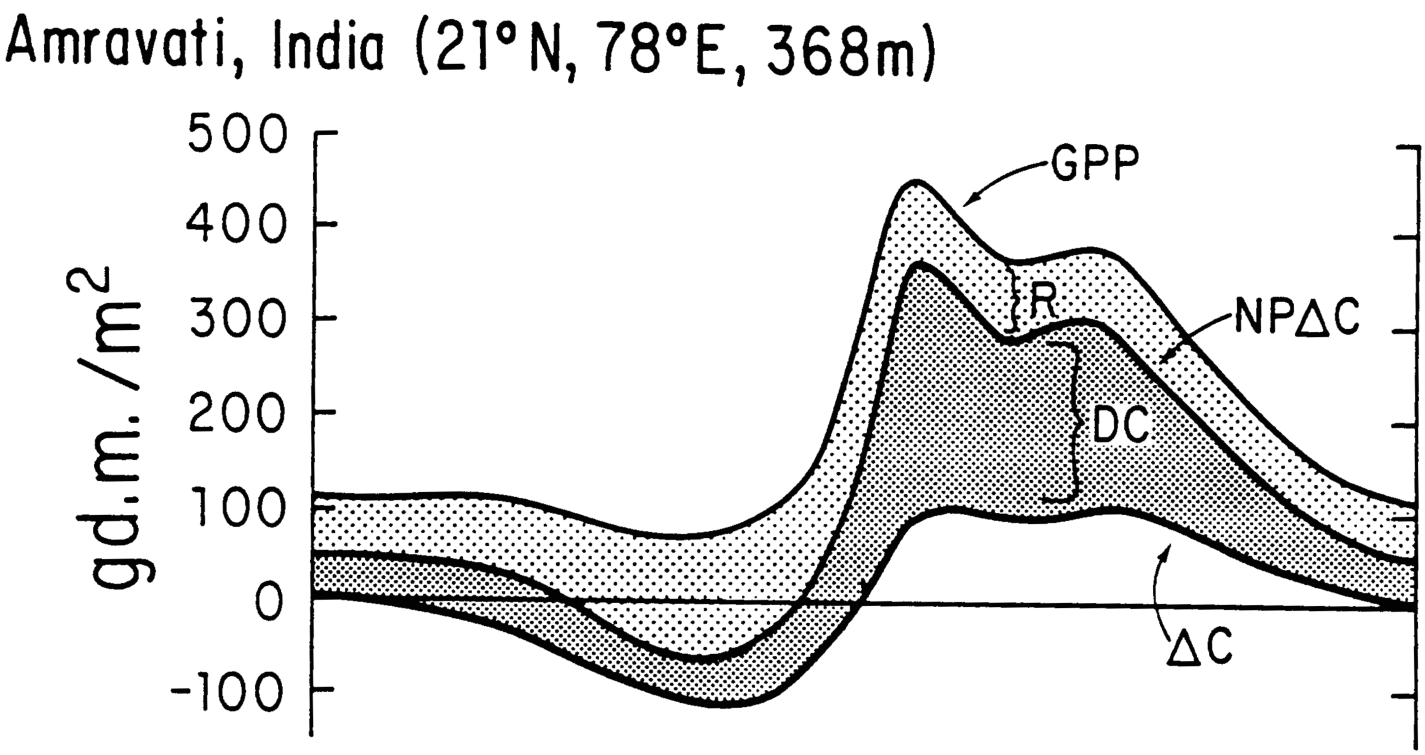


Figure 1. Simulated Biosphere Carbon Balance for a Highly Seasonal Tropical Site.

GPP = gross primary production (photosynthesis)

R = respiration (autotrophic)

NPΔC = net primary carbon balance (= GPP - R), also called net primary "production" when positive

DC = decomposition of dead biomass

ΔC = overall net carbon balance (= net ecosystem production)

The simulation is by the model MONTHLYC (Box, in press; see also Gillette and Box 1986), using only mean monthly climatic data as input. The individual processes are simulated by globally developed, partially verified models or combinations thereof.

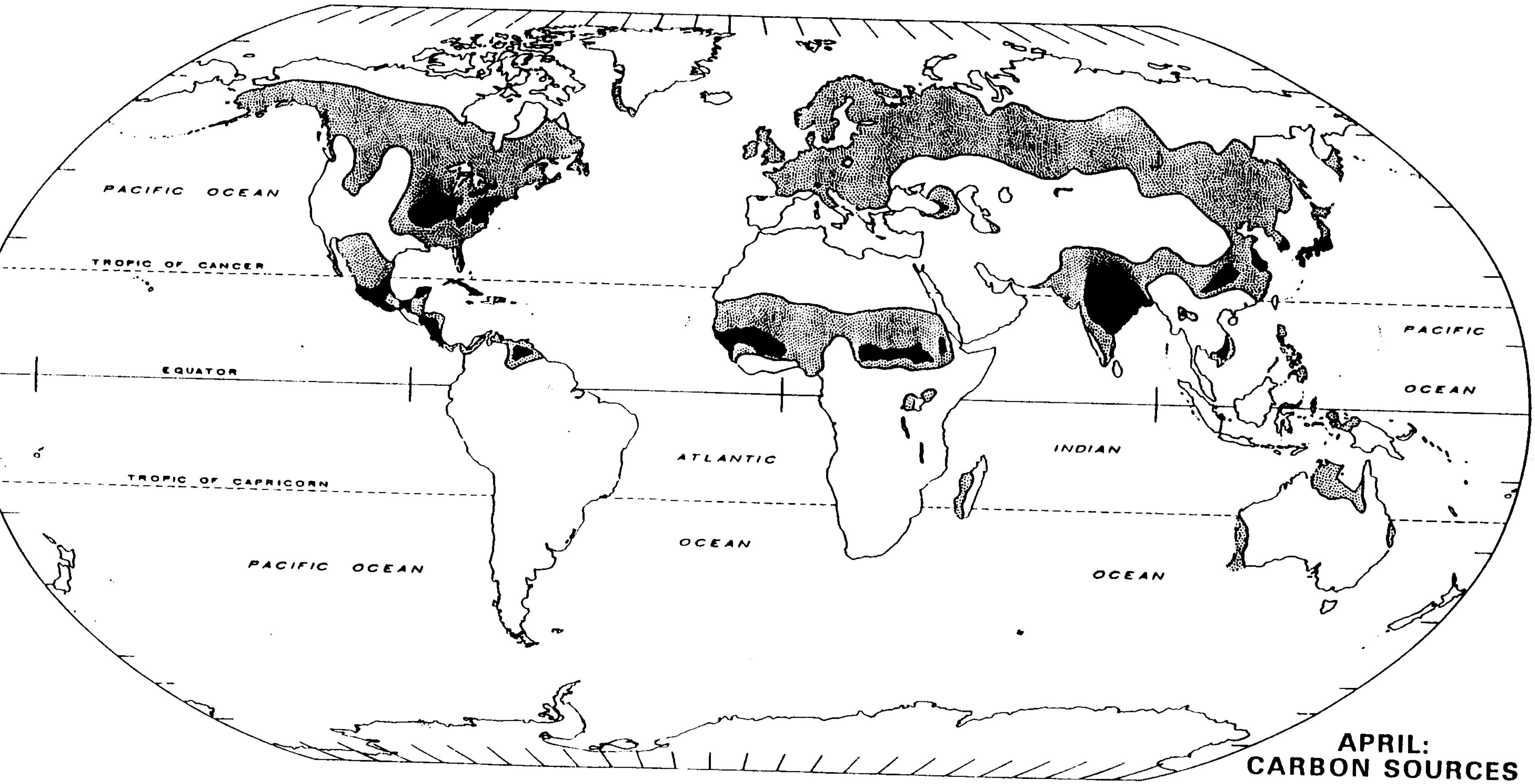
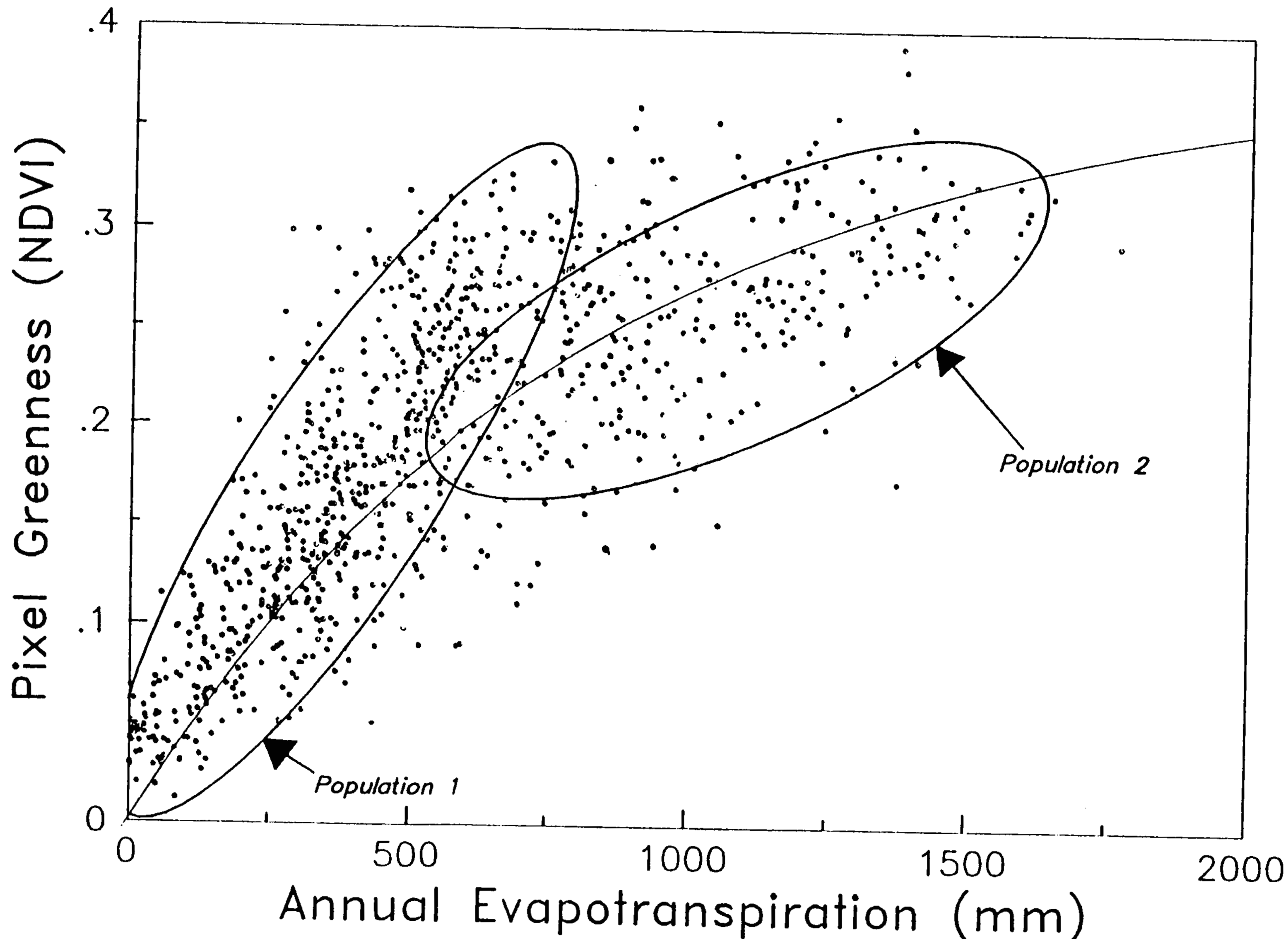


Figure 2. Simulated Regions of Net CO_2 Release by the Biosphere during April.

Solid black represents carbon sources of 100 g dry matter (183 g CO_2) per m^2 or stronger, while dotted regions represent sources of 20 g d.m. (36.6 g CO_2)/m^2. The unexpected burst of CO_2 release preceding springtime CO_2 uptake by vegetation was recently corroborated by Houghton (1987a).

Figure 3. Global Trend:

Integrated NDVI vs Annual AET



This initial plot of NDVI vs AET, the "best" bioclimatic variable, suggests significant differences between the spectral properties of temperate vs tropical vegetation.

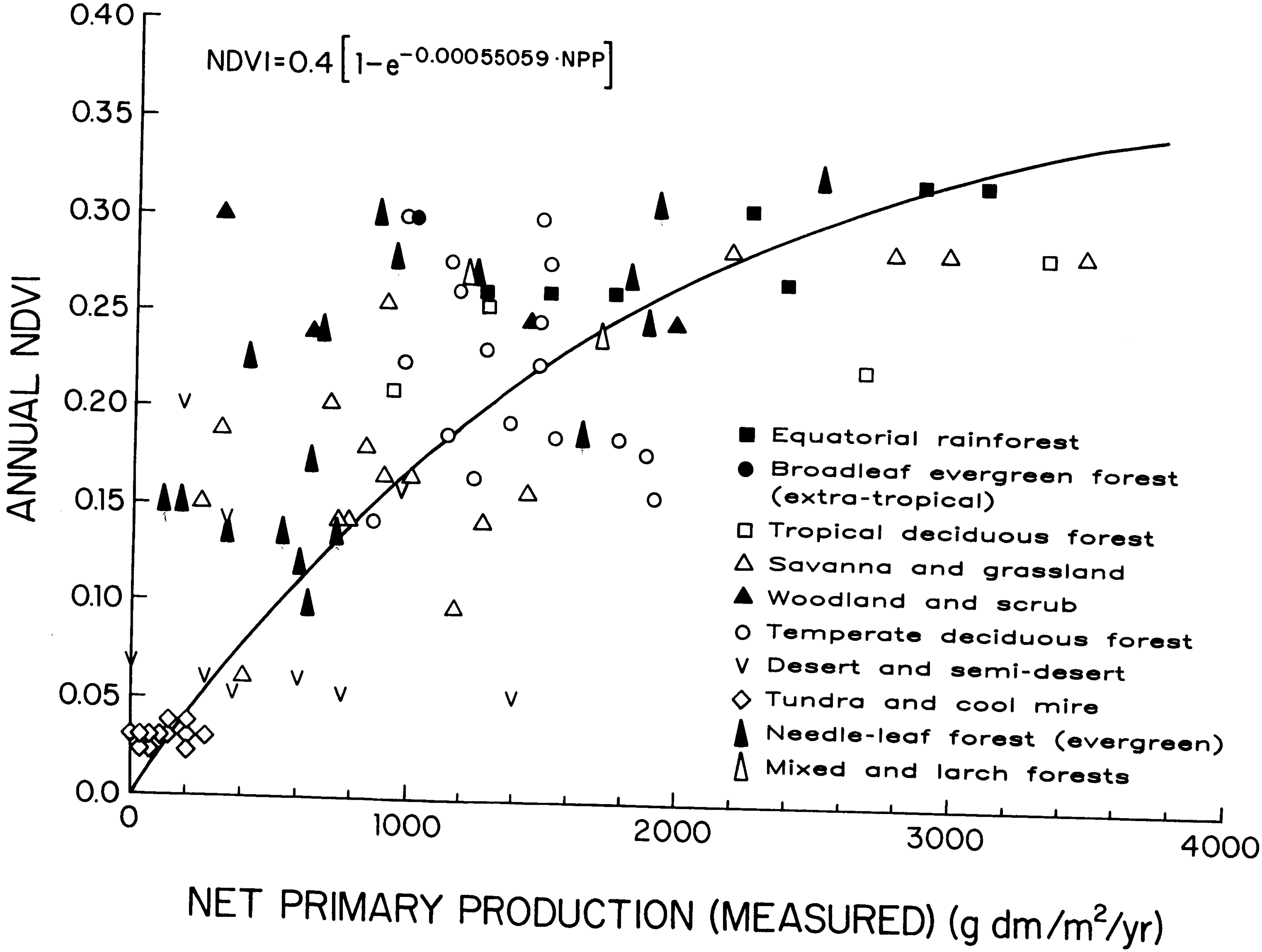
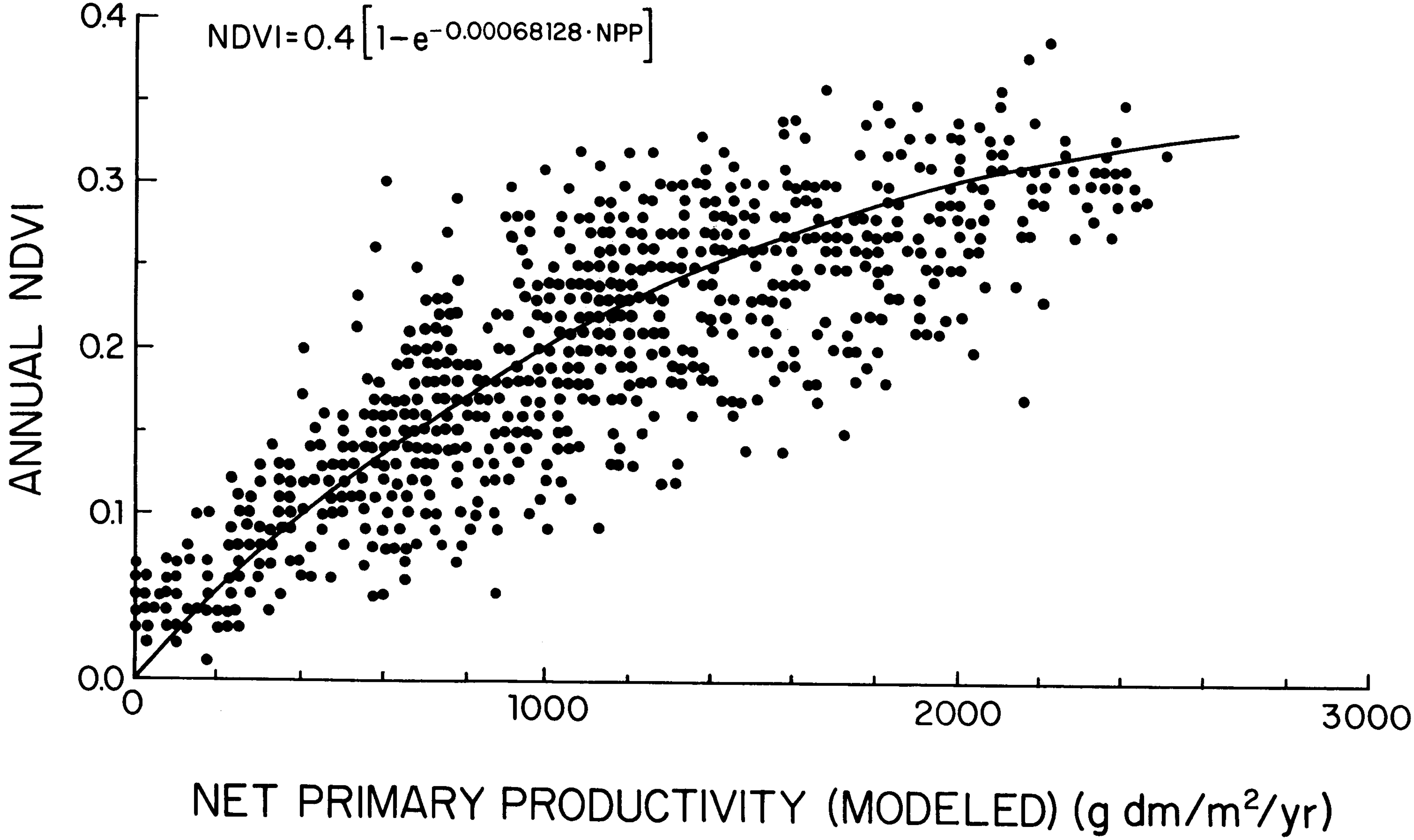

NDVI=0.4 [1−e^{−0.00055059·NPP}]
ANNUAL NDVI
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.0
0
1000
2000
3000
4000
NET PRIMARY PRODUCTION (MEASURED) (g dm/m²/yr)
Equatorial rainforest
Broadleaf evergreen forest (extra-tropical)
Tropical deciduous forest
Savanna and grassland
Woodland and scrub
Temperate deciduous forest
Desert and semi-desert
Tundra and cool mire
Needle-leaf forest (evergreen)
Mixed and larch forests

Figure 4.



NDVI=0.4[1−e^−0.00068128·NPP]
0.4
0.3
0.2
0.1
0.0
ANNUAL NDVI
0
1000
2000
3000
NET PRIMARY PRODUCTIVITY (MODELED) (g dm/m²/yr)

Figure 5.

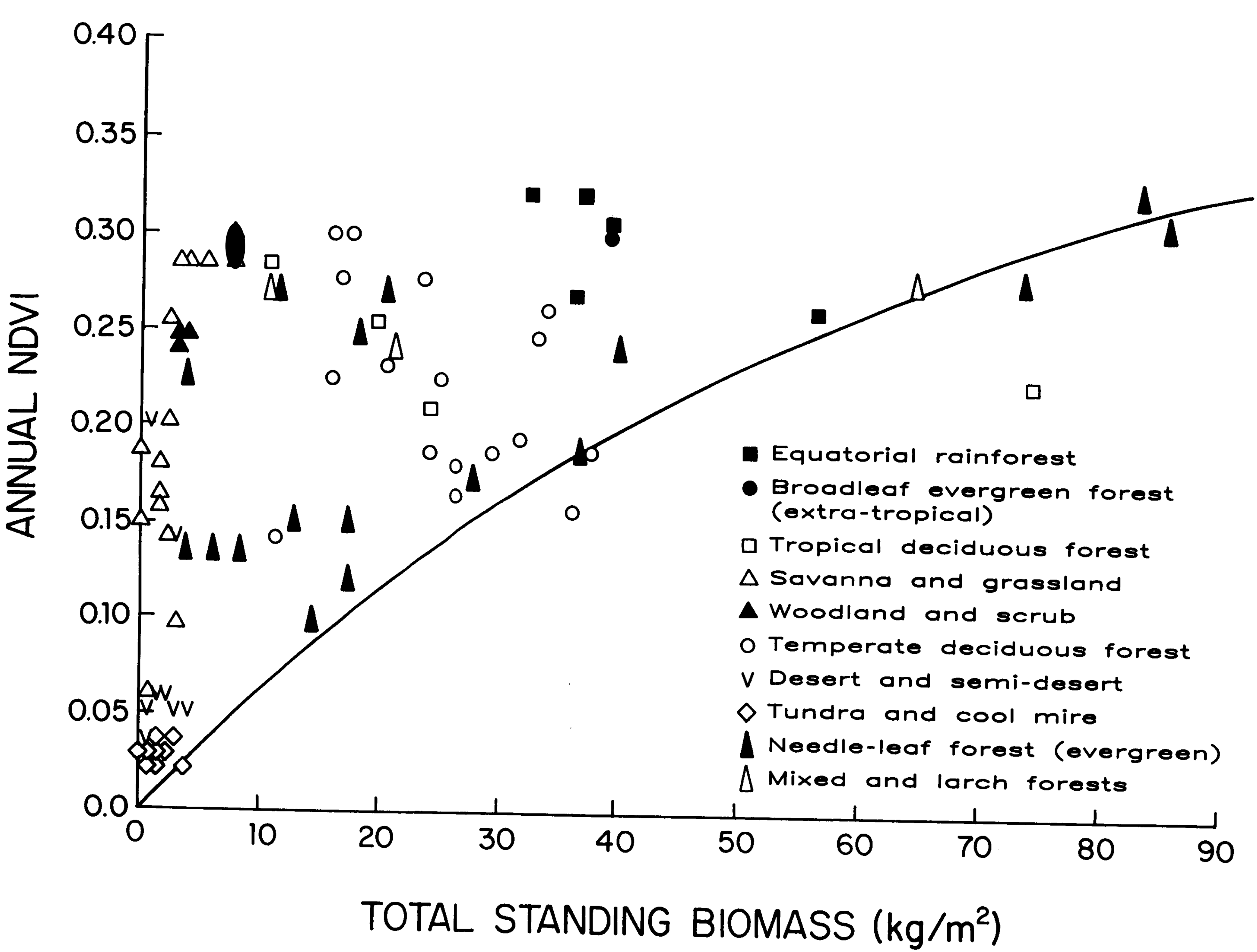

0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.0
ANNUAL NDVI
0
10
20
30
40
50
60
70
80
90
TOTAL STANDING BIOMASS (kg/m2)
Equatorial rainforest
Broadleaf evergreen forest (extra-tropical)
Tropical deciduous forest
Savanna and grassland
Woodland and scrub
Temperate deciduous forest
Desert and semi-desert
Tundra and cool mire
Needle-leaf forest (evergreen)
Mixed and larch forests
Figure 6.

Table 1. Vegetation Cover Types and Codes for the Measurement and Simulation Global Data-Bases.

Vegetation Type	Seasonality Type	Landscape Type	Vegetation Formation Types	Examples
Tropical BL-EG trees (1)	E	F	Tropical rainforest	Amazon Basin, E Indies
Tropical seasonal trees (2)	D,S	F,W	Tropical deciduous/semi-EG forest or woodland	India, miombo woodland
BL-EG trees (extra-trop.) (E)	E	F	Warm-temperate/subtropical "laurel" forest	S Japan, SE China
Semi-EG BL trees (S)	S	F,W	Humid subtropical forest, dry equatorial woodland	SE China, eastern Chaco; E Africa
Summergreen trees (6)	D	F,W	Temperate deciduous forest or woodland	E USA, central Europe; oak woods of NE China, USA
Needle-leaved EG trees (N)	E	F,W	Boreal forest/woodland	Canada, Siberia
Mixed (decid.+needle) trees (M)	S	F	Subboreal and warm-temperate mixed forests	New England, Baltic USSR; SE USA (oak-pine)
Larch trees (L)	D	F,W	Larch forest/open woodland	Eastern Siberia
Mediterranean trees/scrub (4)	E,S,D	F,W,X	Mediterr. forest, chaparral, or dwarf-shrubs (garrigue)	Maquis, matorral, phrygana, fynbos, kwongan, etc.
Scrub (general) (X)	E,S,D	X	Mixed scrub, non-mediterranean shrublands, etc.	Thorn-scrub, shrub-woodlands, juniper scrub, etc.
Savanna (tropical) (V)	E,S,D	V	Tropical savannas	E Africa, sub-humid Australia
Grassland (G)	E,S,D	G	Temperate or montane grass-lands and steppes	US Great Plains, Ukraine, S African veld, pampa
Treeline krummholz (N,M,6)	E,S,D	K	Subpolar and subalpine krummholz	Subpolar birch scrub; subalpine conifer krummholz
Tundra (subpolar) (9)	S,D	T	Tundra: typical (snow) and maritime (little snow)	N Canada and Siberia; Iceland and subantarctic islands
Tropical alpine (P)	E,S,D	X,G,S	Paramo, wet and dry puna	Andes, E Africa
Temperate arid (7)	S,D	X,S,D	Temperate desert/semi-desert	US Great Basin, Middle Asia
Extreme desert (D)	X,-	D	Subtropical/other true deserts	Sahara, Atacama, Takla Makan
Polar desert (9)	D	D	Polar cold-desert	High Arctic (snow-free summer)
Ice cap (no vegetation)	-	I	Ice cap (no vegetation)	Antarctica, Greenland

(Table 1

Abbreviations

Vegetation:

BL = broad-leaved   EG = evergreen   decid. = deciduous

Seasonality:

E = evergreen   S = semi-evergreen   D = deciduous   X = ephemeral

Landscape types (vegetation structure/cover):

D = desert	F = forest	G = grassland	I = ice cap
K = krummholz	S = semi-desert	T = tundra	V = savanna
W = woodland	X = scrub		

Table 2. Data Ranges.

Biome	Measurement Sites (valid, n=95) No. of Sites	Biomass (kg/m^2)	NPP ($g/m^2/yr$)	LAI*	Global Simulation (valid pixels, n=947) No. of Sites	AET (mm/yr)	Median NPP ($g/m^2/yr$)	Median GPP ($g/m^2/yr$)	Annual NDVI (x1000)
ropical Forests									
Rainforest (evergreen)	7	32-56	1273-3101	9-12	33	850-1650	2100	6000	392-272
Deciduous	2	24-74	930-2665	---	50	600-1475	1700	4400	340-173
Semi-evergreen	1	20	1260	4	43	700-1500	1900	4600	361-196
emperate Forests									
Evergreen broad-leaved	1	39	1000	4	34	500-1400	1500	2500	328-151
Deciduous broad-leaved	17	11-37	864-1900	3-7	65	500-900	1400	2600	301-166
Semi-evergreen (broad)	0	---	---	---	10	500-1200	1600	3200	268-152
Evergreen conifer	9	11-85	650-2487	5-12	22	300-1100	1200	2400	300-115
Mixed (broad + conifer)	2	10-65	1196-1484	4-9	90	400-1250	1350	2800	324-143
oreal Forests/Woodlands									
Evergreen conifer	8	3-28	92-719	2-10	100	175-500	700	1150	217-81
Deciduous (larch)	1	21	1713	7	25	80-450	450	700	200-73
oodlands (non-boreal)									
Tropical deciduous	0	---	---	---	28	680-1160	1600	3200	327-111
Mixed tropical	1	11	3340	1	27	470-1350	1500	3100	320-216
Sclerophyll	1	3	403	2	23	425-960	1150	2100	316-141
Mixed extra-tropical	0	---	---	---	54	200-910	1000	1800	253-103
Conifer (evergreen)	0	---	---	---	6	360-710	900	1500	295-147
crub									
Tropical-subtropical	0	---	---	---	19	300-785	1000	1600	318-83
Mediterranean-type	3	3-8	302-1981	2-3	18	275-560	800	1500	299-58
Temperate arid	0	---	---	---	19	140-410	550	900	233-68
Subpolar krummholz	2	3-4	71-198	---	1	250	550	800	157
rasslands									
Tropical savanna	5	0.6-7.1	410-3455	(0.1-0.4)	47	400-975	1200	2300	304-52
Temperate grassland	9	0.3-3.3	296-1425	---	85	165-800	900	1500	264-77
undra									
Typical tundra	12	0.2-2	7-281	(0.1)	20	50-275	300	450	101-27
Maritime tundra	0	---	---	---	3	285-425	450	800	136-65
emi-Desert									
Subtropical	1	---	950	---	80	25-385	400	550	201-13
Temperate	8	0.8-3.4	125-396	---	21	25-200	250	350	108-19
esert (extremely arid)	1	0.004	4	---	17	0-20	10	15	69-21
ecap (permanent)	0	---	---	---	7	0-2	0	0	31-29

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Table 3. Correlations between Annually Integrated NDVI and Biosphere Variables.

	Field Measurements		Global Simulation	
	All Sites (n=113)	Valid Pixels (n=95)	All Sites (n=1021)	Valid Pixels (n=947)
NPP (annual total)	0.679	0.713	0.805	0.835
GPP (annual total)	---	---	0.757	0.780
Respiration (annual total)	---	---	0.707	0.725
NPP_a (above-ground annual NPP)	0.655	0.691	---	---
NPP_b (below-ground annual NPP)	0.377	0.350	---	---
Biomass (total standing)	0.495	0.550	---	---
B_a (above-ground biomass)	0.498	0.545	---	---
B_b (below-ground biomass)	0.481	0.523	---	---
Leaf area index (seasonal maximum)	0.277*	0.234*	---	---
B_a/B_b (biomass shoot-root ratio)	0.008	0.044	---	---
NPP_a/NPP_b (NPP shoot-root ratio)	0.201	0.301	---	---
B_a/B (above-ground biomass fraction)	0.227	0.344	---	---
NPP_a/NPP (above-ground NPP fraction)	0.270	0.335	---	---
Actual evapotranspiration (annual total)	0.752	0.775	0.755	0.780

NPP = net primary production (or productivity)

GPP = gross primary productivity

B = biomass

*n = 47 total sites and 44 valid sites

Table 4. Monthly Correlations between NDVI and Simulated Biosphere Variables.

	Northern Hemisphere only (n=735)			Southern Hemisphere only (n=212)			Entire Globe (n=947)	
	r(AET)	r(NPP)	r(ΔC)	r(AET)	r(NPP)	r(ΔC)	r(AET)	r(NPP)
January	0.73	0.38	-0.42	0.68	0.58	0.24	0.67	0.70
February	0.73	0.42	-0.37	0.71	0.61	0.26	0.82	0.70
March	0.69	0.53	-0.27	0.74	0.69	0.41	0.79	0.70
April	0.67	0.64	0.01	0.80	0.74	0.51	0.72	0.68
May	0.68	0.72	0.28	0.71	0.58	0.19	0.68	0.68
June	0.64	0.67	0.18	0.75	0.57	-0.03	0.69	0.70
July	0.60	0.57	-0.01	0.66	0.49	-0.08	0.67	0.64
August	0.58	0.51	0.05	0.58	0.40	-0.14	0.64	0.58
September	0.70	0.66	0.33	0.55	0.52	-0.02	0.68	0.66
October	0.79	0.74	0.47	0.62	0.61	0.08	0.76	0.71
November	0.79	0.66	0.29	0.67	0.68	0.27	0.81	0.75
December	0.73	0.54	-0.05	0.77	0.77	0.42	0.84	0.78
Annually	0.77	0.83	—	0.79	0.84	—	0.78	0.83

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Box, E. O. 1987 and in press. Effects of Plant and Vegetation Structure on Seasonal Carbon Dynamics in Models of Terrestrial Ecosystems. Abstracts, Internat. Symposium on Vegetation Structure, Utrecht, July 1987. Full manuscript in symposium proceedings, (M. J. A. Werger, ed.), in press.

Box, E. O. (in press). Estimating the seasonal carbon source-sink geography of a natural, steady-state terrestrial biosphere. J. Clim. Appl. Meteorol. (scheduled for July 1988 issue).

Box, E. O., B. N. Holben, and V. Kalb (in review). Global evaluation of a satellite-based vegetation index using field and simulated site data. Submitted to Vegetatio.

(one more in preparation)

Presentations

Box, E. O. 1986. Modeling the Seasonal Carbon Sources and Sinks in Terrestrial Vegetation, with Satellite Feedback. 4th Intern. Congress of Ecology, Syracuse, August 1986.

Box, E. O. 1987. Combining Satellite Data and Bioclimatic Models for Better Global Ecological Monitoring. 12th International Congress of Biometeorology, Purdue University, September 1987.

Box, E. O. 1987. Effects of Plant and Vegetation Structure on Seasonal Carbon Dynamics in Models of Terrestrial Ecosystems. Intern. Symposium on Vegetation Structure, Utrecht, July 1987.

Box, E. O. 1987. Presentation to annual meeting, Association of American Geographers, Portland (Oregon), April 1987.

Box, E. O. 1987. Presentation on "Ecological Modeling and NPP" to GIMMS Review and Planning Meeting, NASA Goddard Space Flight Center, February 1987.