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A Satellite-Based World Map of Current Terrestrial Net Primary Productivity

人工衛星データを基礎とした陸上の現存純一次生産力の世界地図

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Net primary productivity (NPP) represents the basis of ecological energetics but can be measured directly only laboriously and at particular sites. NPP can be estimated indirectly and geographically, however, from its relationship to the NDVI ratio of values from two spectral bands from NOAA satellites. The relationship between annually integrated NDVI and annual terrestrial NPP was quantified from geographically representative global data-bases involving NDVI values at the NPP measurement sites. This relationship is applied to global NDVI satellite imagery to map global actual net primary productivity.

1. Introduction

Primary production is the process by which plants produce new biomass through photosynthesis and assimilation of its products. This is vital for plants but also represents the entire basis of ecosystem energetics, since plants (primary producers) are the ultimate source of food for animals, including man. Net primary production (NPP) is the amount of new biomass produced in a given period of time. It is the resultant of photosynthetic energy fixation (also called gross primary production) and the use of stored energy for maintenance and growth (respiration). Primary productivity (net or gross) is the rate at which new biomass is or can be produced.

Over large areas, these basic metabolic processes are controlled mainly by ambient climatic conditions (cf. Major 1963, Lieth and Whittaker 1975), which was fortuitous for modeling since until recently, climatic (i. e. meteorological) data represented the only environmental data-base available with global coverage. The development of satellite technology, however, has now changed this situation and provides a second, essentially independent global data-base with which to estimate biosphere phenomena. In particular, the Advanced Very High Resolution Radiometer (AVHRR) aboard NOAA satellites provides daily coverage of the whole globe, in a way that can be used to generate global imagery. Visible and near infra-red channels on the AVHRR were combined by Tucker (1979) to create a so-called Normalized Difference Vegetation Index (NDVI) which enhances the spectral signal within the green wavelengths and provides a measure of surface greenness. Annual and seasonal patterns of this "vegetation index" have been shown to be related to various biosphere phenomena, including primary productivity (Goward et al. 1985, Box et al. 1989).

Considering the importance of primary productivity and of the global carbon budget in general, several immediate goals for use of AVHRR satellite data in global ecology can be readily identified:

1. Production of world models and maps of current actual primary productivity, based on satellite data.
2. Comparison of the global pattern of actual primary productivity with that of potential productivity, estimated from climate-based models, in order to identify regions with large differences.
3. Production of satellite-based dynamic global carbon-balance scenarios, as was done for a steady-state biosphere using climatic data (Box 1988).

Achievement of these objectives requires the best possible models and maps of primary productivity. The purpose of this paper is to present a world map of actual (annual) terrestrial net primary productivity, based on annually integrated NDVI data. This map provides more information for environmental managers and represents a further step toward the ability to monitor primary productivity, its changes from year to year, and its

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degradation due to the overuse of landscapes.

2. Net Primary Productivity

Net primary production (NPP) is related to gross primary production (GPP) and respiration (R) by the following definition:

$$NPP = GPP - R \qquad (1)$$

in which all three components represent amounts of biomass but can also be interpreted as equivalent amounts of stored energy, carbon or carbon dioxide (CO_2). Gross production increases with warmth and water availability, both temporally and geographically, as long as sunlight, nutrients, foliage area, and other factors are not limiting (e. g. Kira 1975, Lieth & Box 1977). Respiration rate (i. e. per unit biomass), on the other hand, depends mainly on temperature, increasing rapidly with increasing temperature (e. g. Shidei & Kira 1977). Annual NPP also increases with warmth and wetness (Major 1963, Rosenzweig 1968) but may become a smaller fraction of GPP in warmer regions, where respiration becomes greater (cf. Kira 1975, Box 1978).

Primary production can be estimated in the field by various measurement methods, all of which, however, are laborious and imprecise at best. The most common techniques involve biomass harvesting and weighing, at frequent intervals throughout the growing season (or entire year); gas-exchange methods aimed at estimating plant or leaf-level photosynthesis and then scaling up to whole vegetation stands; and/or some combination of these two approaches. Above-ground terrestrial NPP is usually estimated by harvest and/or allometric methods (e. g. Lieth and Whittaker 1975). Below-ground NPP may be estimated similarly but is often only estimated from assumed ratios between above and below-ground parts. When actually measured, it typically shows greater variability than above-ground NPP, perhaps due to measurement error.

Because all of these methods are quite time-consuming, especially in rapidly growing herbaceous vegetation (which may require sampling every 1–2 weeks over a whole year), the useable field measurements of total NPP (i. e. above and below ground) are still quite few in number and are concentrated in the northern temperate zone, with only spotty geographic coverage elsewhere. Fortunately, however, two of the end-points of the global environmental continuum have been covered somewhat better, tropical rainforests (largely by Japanese ecologists, see Kira 1975) and polar tundra vegetation, due to particular interests in these extreme environments. The other main end-point, arid deserts, has seen very few attempts to measure primary production, due to special measurement problems in the highly variable desert environments.

Although substrate and historical factors are the main controls at local scales, climate controls spatial and temporal patterns of NPP (and many other earth processes) at global scale. For this reason, the first predictive model of NPP (Rosenzweig 1968) was based on annual actual evapotranspiration (AET)— though without any upper limit on production. Two subsequent models of annual NPP, with an upper limit at 3000 g/m^2/yr (based on the NPP data), were based on annual mean temperature and precipitation, and on annual AFT, respectively (Lieth and Box 1972). These models were transformed into predictive world maps using large climatic data-bases (Lieth & Box 1972) and have been used as the basis for various other ecological models. These maps were also quantified by computerized volumetry to provide initial global inventories of NPP (Box 1975, 1978). An improved NPP model involving soil types was presented by Esser et al. (1982) but requires more input data.

3. Satellite Data and Biosphere Phenomena

The availability of satellite data now provides new methods for estimating biosphere phenomena. In particular, the NDVI has been widely used by the remote-sensing community to monitor global ecological patterns (e. g. Murai 1991) and was summarized by Justice et al. (1985) as a possible index of amounts of green biomass and/or primary productivity. Because of the wide swath of the AVHRR, data can be collected daily over the entire earth surface. As a result, it is usually possible to obtain surface coverage for enough cloud-free days per month to construct meaningful monthly and annual composites for continents and the whole world. Monthly NDVI images for Africa (Tucker et al. 1985) graphically showed the advance and retreat of the summer rains and year-to-year differences in vegetation. These images involved mainly savannas and deciduous scrub vegetation, in which seasonal greenness changes are well captured by the NDVI, but suggested that the NDVI may be a useful index of green biomass in other situations as well.

The NDVI was recently compared globally with NPP site measurements and model results (as well as with climatic and water-balance data) in order to identify with which biological and climatic phenomena it seems to be best correlated (Box et al., 1989). This provided the first global, geographically stratified scrutiny of the NDVI as a potentially general estimator of primary production and other biosphere phenomena. Of the four fundamental geographic patterns of physical and ecological phenomena recognized by Box and Meentemeyer (1991), annually integrated NDVI seems to correspond to the "throughput pattern", which represents simultaneous availability / use of warmth and moisture, as represented also, for example, by biotic decomposition rates, soil weathering and water-holding properties, and plant species richness. Recognition of these and perhaps other basic geographic patterns, based on fundamental mechanisms, may represent a useful geographic framework for interpretation of satellite imagery, especially at global scale.

4. The NDVI-NPP Model

4.1 Geographic Modeling

There are several unavoidable criteria for the production and evaluation of general predictive geographic models. They must be developed at world scale in order to cover all the main environment types (at least under the current configuration of land masses and atmospheric composition). They must involve environmental variables for which data are available worldwide. Such models should be based on fundamental processes and should be designed to predict actual patterns and amounts, which can be used for model validation. Finally, such models should be as simple and as general as possible, at least initially, in order that the results will be readily interpretable in all areas.

Functionally general models produce reasonable results in any situation, which can be assured by understanding the most important mechanisms and determinants of the target phenomenon, the scales at which they are important, and by including all of these in the model. Because water and energy are the most important constraints on terrestrial NPP, surprisingly general models could be constructed based only on temperature and water-balance variables. Models of structural phenomena are much more complex than process models, since structure represents balances among individual processes.

Models which are functionally general still may not be geographically general, i. e. applicable to all geographic situations, unless they are parameterized using geographically complete data-bases. A geographically complete data-base must:

1. cover the full range of variation in the input and output variables (i. e. include the extremes and end-points);
2. include all important environmental situations (e. g. main biome types and at least some unusual situations); and
3. represent the different situations in a geographically balanced way.

The same requirements would apply to data-bases used to test model performance. Data-bases for validation of geographic models must be at least as geographically complete as the data-bases used for model development, since different ecosystems may function in quite different ways. Biome types represent the appropriate geographic coverage for testing model results. Predictive global mapping may also represent a useful form of model validation, since major errors can become painfully visible on a predictive map.

4.2 Relationship of NDVI to NPP

The first step in the development of all the NPP models involved collection of primary production measurements from the ecological literature. Initially, 177 measurements of net primary production were found, made at over 100 different sites worldwide. Of these, however, only 95 had readily understandable, measured total NPP (both above and below ground). Only these 95 sites were used in model development.

Relationships between geographic and temporal patterns of the NDVI and net primary productivity (NPP) were studied especially by Goward et al. (1985) and Box et al. (1989). In the latter study, annually integrated NDVI was plotted against biome-labelled values of measured annual NPP, along with a regression curve representing the global trend. This showed an apparent difference in the pattern for evergreen versus deciduous vegetation, especially forests. Evergreen sites fell mainly along and above the trend curve, with a sharper curvature, while the NPP of deciduous sites (mostly temperate deciduous forests and grasslands) seemed to show a less strong relationship to annual NDVI.

Scattergrams and correlations were run similarly between annual NDVI and climate-based model estimates of both net and gross primary productivity, using the models of Lieth and Box (1972, 1977). These scattergrams suggested a slightly more linear relationship between greenness and simulated NPP but a saturation relationship relative to GPP, with an upper limit on the NDVI as GPP continues to increase.

4.3 The NDVI-NPP Model

The relationship of annually integrated NDVI to measured total annual NPP (above plus below ground) is shown in Figure 1, with biome symbolism for the individual sites. These data suggest a saturation relationship, but with outliers both above and below the trend curve. This relationship was quantified by least-squares regression (r = 0.80, n = 95, see Box et al. 1989) to yield a saturation curve of the from:

$$NDVI = 0.4\ (1-e^{-0.00055059\ NPP}) \qquad (2)$$

where NPP is in grams of dry biomass per square meter per year, NDVI is annually integrated NDVI, ranging from 0 to 1, e is the base of natural logarithms (2.71828. . .), and 0.4 is the upper asymptote for annually integrated NDVI values found in the data-base. This relatively low maximum value of "greenness" is the result of the large pixels involved (about 15 × 15 km at the equator), which necessarily contain a mixture of land cover types. Monthly NDVI values (converted to the same 0–1 scale) can be higher during the peak growing season, but even these do not exceed about 0.5. The highest annual NDVI values found in the world are in large unbroken areas of tropical rainforest.

A similar equation was also derived for the relationship to modelled NPP (see Box et al. 1989, figure 3):

$$NDVI = 0.4\ (1-e^{-0.00068128\ NPP}) \qquad (3)$$

Both equations (2) and (3) can be solved explicitly for NPP to yield equations of the following type:

$$NPP = -1\ /\ a\ \log_e \left[1-\frac{NDVI}{0.4}\right] \qquad (4)$$

in which a is the exponential coefficient governing the curvature of the relationship.

5. The Map of Current Terrestrial NPP

5.1 Mapping Methodology

Climate-based models can be used wherever the necessary climatic data are available, but this represents a limited number of sites and requires spatial interpolation to make a map. The resulting map may be rather patchy unless the site network is very dense. Satellite imagery, on the other hand, provides a value for each pixel in an image and thus a much greater density of "sites". No spatial interpolation is needed, and mapping can be done simply by applying the model to each pixel value in the image raster.

Maps produced for this project were based on a three-year average (1985–87) of NDVI values from the so-called GVI imagery (cf. Tarpley et al. 1984). The monthly images were integrated annually to provide the annual NDVI needed by the NPP model. Negative values of annual NDVI, as sometimes occur in deserts and high

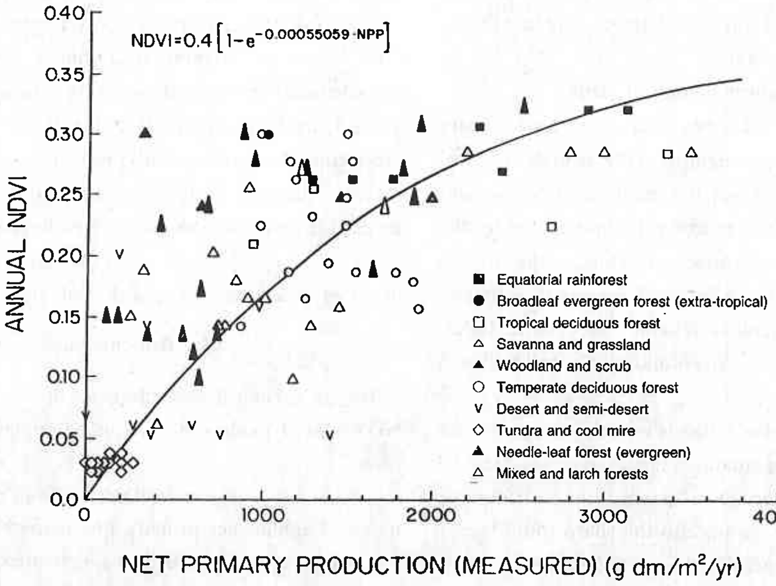

Figure 1 Data and Regression Relationship between Measured Annual Net Primary Production (grams of dried biomass per square meter per year) and Annually Integrated NDVI at the Same Locations.

latitudes, were re-set to zero, and values exceeding 0.4 (the asymptote in equations 2 and 3) were re-set to 0.3999. These necessary corrections are in fact minor and do not affect a large number of pixels. Above 75°N latitude, however, no satellite data are available, due to the low sun angles. These areas are left white on the map.

Maps were produced based on both equations (2) and (3). The latter was chosen for the NPP map presented here since it appeared to minimize overprediction of NPP in desert areas without adversely affecting other parts of the world. This use of a relationship with modelled "data" is justified since modeling smooths the pattern of the individual site measurements (often made only for a single year) for more general applicability. Desert areas may still be overpredicted, since the AVHRR often shows some "greenness" even when no vegetation is present (cf. Holben 1986).

All of these mapping operations were performed on a Sun workstation using a relatively simple C program and an internal map image with 3140 pixels horizontally and 1300 pixels vertically. It was printed on a Canon Pixel Color Copier at A4 size. This reduces both length and width of the internal image by a factor of four, but even at A4 size this map shows much more detail than the various world productivity and related maps printed on a high-speed line-printer. Those maps measured about 1.3 meters across by about 0.7 meters down but contained only 515 × 204 cells within the print raster. The greater level of detail in the satellite-based maps is enhanced, morever, by the direct transformation of data into result, without spatial interpolation.

5.2 The World Pattern of Actual NPP

The resulting map of current actual annual net primary productivity is shown in Figure 2. NPP is high in warm, wet climates and decreases toward drier and/or cooler climates. The large areas of tropical rainforest are readily apparent, as is the more dissected nature of the tropical rainforest in Africa. Some irrigated areas in dry climates are also readily apparent, such as the valleys of the Indus, Nile and Tigris-Euphrates rivers and the Central Valley of California.

The improved level of detail is especially apparent for linear features such as mountain ranges, rivers and coastal strips. The Altai-Tien Shan system, in particular, is striking in its clarity, as are also the sharp south face of the Himalaya, the general outline of the narrow cordillera of the northern and central Andes, the Kopet Dagh, and the central range of New Guinea. Some important coastal features are also well represented, especially the linear Atacama and Namib deserts, the temperate rainforests of Pacific North America and southern Chile, the greener but quite small coastal areas of southwestern Greenland, and even the greener but narrow periphery of Iceland.

In contrast to climate-based maps, which show estimates of potential productivity, the NDVI-based map represents the phenology of the current actual vegetation cover and its actual productive capacity. This can be compared, at least in principle, with maps of potential productivity.

5.3 Discussion and Problems

Although annually integrated NDVI can estimate annual net (and probably gross) primary productivity with some accuracy, the monthly NDVI values which give the annual totals show many problems, including values above zero even in arid deserts and when temperatures are well below freezing (winter months and permanent icecaps). The problem of non-zero values at sub-freezing temperatures can be fixed by arbitrarily zeroing the monthly NDVI value if the site is deeply frozen. Use of this cold-adjusted NDVI (with recomputed annual integrations) significantly increased the correlation coefficients of the NPP models. The other problems in the NDVI imagery cannot be patched so easily.

Although annually integrated NDVI seems to be rather well correlated with annual primary production, NDVI will never be a good measure of seasonal NPP, across all biomes, because NPP often becomes negative or near zero outside the growing season (cf. equation 1), when GPP is low but respiration continues. NPP may even become negative during the growing season (cf. Box et al. 1989, figure 5) if respiration is quite high. Seasonal gross production does not have this problem, so monthly NDVI may be a useful indicator of monthly GPP. NDVI cannot be used to estimate non-green or underground processes (e. g. respiration), and it does not seem to be a good index of green structure, such leaf area of forests.

6. Conclusions

The geographical characteristics of the NDVI and of NDVI-based models/maps can be summarized as follows:

—Annually integrated NDVI appears to be a useful index of annual net primary productivity, especially in less complex terrain and over larger areas with at least semi-natural vegetation.

—There are perhaps significant geographic and vegetation-specific differences in NDVI-NPP relationships, which must be explored further, especially using seasonal data.

—Scale problems are significant in the interpretation of NDVI values and NDVI-based results, due to the large pixel size.

These problems do not preclude use of the NDVI as a reliable index of productivity but do suggest a need for caution and for a good knowledge of global physical and vegetation geography, and of actual land use, before interpreting satellite results.

Major improvements to existing NDVI-based ecological models will require a better understanding of the different NDVI patterns for evergreen and deciduous vegetation, since this involves basic questions of photosynthesis and its spectral behavior. Improved NDVI-based models are being developed, but before independently developed NPP and GPP models can be used together reliably for global simulation, they must be better coordinated to avoid mathematical artifacts and to reflect true global patterns of NPP versus GPP, based on better data, especially for gross production. The most reliable models are probably those for NPP rather than GPP, since the errors in estimating NPP are probably less than for GPP. One strategy for estimating seasonal carbon budgets is to use annually integrated NDVI to estimate annual NPP, then estimate annual GPP from NPP (cf. Lieth & Box 1977), and finally to estimate GPP seasonality from monthly NDVI values. NPP seasonality still depends also on respiration, which probably must be modeled climatically. Finally, further progress also requires better global NDVI data-bases. In order to obtain reasonable results, sporadically unreasonable NDVI values also have to be corrected.

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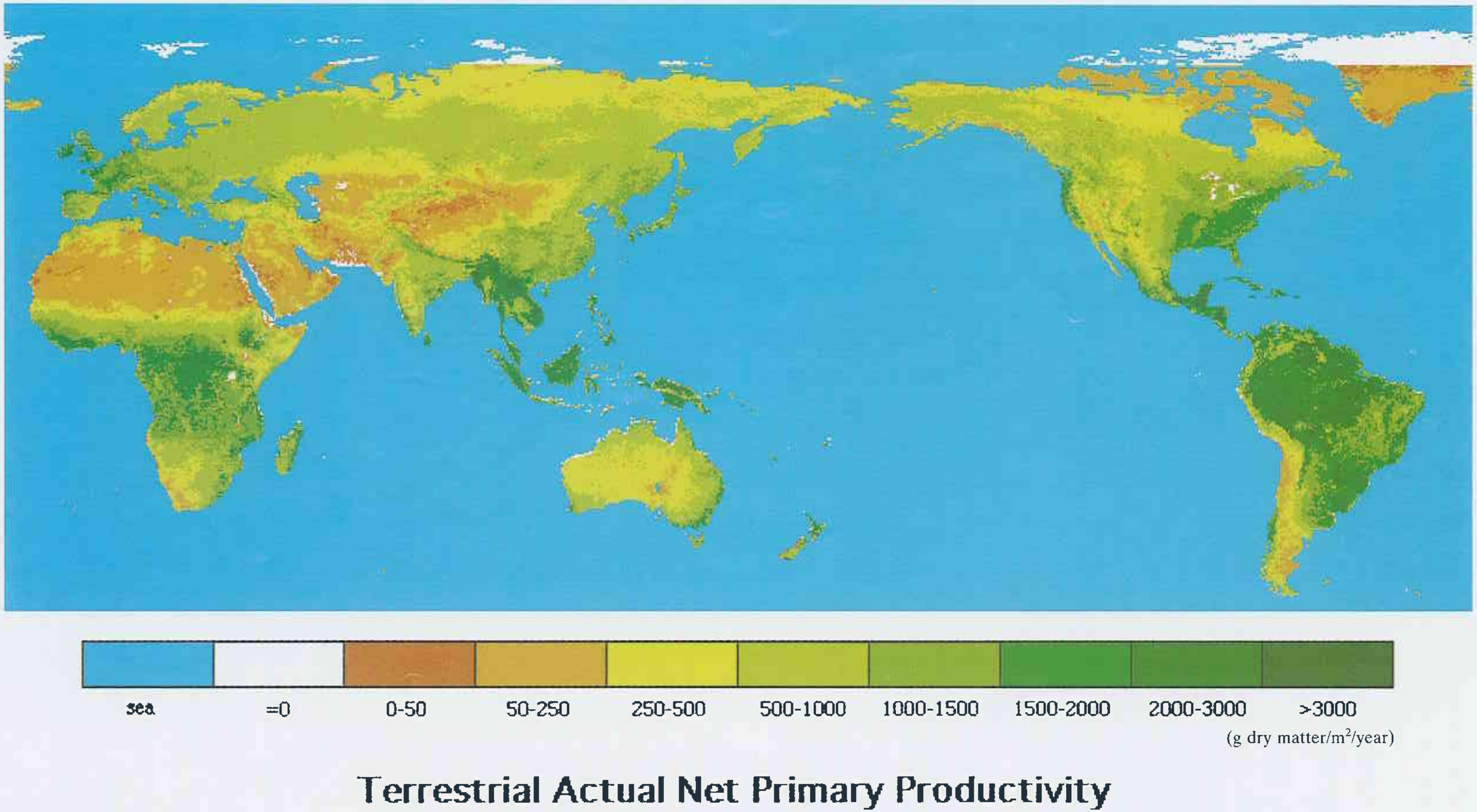

Figure 2 Annual Net Primary Productivity (g d.m./m^2/year) of the Actual Vegetation Cover of the World's Land Areas, estimated from NOAA AVHRR Satellite Data (1985–87 average).