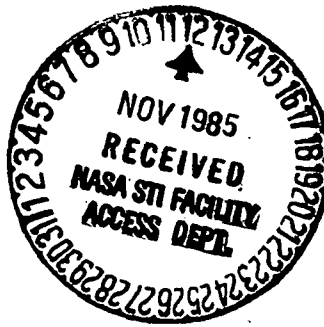GR
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ANALYSIS OF TERRESTRIAL
CONDITIONS AND DYNAMICS

NASA Cooperative Agreement NCC 5-26
Department of Geography
University of Maryland
College Park, Maryland

Principal Investigator
Samuel N. Goward

Progress Report

September 1, 1984-June 30, 1985

I. INTRODUCTION

The cooperative research program between the Department of Geography, University of Maryland and the Earth Resources Branch, NASA Goddard Space Flight Center achieved marked progress during the period Sept. 1984 to June 1985. The two students, Dennis Dye and Sheila Donovan, funded under the program, neared completion of their Master's degrees. The research they carried out - Mr. Dye focusing on ecological modeling and Ms. Donovan concentrating on bidirectional reflectance - has substantially contributed to the objectives of this research program and the expressed needs of NASA's Land Processes program. Mr. Dye's Masters Thesis "Estimation of Vegetation Net Productivity using NOAA7 AVHRR Data" has recently been accepted by the University for completion of his degree. The text of this thesis comprises the main body of this semi-annual report. Additional research progress is briefly discussed in the following paragraphs.

II. RESEARCH PROGRESS

A. Anisotrophy of Land Reflectance

The SAIL canopy reflectance model has been implemented on the NASA 3081 computer as well as systems at the University of Maryland. Mr. Fred Hummerich and Mr. Alan Hope, graduate students in the Geography department funded from sources other than this grant, are using the model to study interception of solar radiation in vegetation canopies and the relation between reflected solar radiation and thermal emissions for vegetation canopies. These studies are in part evaluating the contribution off-nadir measurements will provide to more accurate assessment of vegetation biophysical measurements with remotely

sensed observations. Preliminary results show that two or more off-nadir measurements reduce the "error" in estimating intercepted photosynthetically active radiation with spectral vegetation index measurements. This "error" occurs as a result of the influence of leaf angle distributions on observed spectral vegetation indices. The off-nadir observations improve the IPAR estimates by providing a measure of canopy reflectance anisotrophy which is descriptive of the vegetation architecture.

Ms. Donovan is nearing completion of a Masters' thesis concerned with the use of bidirectional measurements for vegetation discrimination. the body of this thesis will be submitted in a future semi-annual report. She is analyzing field measurements acquired by the NASA/GSFC PARABOLA instrument in West Texas last year. Her results to date suggest that the bidirectional measurements permit discrimination of vegetation types which display differing leaf angle distributions. These results are in agreement with model calculations by Kimes (1985) and others which show that canopy reflectance anisotropy is primarily a function of canopy architecture.

Mr. Tom Brakke, NASA scientist with the Earth Resources Branch, has completed the first draft of a paper he and Dr. Goward are coauthoring. The study is on analysis of bidirectional measurements acquired by the aircraft-based Ocean Color Scanner (OCS) instrument. He noted that derivation of bidirectional measurements from these data is complicated by within-field heterogenity. That is for a given cover type, such as corn or soybeans, there are sufficient variations in ground cover and vegetation density to create variations in the measurements that are equal to the bidirectional signal. These results suggest that space borne measurements of bidirectional reflectance will require a high degree of navigational and pointing accuracy in order to avoid confusion between variations caused by vegetation cover versus

anisotropy. The manuscript is currently being revised and will shortly be submitted for publication.

B. Ecological Modeling

Mr. Dye's master's thesis, presented later in this text, provides a thorough review of the most significant progress achieved in the area. Other activities pursued during this period include acquisition of 1983 World Climate Data, an intensive evaluation and revision of the AVHRR integration procedures and a preliminary inspection of 1983 and 1984 AVHRR North American observations.

After much trauma and discussion with people at the NOAA Climate Data repository in Ashville, North Carolina and researchers at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, world climatic data for 1983 were acquired. Of course the data are in a format entirely different format than 1982 observations acquired last year (which turned out to have been a working file rather than a finished product). As a result the computer software developed last year had to be completely rewritten to handle the 1983 data. This activity is still underway and should be completed in the next few months. Two studies, one comparing the Holdridge climate-vegetation scheme to AVHRR data and the other an alternative ecological modeling study suggested by Dr. John Montieth; are on hold pending availability of the data.

Several problems with the numerical integration scheme for computing seasonal and annual vegetation index patterns where identified over the last year. Particular problems occurred because the NOAA Global Vegetation Index data are recorded in an inverted numerical scale which could not be treated with the the-current integration routine. In addition, there was no ability to threshold the computation to delete from consideration variable NDVI values

where no vegetation is present. In colabration with Mr. Tom Goff, these changes were incorporated into the software and tested for correct operation. An interesting conclusion is that inclusion of NDVI measurements below 0.1 produces integrated values which are less well related to net primary production than values produced for NDVI measurements which do not include values below 0.1.

Observations from 1983 to present for the AVHRR Global Vegetation Index data have been composited for 3-week intervals by Arlene Kerle, NASA Earth Resources Branch. We have computed 12 month integral images of these data and compared 1982, 1983 and 1984. Changes in the NOAA compositing procedures between 1982 and the other dates appear to have produced a serious bias between years. Dr. Tuchu and Dr. Goward are conducting a study from GAC observations to better understand this problem. There appear to be some serious problems with NOAA procedures form producing the GVI data set which may require development of alternative data products. Comparison of 1983 and 1984 observations has produced an interesting observation of variations in the southern United States. Further analysis of this may require detailed climatic observations and awaits the time and staff to investigate.

Analysis of the reflectance spectra acquired in the Canadian subarctic during August of 1984 have revealed that lichens have a distinctive reflectance spectra in the visible portion of the solar spectrum. This may occur as a result of the unusual photosynthesis system these plants possess which is based on a symbiotic relative between fungi and algae. These results are currently being prepared for publication and should be submitted in the near future. Dr. Petzold and Dr. Goward are planning and carrying out a second year of field measurements in Schefferville, Quebec during this summer.
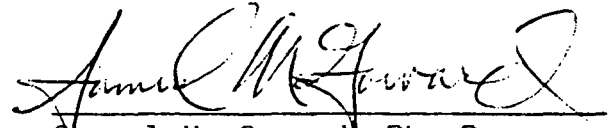
C. Publications and Presentations

Two papers based on this research have been accepted for publication during this time period; 1) Goward, S.N., C.J. Tucker; and D. Dye. North America Vegetation Patterns Observed by NOAA-7 AVHRR, Vegetatio (to be published by late fall) and 2) Goward, S.N., G. Cruickshanks and A. Hope. Observed Relation between Spectral Reflectance and Thermal Emittance for a Complex Vegetated Landscape, Remote Sensing of Environment (to be published in the fall). Copies of the manuscripts for these papers are contained in previous semi-annual reports for this project. Dr. Goward was invited to present his North American research at; 1) A meeting of the NASA Pilot Land Data System research group held at Jet Propulsion Laboratory in December 1984; and 2) a meeting of Scientific Geography, held at the University of Georgia (Athens) in March 1985. In addition Dennis Dye presented his ecological modeling research at the Annual Meeting of the Association of American Geographers and Dr. Goward coauthored a paper with Darrel Williams, NASA/GSFC on remote sensing of acid rain damaged vegetation at the same meeting, held in Detroit, Michigan.

APPROVAL SHEET

Title of Thesis: Estimation of Vegetation Net Primary
                    Productivity using NOAA7 AVHRR Data

Name of Candidate: Dennis G. Dye
                    Master of Arts, 1985

Thesis and Abstract Approved: _____
                              Samuel N. Goward, Ph. D.
                              Assistant Research Scholar
                              Department of Geography

Date Approved: ___8 / 23 / 85_____

CURRICULUM VITAE

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Date of birth: ████████████

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University of Maryland, College Park	1/83-12/85	M.A.	1985

Major: Physical Geography.

Professional positions held: Geographer, NASA Headquarters, Washington, D.C. 20546, May - November 1982.

ABSTRACT

Title of Thesis: Estimation of Vegetation Net Primary
                    Productivity using NOAA-7 AVHRR Data

Dennis Gene Dye, Master of Arts, 1985

Thesis directed by: Samuel N. Goward, Ph.D.
                       Assistant Research Scholar
                       Department of Geography

An ecological model was developed to estimate annual net

primary productivity of vegetation in twelve major North

American biomes. Three existing models were adapted and

combined, each addressing a different factor known to govern

primary productivity. These factors are photosynthesis,

respiration and moisture availability. Measures of intercepted

photosynthetically active radiation (IPAR) for input to the

photosynthesis model were derived from spectral vegetation

index data, on the basis of a linear relationship between the

Normalized Difference Vegetation Index (NDVI) and percent IPAR

which through other research has been shown to exist. NDVI data

were produced from NOAA-7 Advanced Very High Resolution

Radiometer (AVHRR) observations for April 1982 through March

1983. Composite NDVI images were created to represent calendar

month periods, which helped alleviate cloudcover problems and

also provided a data set corresponding in time with available

monthly climatological data. The spatial resolution of the

composite images was reduced from the original 1.1 km to

roughly 15 to 30 km, depending on latitude. NDVI values were

sampled from within the biomes at locations for which

climatological data are available. Monthly estimates of NPP

for each sample location were generated and summed over the twelve month period. These monthly estimates were averaged to produce a single annual estimated NPP value for each biome. Comparison of estimated NPP values with figures reported in the literature produces a correlation coefficient of .85, however, the model consistently underestimates NPP. The results suggest promise for use of course spatial resolution NDVI data for evaluation of continental and global scale patterns of productivity in terrestrial vegetation.

ESTIMATION OF
VEGETATION NET PRIMARY PRODUCTIVITY
USING NOAA-7 AVHRR DATA

by
Dennis G. Dye

Thesis submitted to the Faculty of the Graduate School
of the University of Maryland in partial fulfillment
of the requirements for the degree of
Master of Arts
1985

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CHAPTER 1

INTRODUCTION

Life on the earth is dependent upon maintaining a complex

ecological balance within the biosphere. Fundamental to

current scientific understanding of this ecology is the

recognition that certain interactions occur and balances exist

among several major physical systems in the biosphere. These

physical systems are generally divided into the broad

categories of water systems (hydrological cycling), chemical

and nutrient systems (biogeochemical cycling), and energy

transfer systems (climatology). Together these systems connect

the functioning of the planet's land, oceans, atmosphere and

organisms. In recent decades, conceptual understanding about

the interaction of these systems, as well as the effect human

activities may have upon them, has increased (Revelle and Mark,

1977; Woodwell et al., 1978; Kormandy and McCormick, 1981;

Bolin and Cook, 1982).

In recent years an increased recognition has developed

within the scientific community of the necessity of studying

ecological phenomena in the biosphere at the global scale

(SCEP,1970; Botkin,1982). The concepts providing direction for

this research are found in an emerging science concerned with

"global habitability", involving a multidisciplinary approach

to analysis of biospheric processes. The National Academy of

Science, the National Research Council, the National

Heronautics and Space Administration, as well as foreign and international science groups have begun to address this concern through declared research initiatives (NAS, 1982,1983; NRC,1983; NASA, 1983, 1984).

There is convincing evidence that potential significant change in the earth's climate may occur in the not-too-distant future. A basis of support for this prediction is found in measurements of atmospheric carbon dioxide made at Mauna Loa, Hawaii, since the year 1959 (Bacastow et al., 1985). These measurements show regular annual increases in carbon dioxide concentrations. It is believed that continued increases may lead to an overall rise in average global temperatures, causing a rise in world-wide sea levels, and altered weather and climate patterns around the globe (Seidel, 1983). There are many concerns regarding the potential effect which climate change may bear upon the life support systems of the earth. For example, changing patterns of planetary rainfall could seriously reduce agricultural productivity in regions which have been historically highly productive and depended upon for world food production. Hence, the future habitability of the earth has become of great concern and demands concentrated scientific research efforts to provide fuller understanding of the problem.

Among the portions of the biosphere which comprise the living systems, or biota, by far the most predominate is terrestrial vegetation. Vegetation forms the foundation for the food chain on the earth and also plays a key role in the overall ecology of the biosphere (Odum, 1971). Vegetation has

direct and substantial influence upon the environment through
its control over surface albedo, the energy-exchange regime,
and the way in which water, nutrients, carbon dioxide and
oxygen are cycled through the environment (Botkin, 1982). In
view of this, any analysis of the state of the biosphere
requires substantial study of terrestrial vegetation.

The single most informative measure of vegetation activity
is its rate of primary productivity. In simple terms, primary
productivity in vegetation is the rate at which radiant solar
energy converts raw materials (water, carbon dioxide) into
plant matter through the process of photosynthesis. In studies
of vegetation at the community and formation scales, primary
productivity is typically reported in units of grams of dry
plant matter (carbohydrates) produced per square meter of
ground area per year ($g\ m^{-2}\ yr^{-1}$).

Quantitative knowledge of the primary productivity of the
earth's vegetation is valuable since it provides information
about the degree to which vegetation is actively involved in
and contributing to the ecological cycling processes of the
biosphere. A survey of the scientific literature evaluating
primary productivity in terrestrial vegetation was conducted by
Atjay el al. (1979). The data which they compiled reveals
significant disparity among figures reported by various sources
for major vegetation ecosystems around the world. Aside from
primary productivity, it is evident that much has yet to be
learned and agreed upon concerning spatial and phenological
patterns of global vegetation in general. One obvious

indication of this is found by comparing several of the various
world vegetation maps found in the literature (e.g., Kuchler,
1966; Reichle, 1970; Odum, 1971; Robinson, 1972; Daubenmire,
1978; Vankat, 1979; EPA, 1980; Olson and Watts, 1982). For
the most part, no two are alike in their delineation of
vegetation patterns.

Historically, there have been serious logistical problems
associated with the study of vegetation at regional,
continental and global scales as opposed to the laboratory or
small field sites. In studying the vegetation of larger areas
one must deal with greater variability and the difficulty of
accessing and representing that variability. It can become
prohibitively expensive, time consuming, and generally
impractical task if only traditional field methods are applied
to the problem. Remote sensing has proven to be a useful
technology for providing otherwise unattainable information on
phenomena distributed over large areas of the earth. It is
therefore logical to look to remote sensing as a source of new
information about global vegetation.

The relatively course spatial and high temporal resolution
multispectral measurements from the Advanced Very High
Resolution Radiometer (AVHRR) onboard the NOAA-6 and NOAA-7
meteorological satellites have been increasingly examined in
recent years as a global vegetation data source. Great promise
has been shown for use of the AVHRR in large-area vegetation
analyses (Gatlin et al., 1981; Greegor et al., 1981; Townshend
and Tucker, 1981; Cicone and Metzler,1982; Ormsby, 1982; Tucker
et al.,1982; Norwine and Greegor, 1983; Tarpley et al., 1983;

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Justice et al., 1984; Goward et al. 1985; Malingreau, 1985;
Tucker et al., 1985a,b). This has led to consideration of its
potential utility in estimating vegetation primary
productivity. The research which is described in the following
chapters is an initial attempt to develop an ecological model
which in part uses remotely sensed data from the AVHRR to
estimate the net primary productivity of terrestrial
vegetation.

CHAPTER 2

BACKGROUND INFORMATION

2.1 Existing Field Techniques

Two traditional approaches to the estimation of
productivity of terrestrial vegetation can be found in the
literature. The first approach involves techniques for direct
measurement of changes in plant biomass through the course of
time. This relies upon sampling of biomass either by
destructive or non-destructive means. Destructive sampling is
generally referred to as the "harvest" method and non-
destructive sampling as "dimension analysis". The second
common type of approach involves techniques to measure the
exchange of gases between the plant and atmosphere, referred to
as the "gas-exchange" method. This approach is based upon the
known relationship between carbon dioxide absorption by a plant
and its rate of net photosynthesis. (Woodwell and Botkin, 1970;
Whittaker and Marks, 1975).

2.1.1 Growth Analysis

Both the harvest and dimensional analysis techniques
attempt to determine incremental increases in the biomass of a
plant between specific sampling times during its growth period
(Milner and Hughes, 1968; Satoo, 1970). In the harvest
technique, sample plots of vegetation are removed, dried, and
weighed at regular time intervals, hence the term "destructive"

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sampling. This approach has been applied commonaly to estimate productivity in grassland, crops, and herbaceous vegetation. In investigations of productivity of forests, the dimension analysis technique has been considered more practical. Again, periodic sampling of biomass amounts are acquired, but typically in a non-destructive manner. The height and diameter of individual trees are measured, and based upon correlations, productivity rates are estimated from the observed changes in biomass observed (Barbour, et al., 1980; Newbould, 1967).

2.1.2 Gas-exchange Techniques

The relationship between the production of plant material and the physical and chemical processes involved has led to biophysically-based approaches to the estimation of plant productivity. In this category, gas-exchange techniques have been most commonly employed. In general, gas-exchange techniques involve measurments of the rate at which gases, carbon dioxide in particular, are exchanged between a leaf, plant or plant canopy and the surrounding atmosphere (Monteith, 1962; Lemon, 1967; Chartier, 1970; Hesketh, 1980; Long, 1982). From measured rates of carbon dioxide uptake, the rate of assimilation, or net photosynthesis can be inferred. Typical gas-measurements made during daylight necessarily provide estimates of net photosynthsis. This is because only net changes in carbon dioxide concentrations can be directly measured. At present, the gross rate at which carbon dioxide is absorbed and converted to carbohydrate through

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photosynthesis cannot be separated from the rate at which
carbon dioxide is released through photorespiration. Gas-
exchange measurements made during darkness, however, provide
useful data on dark respiration rates.

2.1.3 Deficiencies of Existing Data for Large Area Studies

The approaches described above are suitable for
investigations of vegetation productivity in well-defined plots
at specific locations under specific environmental conditions.
These methods all entail intensive field work over long periods
of time which is both laborious and expensive. Such samples
represent conditions at point locations which must be
extrapolated to account for thr spatial and temporal
variability in vegetation productivity across large terrestrial
areas. It is impractical to create a network of sampling sites
which is dense enough to assure comprehensive representation on
continental and global scales and reliable enough to provide a
continual source of measurement and monitoring.

According to Lieth and Whittaker (1975), existing methods
of estimating primary productivity at point locations have not
reliably achieved accuracies better than +/- 10%. A survey of
the literature evaluating net primary productivity of the
world's major vegetation ecosystems reveals substantial
variance among reported values. Estimates made during the past
twenty years of the total annual net primary productivity for
all terrestrial vegetation in some cases differ by as much as a
factor of 6 or more (Rodin et al., 1975; Whittaker and Likens,
1975; Atjay et al. 1979).

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2.2 Analysis of Continental and Global Scale Vegetation NPP Patterns

As knowledge in the plant and ecological sciences has advanced over the decades, knowledge and understanding of continental and global patterns of vegetation productivity has lagged behind. This situation is not surprising, considering the the scarcity of dependable information on vegetation productivity and the difficulties associated with collecting it over wide or remote areas. Much of the information provided in major sources of literature in this area is based on statistical correlation, extrapolation, and conjecture (Lieth, 1974, 1975; Whittaker, 1970; Rodin et al, 1975).

The map displayed in Figure 1 represents an attempt conducted by Lieth (1973) to evaluate the global patterns of net primary productivity in vegetation. The map was generated from a collection of annual net primary productivity estimates representing 52 point locations around the world. Based upon statistical correlation between the productivity values and averages of annual temperature and precipitation at each of the sample locations, productivity estimates were generated extrapolatiing over the entire terrestrial surface (Lieth, 1972,1973). In two related studies, correlations were based on evapotranspiration (Lieth and Box, 1972) and length of growing season (Lieth, 1974). Rodin et al. (1975) generated predictions of global NPP patterns by associating productivity estimates with the areas of different soil-vegetation formations.

LAND ▨▨▨▨▨▨ OCEAN ▨▨▨▨▨

| A | B | C | D | E | F | | 1 | 2 | 3 | 4 | 5 |

> 50 $\frac{50}{250}$ $\frac{250}{500}$ $\frac{500}{1000}$ $\frac{1000}{2000}$ 2000 <   50 $\frac{50}{100}$ $\frac{100}{200}$ $\frac{200}{400}$ 400

Productivity ranges (g/m² /year, dry matter)
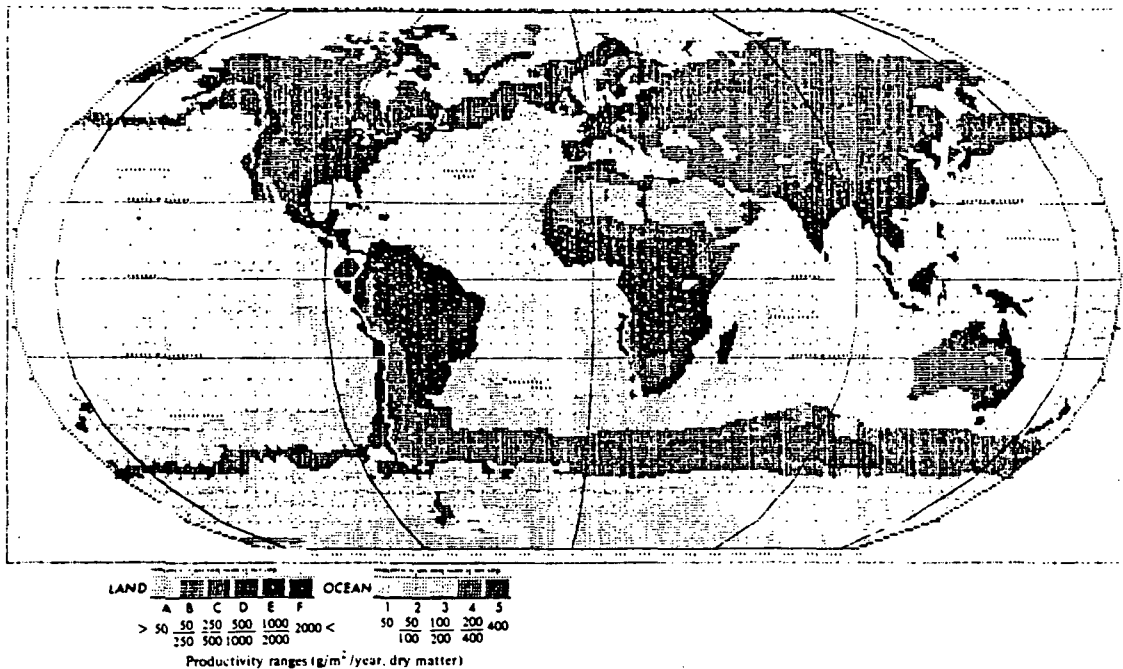
Figure 1. Global NPP patterns estimated by statistical
methods (Lieth, 1973)

If the ultimate goal is to fit knowledge gained about
global patterns of vegetation productivity into dynamic models
of biogeochemical cycling between the atmosphere, land, and
oceans, then the value of these predictive approaches is
limited. For instance, the methods described above provide
only a single productivity estimate for any location. Without
a continual source of data collection, sensitivity to seasonal
or annual fluctuations in terrestrial vegetation activity
cannot be maintained through time. The dependancy placed upon
correlations and extrapolation to generate values for non-

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sampled areas greatly diminishes the reliability of the
estimates. Moreover, since the approach is basically
statistical in nature, it lacks a theoretical foundation in the
actual biophysical processes and environmental controls which
determine vegetation productivity. More meaningful and
scientifically useful models of plant growth dynamics and
global ecology in general need to be developed.

2.3 Application of Remote Sensing

    Previous approaches involving site specific, ground-based
techniques for estimating vegetation productivity do not appear
to be adequate in satisfying current information needs about
continental and global scale vegetation productivity patterns.
Therefore it is necessary to consider alternative approaches.

    The most obvious and promising approach is to employ
information obtained through satellite remote sensing
techniques. Spectral observations of surface conditions
obtained by satellite-based sensors can provide a system of
data collection which offers improvements over previous
approaches in at least two ways. First, data collection can be
achieved in a spatially comprehensive manner over the entire
surface of the globe. This assures thorough representation of
variation existing across the land surface. Second, satellites
provide the capability to monitor surface conditions
continually through regular and repetitive data collection,
thereby providing sensitivity to changes which occur through
time.

2.3.1   Spectral Vegetation Indices from Remotely Sensed Data

Since vegetation most often is a dominant element of the
terrestrial landscape, much of the remote sensing research
literature has centered upon the analysis of vegetation.
Linear combinations of reflected visible and near-infrared
radiation measurements, referred simply to as spectral
"vegetation indices", have in numerous studies been shown to be
useful in characterizing the presence, condition, and quantity
of photosynthetically-active "green" vegetation (e.g. Rouse et
al., 1974; Tucker and Holben, 1980; Tucker et al., 1981).

A spectral vegetation index is derived in its simple form
by computing the ratio between sensor measurments of the
reflected visible radiation and the reflected near-infrared
(NIR) radiation. A widely adopted variation of this simple
form of the vegetation index is the normalized difference
vegetation index, or NDVI. The NDVI is computed from the
difference of visible and near-infrared spectal measurements
divided by their sum. It was formulated originally for use
with Landsat Multispectral Scanner (MSS) data in a study of the
grassland vegetation in the Great Plains of the United States
(Rouse, et al., 1974). The NDVI has become the most commonly
used form of the vegetation index because it has been shown to
normalize the effects of variable sun-angle and insolation
conditions.

The spectral vegetation index is informative with regard
to the biophysical attributes of the vegetation observed
because of the mutually distinct manner in which visible and

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NIR radiation interact with green leaves. Visible radiation is strongly absorbed by chlorophyll and other leaf pigments, whereas NIR radiation is predominately reflected by materials forming the internal structure of the leaf (Knipling, 1970). Use of a spectral vegetation index enables one which to take advantage of the unique optical properties of green vegetation, and thereby provide data which is informative specifically about the photosynthetically active vegetation component of a landscape.

Remotely sensed data in the form of the NDVI may be particularly useful for evaluating the seasonal growth dynamics of plant canopies or communities. Research conducted by Hatfield et al. (1984) shows that the NDVI is related to the amount of photosynthetically active radiation (PAR) which is intercepted by a plant canopy (IPAR). These researchers quantified the NDVI relationship based on field measurements of IPAR and reflected visible and near-infrared radiation for a wheat canopy. They found a remarkably strong, linear relationship exists, with a coefficient of determination of .974. Since the amount of PAR available to a plant canopy is known to be a major and fundamental variable governing the occurence and rate of photosynthesis, it is an important and informative variable for a model of vegetation productivity. The NDVI-IPAR relationship provides a sound theoretical basis upon which to employ spectral measurements collected by satellite in the modelling of vegetation growth, and provides much of the impetus for this research.

2.3.2 Use of NOAA Satellite Data

Analysis of continental to global regions of the earth
requires special consideration of the spatial resolution of the
sensor employed. The 80 meter spatial resolution of the
Landsat Multispectral Scanner System (MSS) renders this sensor
inappropriate for very large area vegetation analyses. With an
individual MSS scene covering an approximate 185x185 km area,
many thousands of scenes are required to cover the continental
areas of the globe, and this would represent only a single
observation. As suggested in Tucker et al. (1985), tremendous
costs and overwhelming data volume, particularly if continual
monitoring is desirable, combine to illiminate reliance upon
Landsat MSS data for continental and global scale coverage. For
these same reasons, the Thematic Mapper's 30-meter resolution
is even less suitable for large area coverage. As with the
MSS, Thematic Mapper data are most practical for application to
local or regional analyses.

The AVHRR, with its relatively course 1.1 km spatial
resolution, is a more practical sensor for large area analyses.
An advantage of the AVHRR is that the data volume is reduced to
manageble levels. Another factor contributing to the
usefulness of the AVHRR is its temporal resolution. A large
scan angle and 9-day repeat cycle in combination provide
coverage at all locations on the earth on a daily basis.
Landsat, on the other hand, has a full 18-day interval between
repeated coverage of a single location. The frequency of scene
coverage is an important consideration, particularly for data

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collection over areas prone to cloudcover, such as the tropics or the Pacific Northwest in North America. A greater frequency of observation results in a greater liklihood of obtaining cloudfree, and therefore usable, image data. Recent investigations demonstrate the successful use of AVHRR data for analyzing and mapping vegetation over very large areas. These include Gatlin et al. (1981), Greegor et al. (1981), Townshend and Tucker (1981), Ormsby, (1982), Tucker et al. (1982), Norwine and Greegor (1983), Tarpley et al. (1983), Justice et al. (1984), Goward et al. (1985), Malingreau (1985), NOAA (1985), and Tucker et al. (1984, 1985a, 1985b).

An investigation of the spatial and temporal patterns of vegetation on the North American continent was conducted by Goward et al. (1985) using digital AVHRR data collected through the growing season. This study showed that NDVI data from AVHRR observations appear to contain substantial information about continental patterns of phenology and annual production. In this preliminary investigation, "integrated" NDVI values were computed to represent each of the major vegetation communities, or biomes, on the continent. These integrated values were derived by computing the integral of the curve defining the change in NDVI over the growing season for selected locations.

Correlation of the integrated NDVI values with estimates of annual net primary productivity for corresponding ecosystem types showed a strong, direct linear relationship (figure 2). These results suggest that NDVI data from the AVHRR are in some

manner highly sensitive to the continental-scale productivity characteristics of terrestrial vegetation. The focus of this study is an attempt to explain this relationship on a biophysiological basis by using the satellite data in an ecological model of plant productivity.

① TUNDRA	⑦ OAK-PINE SUBCLIMAX
② TUNDRA-CONIFEROUS ECOTONE	⑧ PINE SUBCLIMAX
③ BOREAL CONIFEROUS	⑨ GRASSLAND
④ TEMPERATE MOIST CONIFEROUS	⑩ CULTIVATED
⑤ CONIFEROUS-DECIDIOUS ECOTONE	⑪ WOODLAND & SCRUB
⑥ DECIDIOUS	⑫ DESERT
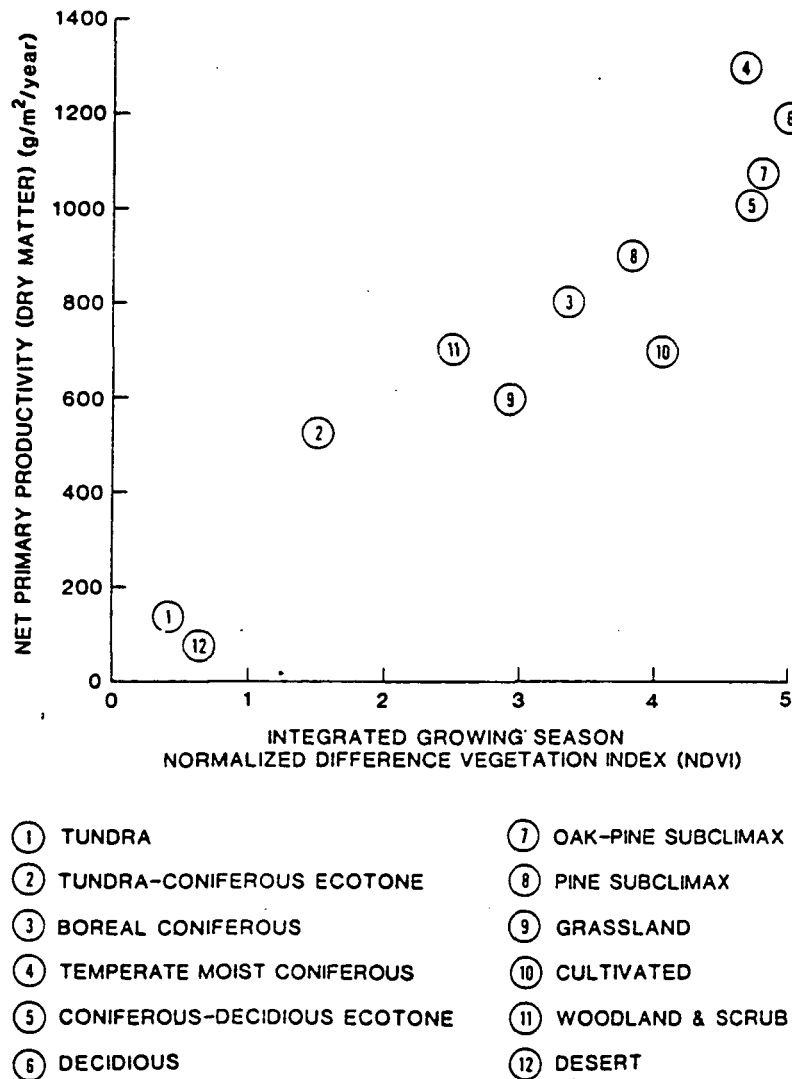
Figure 2. Relationship between integrated NDVI and reported annual net primary productivity for major North American biomes (Goward et al., 1985).

DESCRIPTION OF THE MODEL

The model used to estimate net primary productivity in this study is a combination of three separate models which address three major environmental factors governing photosynthesis in living plants. These factors are solar radiation, temperature, and water. Solar radiation is addressed through a model originally developed by Monteith (1965), temperature by Terjung (1976), and moisture availability by Thornthwaite and Mather (1957). Each of these three major components are explained in the sections which follow.

3.1 Monteith Plant Canopy Photosynthesis Model

Monteith (1965) developed a theoretical model to account for the distribution of radiation within a vegetation canopy. He combined this with two parameters (variables "a" and "b") from an equation fitting the curve which describes the typical photosynthetic response of leaves to variations in light intensity. The equation is,

$$\bar{P} = (a + b/I)^{-1}$$

where I is light intensity and P is rate of photosynthesis. With these parameters "a" and "b", and an estimation of solar radiation conditions, Monteith formulated an equation to

calculate the total daily photosynthesis by leaves in a canopy.

The Monteith model was originally intended to describe photosynthesis in field crops. It assumes moisture and temperature conditions are adequate to meet the optimum growth requirements of the plants. In other words, water and temperature are not considered limiting factors affecting the rate of photosynthesis and therefore are not addressed in the model.

In non-irrigated vegetation environments, moisture conditions are controlled primarily by climatological conditions which may vary widely between locations and environments. The Monteith equation by itself is therefore insufficiently formulated to model photosynthesis in natural environments, where moisture and temperture cannot be assumed to be continuously favorable and non-limiting factors. It is therefore necessary to adapt the model to address the controlling effect of moisture availability and temperature upon plant productivity. These adaptations are realized through the addition of two other models explaining moisture availability and the photosynthetic response of leaves to temperature. The approaches adopted in this regard are described in subsequent sections.

The general form of the equation given by Monteith (1965) for photosynthesis in a plant canopy is:

$$P = ha^{-1}[A_0\{1-f(n_0)\}+A_1\{1-f(n_1)\}]$$

where:

P = daily gross photosynthesis (g m^{-2} day^{-1})

h = daylength (minutes)

a = sum of resistances to carbon dioxide diffusion into choroplasts (m^{2}hr g^{-1})

A_0= area of leaves intercepting radiation directly, without prior transmission through a leaf (no units)

A_1= area of leaves which intercept radiation after one transmission through a leaf (no units)

A_0 and A_1 are areas based upon a theoretical unit leaf-area of a single layer of leaves, and are dimensionless.

A simplification of the model formulation was neccessary to enable direct substitution of a single light interception value. Otherwise, it would be necessary to divide it into components of directly intercepted (A_0) and transmitted (A_1) light, and this was not considered feasible. To this end, it is reasonable to assume that the amount of photosynthesis which occurs as a result of energy which has been previously transmitted through leaf material is insignificant in comparison to the amount which occurs as a result of energy received directly. Therefore, A_1 is considered insignificant, or zero, and the second half of the general photosynthesis equation is dropped.

The function $f(n_0)$ describes the photosynthetic response behavior of a canopy under a given solar radiation intensity.

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To understand fully the photosynthesis equation, this function must be considered in some detail. The variable "n" may be regared as a "light saturation factor". It is computed from following factors: 1) the carbon dioxide resistance factor "a", 2) the maximum mid-day solar radiation intensity "I^*", 3) the parameter "b" which Monteith relates to the photochemical resistance of photosynthesis (cal/g), and 4) "s", the light passing through the first theoretical leaf layer without interception. The equation is given as:

$$n_0 = \{a(1-s)I^*-b\}/\{a(1-s)I^*+b\}$$

The variable n_0 as defined by this equation may vary between limits of -1 and +1. Monteith attaches biophysical meaning to this, explaining that as n approaches -1, carbon dioxide diffusion is limited by low irradiance conditions. It approaches a value of +1 at higher levels of irradiance when all leaves are assumed to become light saturated. A simple sensitivity analysis was performed on the model which confirmed that this relationship is expressed in the model (Figure 3).

The mathematical definition of the function $f(n_0)$ then depends upon the value of n , i.e. the computed light saturation conditions within the leaf canopy. This is summarized as follows:

when $0 < n_0 < 1$ (n_0 is positive), then

$$f(n_0) = (1/\pi)\{(1-n_0)/\sqrt{n_0}\}\ln\{(1+\sqrt{n_0})/(1-\sqrt{n_0})\}$$

when $-1 < n_0 < 0$ (n_0 is negative), then

$$f(n_0) = (2/\pi)\{(1-n_0)/(-n_0)^{-1}\}\tan^{-1}\left(\sqrt{|n_0|}\right)$$

when $n_0 = 0$, then

$$f(n_0) = 2/\pi$$

By referring back to the general photosynthesis equation, it can be seen that ha A is the maximum possible photosynthesis with theroretically unlimited radiation. The term $(1-f(n_0))$ is the efficiency with which available radiation is used, and is related to the length of time spent in saturated light conditions.
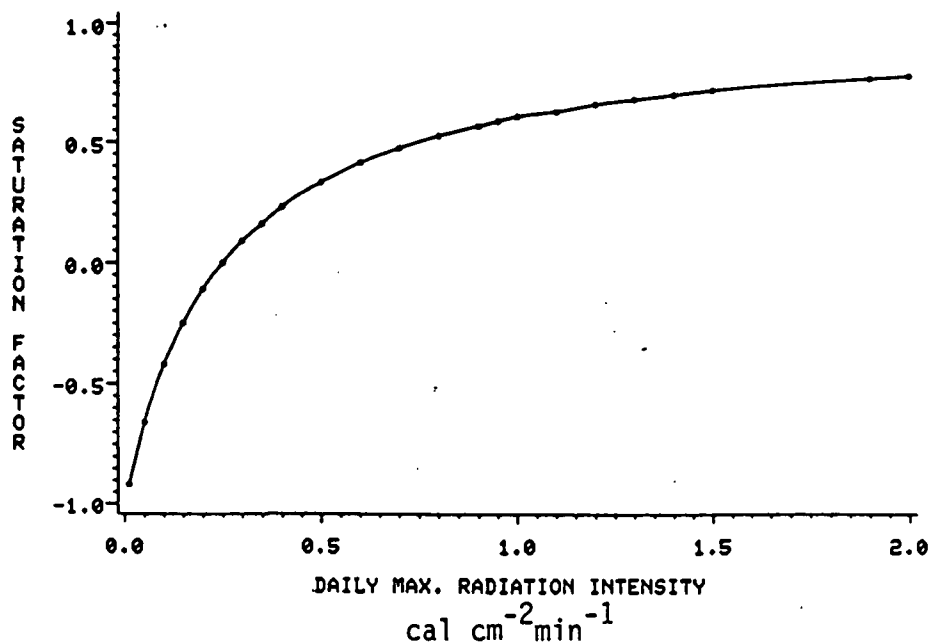
Figure 3. Relationship between daily maximum radiation intensity and saturation factor, n_0.

3.1.2 Determination of Model Variable Values

Each of the variables in the Monteith equation are listed
below. Data sources, or methodologies adopted to determine
their values, are explained.

1) h, daily duration of sunlight

The average monthly duration of sunlight was computed from
the following equation given by Sellers (1965),

$$\cos H = -\tan \alpha \tan \delta$$

where: H = half-day length
          α = latitude
          δ = solar declination

This equation requires known values of latitude and solar
declination. Latitude was determined from the known geographic
coordinates of the sample locations. Average monthly solar
declination values were calculated based upon daily values
reported in the 1982 and 1983 Astronomical Handbook, available
from the U.S. Government Printing Office.

2) s, fraction of light passing through a unit leaf layer
   without interception.

The value of this factor will vary according to the
density and structure of the leaf canopy. Monteith reports "s"
to vary between about 0.4 and 0.8 for the crop canopies he
evaluated. To simplify specification of this variable, the
median value of 0.6 was selected to represent "s" for all
canopies.

3) b, photochemical resistance (cal/g)

Monteith (1965) explains that the quotient b/I, where I is radiation intensity, may be considered to represent the photochemical resistance to photosynthesis. This is better understood by considering that if b is constant, an increase in the value of I results in a decrease in the quotient b/I. That is, b/I is inversely proportional to radiation intensity. As radiation intensity increases, the resistance to photosynthesis attributable to radiation intensity decreases. So, at high intensities, radiation becomes less significant in determining the rate of photosynthesis. At very low light intensities, b is inversely proportional to the quantum efficency. In effect, b describes the photosynthetic response of plants under non-saturated light conditions. Monteith cites the findings of Gaastra (1959), Hesketh and Musgrave (1962), and Hesketh and Moss (1963) which report b to be 0.5 cal/g regardless of plant species.

4) a, resistance to carbon dioxide absorption ($m^2 hr\ g^{-1}$)

Monteith (1963,1965) describes "a" as the resistance to carbon dioxide diffusion into the choroplasts, and has shown it to be proportional to the inverse of the maximum rate of photosynthesis under saturated light conditions. As this resistance value increases, carbon dioxide diffusion and photosynthesis decrease. For a constant radiation intensity, photosynthesis occurs at a rate largely dependent upon the temperature of the leaf and atmospheric concentration of carbon dioxide.

Knowledge of the photosynthetic response of a plant canopy to temperature under saturated light conditions enables the maximum potential photosynthesis to be determined for any given temperature. The value of "a" can thereby be determined, and this also provides a means by which to incorporate the controlling effects of temperature in the photosynthesis model.

Such an approach is feasible by referring to the work of Terjung (1976). Terjung generated a series of 20 sets of curves to represent the photosynthetic response to temperature under a full range of radiation intensity conditions. The 20 sets of curves are related to terrestrial regions of the earth based upon plant species composition and environmental variables. The map shown in Figure 4 depicts the North American regions. Numbers shown in the map correspond to different photosynthetic response curves determined by Terjung. The complete set of curves is shown in figure 5. The top curve in each set represents photosynthetic response to temperature under saturated light conditions. These top curves were incorporated into the model.

Terjung (1976) does not include mathematical descriptions of the photosynthetic response curves. In order to incorporate the relations expressed in the curves into the computer-based model, it was necessary to translate them from their analog form to a mathematical form. This was achieved by digitization of the curves on an Altek digitizing table with associated software, operated with a PRIME 550 minicomputer. The digitizing procedure generated a series of (x,y) coordinate pairs for each curve; these were then used as input to a non-

Figure 4. Distribution of Terjung's (1976) Photosynthetic Response Models within North America.
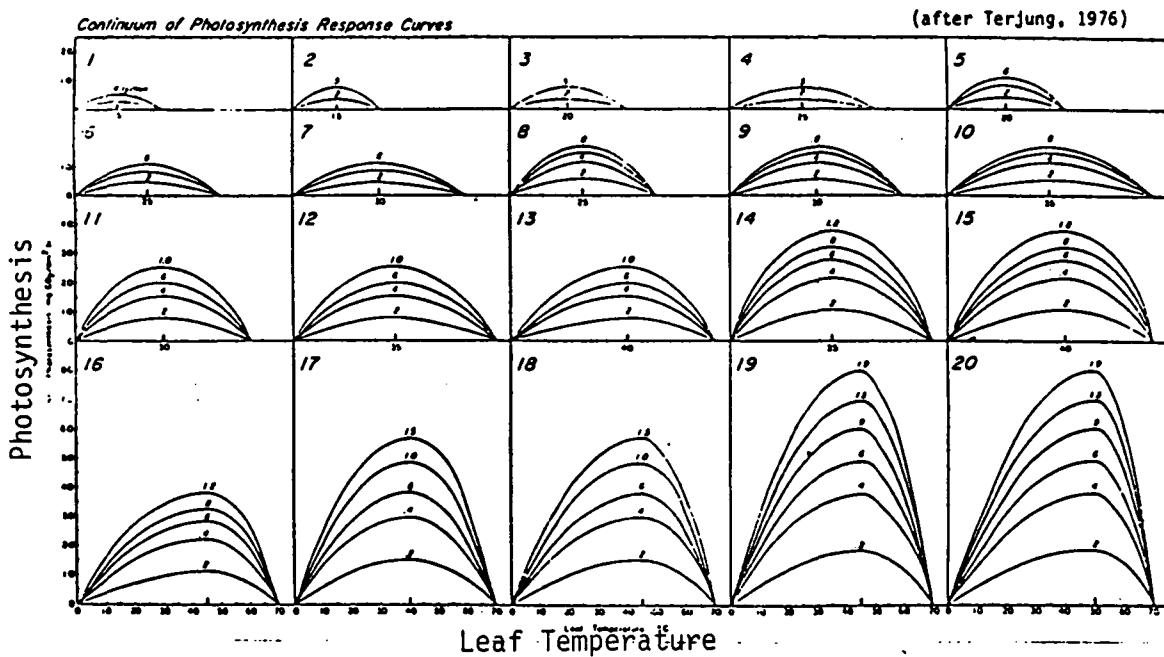
Figure 5. Photosynthetic response of vegetation to various intensities of radiation under varying temperature conditions. Top curve in each set represents light saturation.

linear regression routine in the SPSS statistical software.
For each set of coordinates, a single polynomial equation was
determined. These polynomials describe the curve of "best-fit"
passing through the sample points defined by the coordinate
pairs.

The scale of temperature values used in Terjung's graphs
are for the temperature of the leaf itself. Because it was not
possible to acquire actual leaf temperature measurements, it
was assumed that average leaf temperature is roughly equivalent
to the average ambient air temperature. This reasoning allows
use of readily available weather records as a source of the
temperature measurements required for the model.

5) A_0, intercepted photosynthetically active radiation

The linear equation describing the NDVI-IPAR relationship
developed by Hatfield, et al. (1984) enables the use of NDVI
data obtained from the AVHRR to estimate the percent of total
incoming photosynthetically active radiation intercepted by the
canopy. Assuming percent IPAR is directly proportional to the
area of leaves receiving radiation, it was substituted for A.

The equation presented by Hatfield et al. (1984) was
based on ground level measurements. In order to apply the
relationship to NDVI data obtained from the spaceborne AVHRR,
two adjustments were necessary. The atmosphere between the
ground and the sensor absorbs and scatters both direct and
ground-reflected solar radiation passing through it (Slater,
1980). Measurements made of the reflectivity of the earth's
surface from space therefore contain an added reflective

component. This phenomenon produces an apparent increase in
radiance from that which would be observed near the ground.
Holben and Fraser (1985) quantified the effect atmosphere has
upon NDVI values computed from NOHH-6 HVHRR measurements. For
a range of vegetation cover types and biomass amounts, the NDVI
was found to decline in magnitude with increased atmospheric
pathlength. Data generated from their investigation was used
to adjust the NDVI-IPHR relationship for atmospheric effects.
A second adjustment was made to the relationship by
incorporating sensor calibration data obtained for the NOHH-7
HVHRR prior to deployment (ITT, 1981). These data enables the
raw count data from the sensor to be properly adjusted to their
equivalent measures of radiance. Figure 6 shows the original
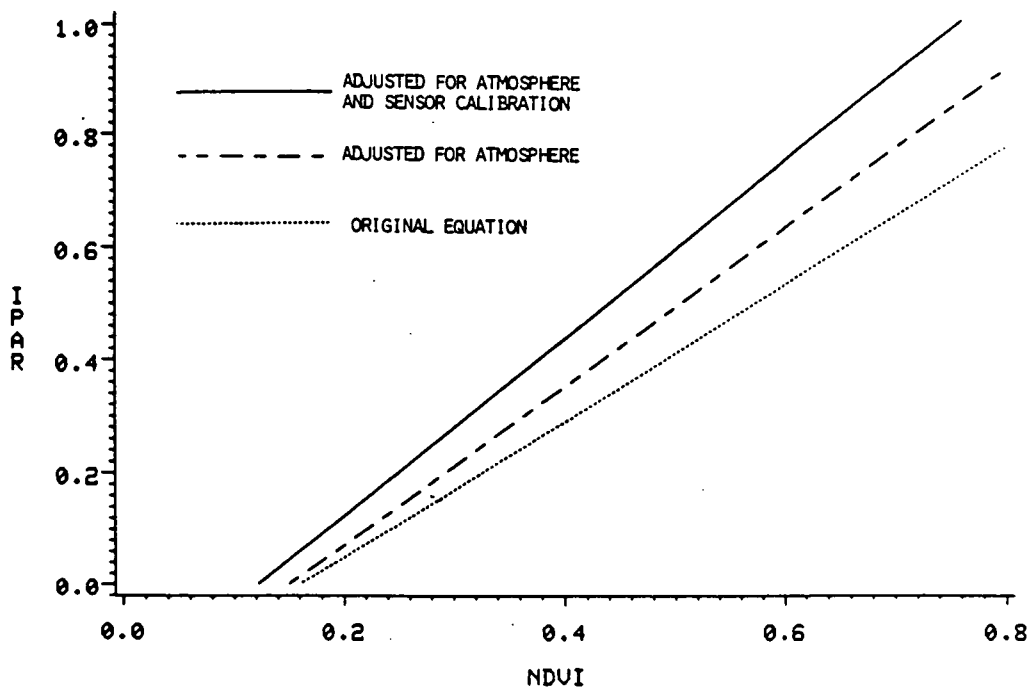
Figure 6. NDVI-IPHR relationship, original and corrected
forms.

NDVI-IPAR relationship from Hatfield et al. (1984), and the relationship after application of the corrections.

3.2 Respiration

Respiration is the process by which energy is made available to the plant to support its life and growth processes, such as cell reproduction and cell maintenance. In a basic sense, respiration is simply the reverse of photosynthesis: through the breakdown of carbohydrates, chemical energy is released while oxygen is consumed and carbon dioxide generated. Net primary production (NPP), then, is the gross primary production (GPP) less the carbohydrates used in respiration. This is commonly summarized by the following simple formula (Woodwell and Whittaker, 1968; Barbour et al., 1980),

$$NPP = GPP - RESP$$

Through an empirical investigation, Chang (1967) derived a general equation relating plant respiration to air temperature. Chang's equation is given as:

$$R = 7.825 + 1.145T$$

where:

R = percent of gross production consumed by respiration

T = temperature (^{o}C)

In this research, net photosynthesis was computed by reducing the estimated monthly gross photsynthesis by the amount determined from the respiration factor, R.

3.3 Moisture Availability

Water is a fundamental element in the photosynthetic process and is required to support plant life. In general, an adequate supply of water must be available in order for photosynthesis to proceed at its maximum potential rate under given conditions of temperature and radiation. A fundamental role of water in plant production is, of course, supply of the hydrogen molecules for creation of carbohydrates. In addition to the transfer of nutrients from the soil to plant, water helps perform the critical function of maintaining tolerable leaf temperatures for plant survival under variable radiation and heat conditions. Leaf temperature may be regulated in part through the heat conduction which occurs during the transpiration of water vapor from the plant surface (Gates, 1976).

When moisture is not sufficiently available to meet a plant's transpiration demands, the plant may experience a condition known as "moisture stress". One typical biophysical response of a plant experiencing moisture stress is to maximize water retention by minimizing its rate of water loss through transpiration. This is achieved by a reduction in the size of its stomatal openings (Larcher, 1965; Slatyr, 1963; Hsio, 1973). Stomatal closure creates a reduction in the area available for gas exhange, and this causes increased resistance to carbon dioxide intake from the atmosphere (Gaastra, 1959). Another associated response is a reduction in leaf turgor, such that leaves wilt and droop, thereby reducing the effective leaf

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area for radiation interception. The combined effect of the responses to moisture stress is an overall decrease in photosynthetic activity (Boyer, 1976).

Two assumptions have been made to address conditions in which photosynthesis occurs below the potential rate because of an inadequate moisture supply and moisture stress in the plant. The first defines the conditions under which moisture stress is considered to occur. The second defines how moisture stress reduces the actual photosynthesis from the potential photosynthesis estimated for conditions in which water is non-limiting.

Vegetation is considered to experience moisture stress whenever the actual rate of evapotranspiration is less than the potential rate. The logic supporting this is straightforward. When there is insufficient soil moisture present to satisfy the evaporative demands dictated by the climate conditions over a given period of time, then it is likely that plants in that environment also lack adequate soil moisture to satisfy transpiration demands under those same conditions.

It has been shown that, for fully vegetated and well-watered land surfaces, evapotranspiration occurs at the potential rate (Thornthwaite, 1948). For a fully vegetated land surface it is reasonable to believe that the greatest loss of soil moisture from the surface occurs through transpiration as opposed to evaporation. It therefore follows that because moisture stress inhibits photosynthesis, any reduction in the actual evapotranspiration (AE) from the potential rate (PE)

will be accompanied by a reduction in actual photosynthesis from its potential rate. It is assumed that reduction in actual photosynthesis from potential photosynthesis is directly proportional to the reduction of HE from PE. On this basis, the estimated potential NPP was reduced by the fraction determined by the ratio HE/PE to produce actual net NPP estimates.

Estimates of potential and actual photosynthesis were obtained using the monthly water budget equation developed by. Thornthwaite and Mather (1957). This method was chosen above other well-recognized methods for three major reasons. First, the Thornthwaite approach requires only measurements of temperature and precipitation. These data are readily available for a relatively large and spatially comprehensive network of stations across the North American continent. Other notable climatological approaches were considered, including Penman (1956), but the Thornthwaite and Mather technique was considered more suitable in terms of practicality. Second, it is well suited for long-term estimates, including monthly and annual periods (Pelton et al., 1960). This corresponds well with the temporal attributes of the available satellite and climate data. Third, the Thornthwaite equations were originially derived for fully-vegetated surfaces and this provides support for the previously stated assumptions with regard to evapotranspiration, moisture stress, and photosynthesis.

CHAPTER 4

METHODOLOGY

4.1 Advanced Very High Resolution Radiometer

Normalized-difference vegetation index (NDVI) data for use
in the photosynthesis model was obtained from daily
observations of the North American continent taken by the
Advanced Very High Resolution Radiometer (AVHRR) sensor aboard
the NOAA-7 meteorlogical satellite. The satellite data used in
this research were collected during the one year period between
April 1982 and March 1983. The AVHRR has a spatial resolution
of approximately 1.1 km at nadir (Kidwell, 1984). A scan angle
of ±56 degrees from nadir provides an observation area of 2,700
km across within each swath. A nine-day repeat cycle and the
wide swath width provide coverage of all areas of the globe on
a daily basis. Five spectral bands are recorded by the sensor,
including one in the visible wavelengths (0.55-0.68 μm) and one
in the near infrared portion of the spectrum (0.7-1.1 μm). The
NOAA-7 satellite is in a polar orbit and operates with a local
overpass time of 14:30 UCT (2:30 p.m. local time).

4.2 AVHRR Data Products

Data from the AVHRR were available from the National
Oceanic and Atmospheric Administration in several forms. HRPT
(High Resolution Picture Transmission) data were collected at
the full 1.1 km resolution of the sensor and directly

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transmitted to ground stations within receiving range. For a

requested portion of a single orbit, the 1.1 km data can be

recorded onboard the satellite for later transmission when a

ground station is within range. This data product is referred

to as LAC (Local Area Coverage). The 1.1 km measurements are

continuously sampled onboard for production of GAC (Global Area

Coverage) data. The sampling routine retains four out of every

five consecutive pixels along a row, and one out of every three

consecutive pixel lines. The mean of the pixels retained is

then used to represent the 3 x 5 pixel array. This provides a

ground resolution of about 4 kilometers at nadir for GAC data.

GAC data are produced on a daily basis for the entire surface

of the globe.

GVI (Global Vegetation Index) data are created from the

Channel 1 (visible) and Channel 2 (near-infrared) spectral

measurements contained in the daily GAC data set. The

Normalized Difference Vegetation Index (NDVI) is computed at

all pixel locations using the following equation:

$$NDVI = \frac{Ch. \ 2 - Ch. \ 1}{Ch. \ 2 + Ch. \ 1}$$

The NDVI data produced in this way from GAC data were mapped to

a grid in a polar sterographic projection. The spatial

resolution represented by the grid cells varies from about 15

km at the equator to about 30 km at the poles. From a seven-

day set of GAC data, a single, maximum NDVI value is selected

from those falling within each grid cell and retained to

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represent that grid cell. The procedure by which the NDVI
pixel is selected from each intra-cell array has varied, and is
summarized in the NOAA Vegetation Index User Note (NOAA, 1979).
GVI image data sets represent one-week time periods and provide
coverage of the entire world. GVI data have been produced
routinely by NOAA since April 1982.

4.3 Vegetation Index Composite Images

A single GVI image data set represents the maximum NDVI
values computed at each pixel location during a one-week period
of time. Because the source of the maximum values may
potentially be any one of the seven daily images, the images
created in this manner are generally referred to as "composite"
images.

The benefits obtained by producing composite images rather
than relying upon the daily obsevations can be understood by
considering the problems confronted when observing land areas
obscured by persistent cloudcover. At any given time,
atmospheric moisture in the form of visible or opaque clouds
obscure a substantial portion of the earth's surface as
observed from space. Therefore any satellite observations
covering a large area of the globe on a single date are likely
to have portions of the surface obscured because of intervening
cloudcover. However, because of the dynamic nature of the
atmospheric circulation system, the distribution of clouds
tends to continuously change, particularly in the middle
latitudes. This creates a situation in which any ground area
which is cloud covered on a given day, is likely to have

experienced cloudfree conditions during the one to six days which either immediately precede or follow.

The image compositing routine used in production of GVI data takes advantage of changing cloud-cover conditions thereby reducing the overall effects of clouds at all locations within an image. Pixels representing measurements taken under the most cloud-free conditions are automatically selected by this strategy. Because of the absorption and reflection characteristics of moisture in the visible and near-infrared portions of the spectrum, cloud observations will produce NDVI values consistently lower than either a vegetated landscape or bare soil (Knipling, 1970; Colwell, 1974; Jensen, 1983).

For this study, subimages of the North American continent were extracted from the weekly GVI image data sets. Using the image composite strategy outlined above, these images were further processed to produce NDVI composite images, representing the twelve calendar months from April 1982 to March 1983. Again, this further reduced cloud cover effects and also provided images which correspond directly in time with the monthly average climatological data used in the ecological model.

All image processing was performed with custom-designed software on a Hewlett Packard 1000 minicomputer and Ramtek color image display device. This computer system is part of the laboratory facilities which support the Global Inventory, Monitoring and Modelling Studies (GIMMS) in the Earth Resources Branch of the Laboratory for Terrestrial Physics at NASA-

figure 7. Monthly NUVI image composites of North America.
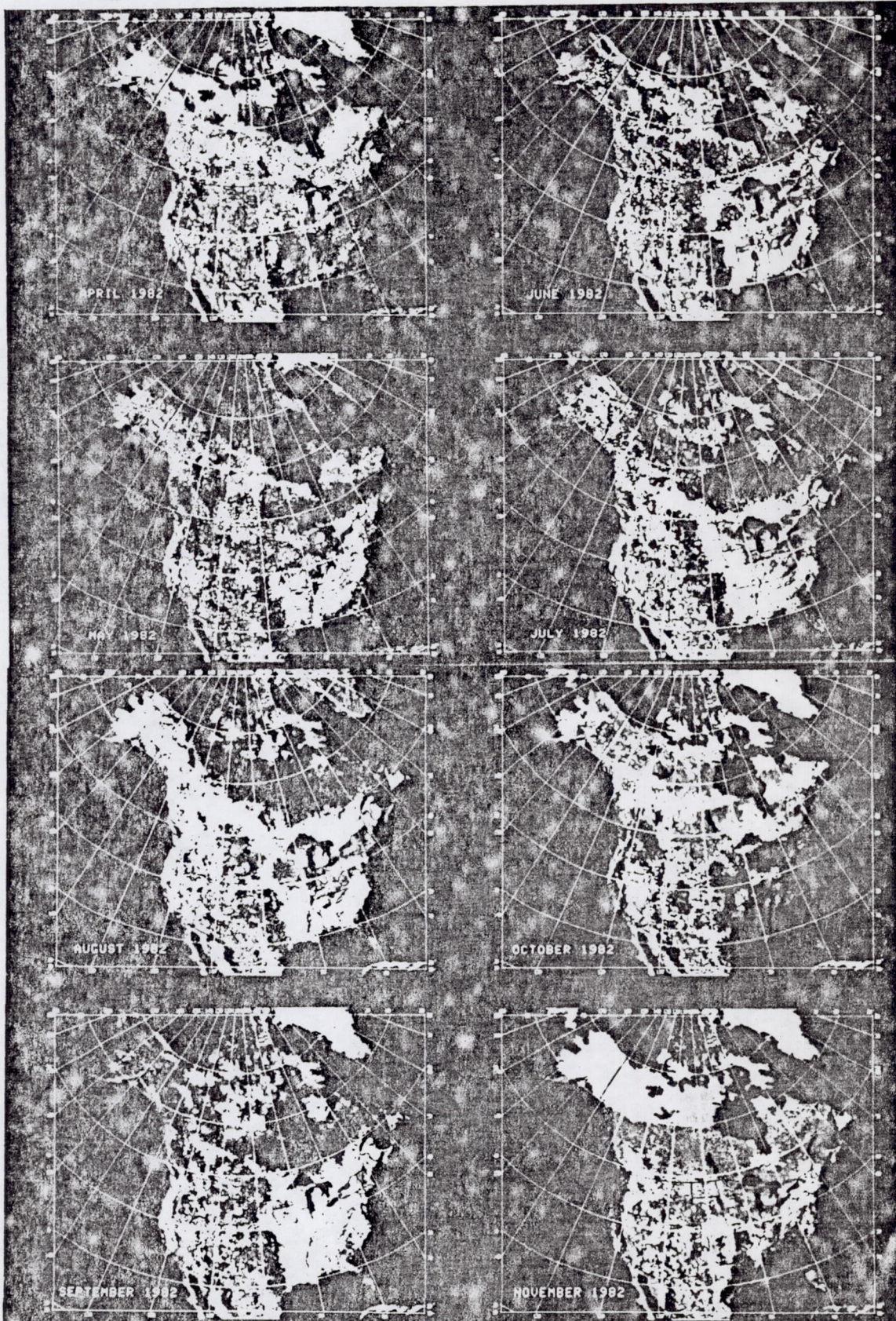
figure 7, cont.

DECEMBER 1982

FEBRUARY 1983

JANUARY 1983

MARCH 1983

0   0.2   0.4   0.6

NORMALIZED DIFFERENCE VEGETATION INDEX
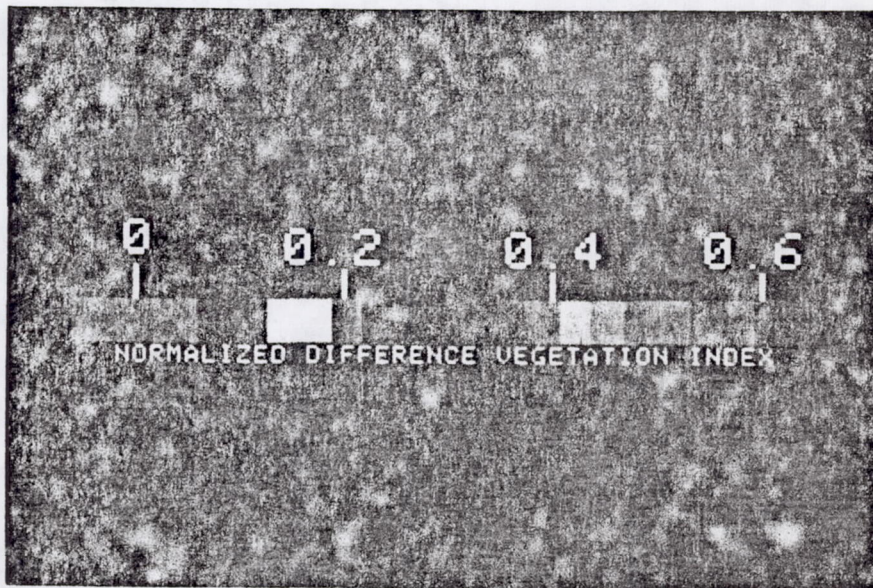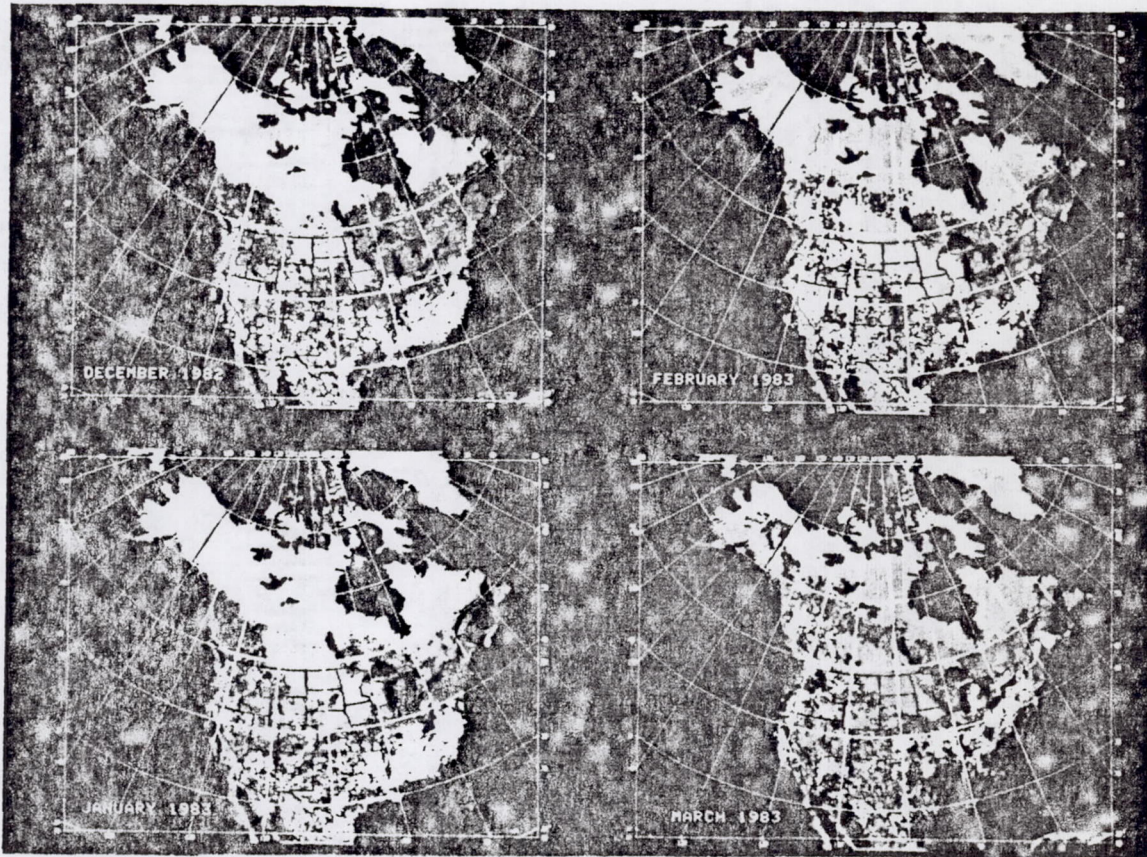
Goddard Space Flight Center, Greenbelt, Maryland.

The twelve monthly NDVI data sets used in this research are displayed in image form in figure 7. The color bar included in this figure defines approximately the scale of vegetation index values with which the image colors are associated. Simple visual interpretation of these images reveal a remarkable amount of information concerning the spatial and phenological patterns displayed by the vegetation across the continent. A more detailed discussion of this can be found in the study conducted by Goward et al., (1985).

4.3 Ecosystem Classification

In studying the patterns of vegetation productivity at a continental and global scale it is useful, at least in the current stages of research in this area, to refer to an existing type of vegetation classification scheme to provide a logical and practical division of the world's terrestrial vegetation. This assumes that the overwhelming diversity of individual vegetation types may be categorized and simplified in a manner appropriate to the scale of the study and thereby contribute to a manageable research design.

Biogeographers and plant ecologists have found it useful to group terrestrial vegetation into units or categories representing homogeneous characteristics in terms of species composition and/or environmental variables. These divisions of the biosphere are referred to as "plant formatations" when concern is restricted to vegetation, and "biomes" when considering all biota.

Previously published reports evaluating world vegetation productivity provide estimates associated with major biomes (Whittaker, 1970; Lieth, 1975; Whittaker and Likens, 1975) This study was also designed to estimate productivity at the biome scale, as opposed to the scale of individual plants or small communities. This is appropriate considering the 15 km spatial resolution of the GVI image data. Moreover, productivity estimates generated for biomes could be readily compared with published estimates for equivalent biome types which can serve as an initial standard by which to evaluate the performance of the model.

The species composition and density of terrestrial vegetation vary across the land surface by often subtle transitions in general response to variations in environmental conditions. Biomes do not exist as discrete entities; rarely is there one precise boundary at which one community type ends and another type begins. Rather, there usually exists a continuum of transition between two separate, relatively homogeneous vegetation regions. These transitional zones are referred to as ecoclines. These charateristics of vegetation distribution give rise to the present circumstance in which there is no single, authoritative map delineating separate biomes. Instead, several maps can be found, each of which may delineate biome boundaries in slightly or significantly different manners (e.g. Kuchler, 1966; Reichle, 1970; Udum, 1971; Robinson,1972; Daubenmire, 1978; Vankat, 1979; Walter, 1979; EPA, 1980; Olson and Watts, 1982).

The map of major North American biomes from Odum (1971)

was selected to serve as the basis for defining vegetation unit

boundaries in this research (Figure 8). This particular map

was chosen for the following reasons:

1. The biome types mapped correspond well with the those for
which productivity estimates can be found in the literature.

2. The source of the map is E.P. Udum's book "Fundamentals of
Ecology" (1975), a standard and widely-accepted text on
ecological concepts.

3. The map is displayed in a geographic projection which
closely resembles the projection in which the AVHRR images are
produced. This similarity facilitates visual comparison and
cross-referencing of information.

Figure 8. North American biomes (from Odum, 1971).

4.4 Selection of Data Sampling Locations

       Arrays of 3x3 pixels were systematically sampled at point

locations within the series of monthly NDVI composite images.

The mean values from these pixel arrays were computed and used

as input to the model. The full list of the sample stations

are found in Appendix A. The map in Figure 9 shows their

distribution throughout the continent. An effort was made to

draw as many samples as possible from locations distributed

throughout the area of each biome. This allowed productivity

estimates to be generated for each sample location, and the

resulting values averaged to produce a single value

representating the average productivity of the entire biome.

This approach was undertaken to minimize any sampling bias

occuring as a result of too few sampling stations and poor

representation of the productivity variation within the biomes.

       The major determinant in the selection of the sample

locations was the availability of the climatological

measurements required for the model. These data include

temperature and precipitation (for the water budget and

temperature controls on photosynthetic response) and incident

solar radiation data (for the plant canopy photosynthesis

model).

Figure 9. Distribution of data sample locations.
Letter-number identification corresponds to station
list in Appendix A.

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4.5   Sources of Environmental Data

Temperature and precipitation data in the form of monthly average values were acquired from the Monthly Climatic Data for the World (MCDW) 1982 and 1983 data sets. These data are produced by the NOHH National Climatic Data Center and are available in both printed and digital form. North America is represented by data recorded for approximately 117 locations throughout the United States and Canada, excluding the Mexican stations.

Solar radiation data for the months of concern in 1982 and 1983 were obtained from several sources, both published and unpublished. The majority of the radiation data for stations within Canada were obtained from the Monthly Radiation Summary, a publication of the Atmospheric Environment Service of the Canadian Government. Solar radiation measurements for two locations in the United States, Rockville and Barrow, are collected on a regular and ongoing basis by the Smithsonian Institution. These data are published periodically, although data for 1982 and 1983 were not in print at the time of this research. Data for these years were obtained through personal communication with Dr. B. Goldberg of the Smithsonian Radiation Laboratory in Rockville, Maryland.

The U.S. National Oceanic and Atmospheric Administration had in past years maintained a network of at least 35 solar radiation monitoring stations distributed throughout the United States. Data provided through this program were combined, edited, and published on a monthly basis. In what is a very

unfortunate circumstance for the scientific community, this progam of solar data collection is no longer fully supported and operated by NOHH. However, some data is still reported to NOHH, on an upredictable basis, and these are collected on microfiche in their unedited form. These data for the years 1982 and 1983 were evaluated for possible use in this research. It was concluded that the data was inadequate in terms of the consistancy with which it is available for any particular station and the acccuracy with which the measurements are reported. The generally poor dependability of the data is the apparent result of nonoperational, noncalibrated or miscalibrated sensors. Personal conversations with atmospheric scientists at the NOHH/National Climatic Center in Asheville, North Carolina, confirmed this conclusion.

Owing to the insufficient availability of solar radiation data for the time period of interest and inadequate distribution in the United States of the data which are available, an additional source of solar data was used. A set of monthly solar radiation data for stations throughout North America and the world, was compiled by Lof et al. (1966). These data represent long-term means (1 to 10 or more years) and were drawn upon to supplement available data.

Because meteorlogical conditions at any particular location through the course of a year are not necessarily repeated exactly in other years, the amount of solar radiation received at the location may can also be expected to fluctuate. Since radiation is an important factor in the photosynthesis model, the use of radiation data which represents long-term

trends rather than actual conditions in the 1982-1983 period

must be recognized as a potential source of error in the model.

CHAPTER 5

DESCRIPTIONS OF NORTH AMERICAN BIOMES

Although GVI data are available for all continents of the world, North America was selected as the study area for this research. One simple reason for the selection of North America is that it is familiar, in part from exposure gained through travel. It was reasoned that this familiarity would provide useful insights into the observed vegetation patterns. Such experience could not be drawn upon in the analysis of other less familiar regions of the globe. A second factor is the presence of an extensive network of climatological stations, a source of temperature, precipitation and solar radiation measurments required for the model. The other major continents were considered inadequate with regard to the distribution and availability of climatological data.

In this chapter, the vegetation of the twelve North American biomes evaluated in this research is described briefly with respect to dominant vegetation types and climate charateristics. Several sources were referred to in compiling these descriptions, namely Odum (1971), Robinson (1972), USDA (1980), Vankat (1979), Daubenmere (1978), and Barbour, et al. (1980).

5.1 Tundra

The tundra formation is found in the most northerly portions of the continent, at latitudes approaching and within the arctic region. At high latitudes, the length of daylight is zero or short during half of the year. Insolation and temperature are critical factors determining the nature of the tundra environment.

Low temperatures occur throughout the year in the tundra; the warmest month never exceeds $10\,^{\circ}C$. These temperature conditions support only a very short growing season, confined to about 2 to 9 weeks in mid-summer when daylength, insolation, and temperature are at there highest levels. Annual precipitation is also very low, averaging about 180 mm. The ground remains frozen except during the growing season, when the "active" (top) layer melts. Permafrost, a layer of permanently frozen soil beneath the surface layer, is a common characteristic of the tundra zone.

The vegetation types most commonly associated with the tundra formation are various species of lichens, grasses, sedges, and dwarf woody plants. The tundra vegetation is adapted to the extreme environmental conditions to which it is exposed. The vegetation grows close to the ground surface with minimal vertical extension. This is an apparent adaptation to microclimate, reducing exposure to strong, cold winds, and maximizing thermal efficiency.

According to figures reported in Lieth (1975) and Whittaker and Likens (1975), annual net primary productivity of the

tundra normally ranges between 100 and 400 g $m^{-2}yr^{-1}$. The
approximate mean annual value is 140 g $m^{-2}yr^{-1}$.

5.2 Tundra-Coniferous Forest Ecotone

The tundra-coniferous ecotone is a broad zone of
transition between the tundra and the coniferous forest to the
south. Environmental conditions in this zone vary across the
margin at which tree life can be sustained.

The tundra-coniferous ecotone begins in the area at which
the coniferous forest coverage begins to decline. It extends
northward as the increased open space between the trees becomes
occupied by tundra vegetation. The locations most supportive
of tree vegetation are in the south, or in low-lying,
topographically protected areas in the north. The coniferous
tree types most often found here are black spruce, white
spruce, balsam fir, and larch. As the severity of
environmental coniditions increased, dwarfed shrub-like species
become more prevalent. The most notable of the dwarf trees are
the krummholz spruce and dwarf birch. Lichens, mosses, and
sedges occupy the open spaces associated with higher latitudes
or rises in local topography, often in combination with exposed
rock or stones.

Annual net primary productivity of a tundra-coniferous
forest ecotone environment is reported in Rodin et al. (1975)
to be 500 g m^{-2} yr^{-1}. No data regarding the range of NPP values
were found in the literature for this biome. However, it is
assumed to vary between the mean values for Tundra
(140 g $m^{-2}yr^{-1}$) and Boreal Forest (800 g m^{-2} yr^{-1}).

5.3 Coniferous (Boreal) Forest

An extensive belt of coniferous forest stretchs across much of Canada and Alaska above 45 degrees N. latitude. This forest biome is also referred to as the boreal forest, or taiga.

The most common tree species found in the boreal forest are white and black spruce, balsam fir, jack pine, tamarack, alpine fir, and lodgepole pine.

Whittaker and Likens (1975) report the mean annual net primary productivity of the boreal forest to be 800 g $m^{-2}yr^{-1}$, with a normal range between 400 and 2000 g $m^{-2} yr^{-1}$.

5.4 Moist Coniferous Forest

The moist coniferous forest forms a dense canopy of evergreen vegetation along the mountainous west coast of North America from central California to Alaska. Because the region is adjacent to the Pacific Ocean, maritime conditions have a dominant influence upon the climate. Temperatures remain mild throughout the year, averaging between 2 and 10 ^{0}C annually. Precipitation in parts of this biome is the most abundant in North America, in the range of 750 to 3,800 mm per year. Maximum rainfall occurs during winter months.

The tree types most commonly found in the moist coniferous forest are Douglas-fir, western red cedar, western hemlock, grand fir, silver fir, Sitka spruce, and Alaska cedar.

Mean annual net primary productivity for the moist coniferous forest is repoted to be 1300 g $m^{-2} yr^{-1}$, with a normal

range between 600 and 2500 g m^{-2} yr^{-1} (Whittaker and Likens, 1975).

5.5 Coniferous-Deciduous Forest

The coniferous-deciduous ecotone is zone of transition between the taiga in the north and the Deciduous forest of the eastern United States. This ecotone is centered on southern Maine, northern New York, and northern Michigan, and extends northwest across northern Wisconsin and northeastern Minnesota.

The conifers which are dominant in the taiga, such as balsam fir, white spruce and red spruce, decline in abundance toward the south of the coniferous-deciduous ecotone. Conversely, hardwoods such as sugar maple, yellow birch, beech, paper birch and basswood increase toward the south. The result is a mixed forest of varying composition generally dependent upon latitudinal position within the ecotone.

A net primary productivity figure was not found in the literature for the coniferous-deciduous forest ecotone. Therefore, a value was assumed by taking the average of the mean annual NPP figures reported for the coniferous (boreal) forest and deciduous forest, since these are the biomes between which the ecotone exists. Mean annual NPP for these biomes are reported in Whittaker and Likens (1975) to be 800 g m^{-2} yr^{-1} and 1200 g m^{-2} yr^{-1}, respectivley. Therefore, the annual net primary productivity for the coniferous-deciduous ecotone is assumed to be 1000 g m^{-2} yr^{-1}.

5.6 Deciduous Forest

The deciduous forest, sometimes called temperate deciduous forest, covers much of the Eastern United States. The biome extends from the Appalacian Mountain region westward beyond the Mississippi Valley, and from the Great Lakes region southward as far southern Louisiana and Mississippi. Tall, broadleaf deciduous trees create a dense vegetative canopy during the summer growing season. These trees shed their leaves completely when dormant during the winter months.

The composition of tree types varies by region, but species commonly found throughout the formation include hickory and several varieties of oak. Beech and maple are widespread to the west, while sweet gum are common in the east.

Temperatures within the decicuous forest vary widely according to season, which are characterized by warm summers and cold winters. The average annual temperature is between about 5 and 15 degrees C. Precipitation occurs throughout the year, though maximum rainfall occurs during summer. The average annual precipitation is between about 900 and 1,500 mm.

The most recent estimates of net primary productivity found for the deciduous forest ecosystem are from Whittaker and Likens (1975). They report a mean annual NPP of 1200 g m^{-2} yr^{-1}, with a normal range between 600 and 2500 g m^{-2} yr^{-1}.

5.7 Oak-Pine Subclimax Forest

The oak-pine subclimax forest is a zone of transition
between the pine subclimax forest and deciduous forest. This
formation extends from the southern New Jersey and Chesapeake
Bay region along the eastern Appalacians and reaches well into
the the Southern states of Mississippi, Alabama, and Georgia.

The mean annual net primary productivity of the subclimax
oak-pine forest is reported in Whittaker (1970) to be 1060 g m^{-2}
yr^{-1}. No range of NPP values was reported for this biome.

5.8 Pine Subclimax Forest

The pine subclimax forest covers much of the extreme
southeastern portion of the United States. This region is
believed to have been originally a climax broad-leaved forest,
but has undergone transformation because of human interference
through cultivation and burning. Today various species of pine
are widespread, such as loblolly pine, shortleaf pine, and
slash pine. (Eyre, 1963; Robinson, 1972).

The regional climate is characterized by mild winters and
hot, humid summers. Average annual temperatures normally range
between about 15 and 20 ^{0}C. Annual precipitation is between
about 1,000 and 1,500 mm. Precipitation is distributed
throughout the year, usually with slight peaks in early spring
or midsummer.

An annual net primary productivity of 900 g m^{-2} yr^{-1} is
reported for pine subclimax forest in Whittaker (1970). This
figure agrees well with values of 875 and 991 g m^{-2} yr^{-1}

reported by Olson (1969).

5.9 Grassland

The interior of North America contains a vast area of grasslands as the natural vegetation type. The natural grassland areas extend from approximately 32 degrees N. in Texas to approximately 53 degrees N. in Canada, and from the central states of Iowa, Kansas and Oklahoma to the eastern slopes of the Rocky Mountains.

Grassland vegetation occurs where rainfall is inadequate to support forest vegetation, yet more abundant than in desert and scrub-woodland vegetation areas. Average annual precipitation is generally between about 250 and 760 mm. Three types of grassland are usually distinguished: "tall" , "mid" and "short" grasses. These vary from tall in the east to short in the west, in correspondence to the east-west precipitation gradient. Today, most of the natural grassland has been disturbed by grazing or completely replaced by cultivation. As Odum (1975) states, "no biome type has probably been abused to a greater degree by man" than the grasslands.

The mean annual net primary productivity of grassland is reported in both Lieth (1975) and Whittaker and Likens (1975) to be 600 g m yr , with a normal range of 200 to 1000 g m^{-2} yr^{-1} .

5.10 Agriculture

About 21 percent of the total land area in the United

States is in the form of irrigated or non-irrigated cropland

(CHSI, 1975). The figure for Canada is much smaller, as is

expected given the large fraction of land area at high

latitudes where climatic conditions are not suitable for

agriculture. A substantial portion of the natural vegetation

systems of the continent has been replaced by agricultural

systems, particularly in the areas where climate and topography

are most suitable for cultivation. The map displayed in Figure

10 represents the varying densities with which croplands are

distributed throughout the United States.

PRINCIPAL CROPLAND AREAS 1959

More than 60 per cent cropland

30 to 60 per cent cropland

Less than 30 per cent cropland

Land areas without cropland or with small scattered tracts

| 0 | 250 | 500 MILES |
| 0 | 400 | 800 KILOMETRES |
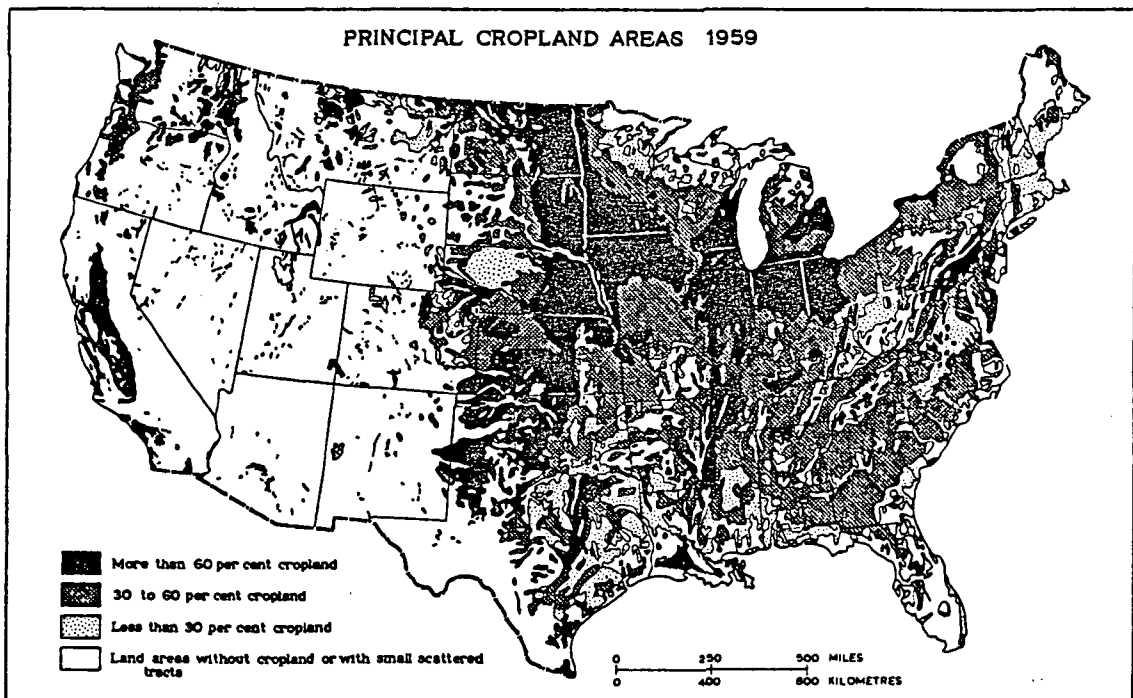
Figure 10. Distribution of cropland densities in the
United States in 1959. (Committee for World
Atlas of Agriculture, 1968)

There is tremendous diversity in the types of crops
produced in North America. However, there exists large
identifiable regions which are devoted to the production of
similiar crop types and share common cropping techniques. Most
notable is the cereal-producing region in the mid-west portion
of the continent, predominantly a non-irrigated agricultural
system.

The annual net primary productivity of cultivated
agricultural systems is reported to vary between 100 and 4000 g
$m^{-2} yr^{-1}$. The mean value is reported to be 650 g $m^{-2} yr^{-1}$
(Whittaker, 1970; Lieth,1975; Whittaker and Likens, 1975).

5.11   Scrub-Woodland

For the purposes of this research, the scrub-woodland is
more appropriately considered to be a category of combined low-
producing vegetation formations rather than a discrete
vegetation community type. Depending upon the region, the
scrub-woodland is dominated by shrubs, dwarf trees, or widely
spaced trees with interspersed shrubs. This includes sagebrush,
coastal chapparal, pinon-juniper, and interior chapparal. In
North America, these vegetation types are found in marginally
arid zones in western and southwestern United States.

The annual net primary figures reported by Lieth (1975) and
Whittaker and Likens (1975) for the woodland and shrubland
ecosystem type were used as a reference for this biome. These
reports estimate a mean annual NPP of 700 g $m^{-2} yr^{-1}$ and a
normal range of 250 to 1200 g $m^{-2} yr^{-1}$.

5.12 Desert

The desert areas of North America lie south and southwest of the Rocky Mountains. The basic climatic characteristics of this biome are extreme aridity and very high temperatures. Annual precipitation is less 200 mm. The average annual temperature is between about 15 and 25 ^{0}C).

Desert vegetation is generally sparse in abundance and distribution. Cacti and thorny shrubs may be prevalent. Areas with better moisture conditions support widely spaced shrubs such as creosote bush, sagebrush and mesquite.

Mean annual net primary productivity for the desert and semidesert scrub biomes is reported to be 90 g m^{-2} yr^{-1}, with a normal range between 10 and 250 g m^{-2} yr^{-1} (Whittaker and Likens, 1975).

CHAPTER 6

RESULTS AND DISCUSSION

The mean and range values of the model-generated estimates of annual net primary productivity for the twelve North American biomes evaluated are contained in Table 1. The NPP figures reported in the literature are included in the table for comparison. The model results for each of the sample locations are summarized individually in Appendix B.

Because the reported figures of NPP are used in this research as a standard against which to evaluate the performance of the model, it is wise to give first consideration to the accuracy of these values. The mean and range values given in Table 1 were originally derived from compilations of NPP estimates from a diversity of sources (references in Chapter 5). As mentioned in Chapter 2, the NPP measurements have at best an error margin of +/- 10 percent, regardless of the method used. Compounding any measurement error associated with the reported figures is the fact that the original measurements are representative of very specific field sites, and probably single, limited time periods, as well. Given the spatial variability of vegetation composition and density which may exist within any biome, it is logical to question whether or not these measures are truly representative of average production characteristics over a larger areas and over different time periods. It is therefore recognized that

the reported figures are not to be considered completely
reliable, and should be considered with some skepticism.
Without a means by which to obtain reliable verification of
average NPP at the biome scale, it can be argued that it is not
feasable to determine exactly which is more correct in which
cases, the reported figures or the model estimates, if either.
Nevertheless, the reported figures provide the only practical
means by which evaluate the results from the model, but they
should be considered with the above-mentioned cautions in mind.

The estimated NPP values have been plotted against the
reported NPP figures for corresponding biome. This graph is
displayed in Figure 11. If all the model-generated estimates
exactly equalled the reported figures for each biome, the
points plotted would lie along a single straight line with a
slope of 1. The vertical distance at which a point lies away
from this line is a measure of the magnitude of estimation
error for that particular biome. This line is included in the
graph, and is a useful reference for evaluating the performance
of the model in estimating NPP for individual biomes.

Figure 11 shows that the model consistently underestimates
NPP for the biomes. Correlation of the 12 pairs of NPP values
produces a correlation coefficient (R) of .85. Although the
correlation coefficent provides no evaluation of the closeness
to which the estimated and reported numbers agree in actual
value, it does indicate that the model-generated estimates to a
significant extent maintain the same relative differences in
magnitude of NPP between the various biomes as those exhibited
by the reported NPP figures.

Table 1. Biome Types, number of sample locations representing each biome, reported and model-estimated values of the mean and range in annual NPP.

Biome Type	No. Samples	Rep. NPP	Reported Range	Est. NPP	Estimated Range
			$g\ m^{-2}yr^{-1}$		
Tundra	5	140	100-400	23	0-70
Tundra-Coniferous Ecotone	8	500	140-800	261	98-538
Coniferous (Boreal) Forest	5	800	400-2000	573	269-774
Moist Coniferous Forest	5	1300	600-2500	592	421-882
Coniferous-Deciduous Ecotone	5	1000	*	752	678-798
Deciduous Forest	2	1200	600-2500	696	524-867
Oak-Pine Subclimax Forest	2	1060	*	822	786-858
Pine Subclimax Forest	1	900	*	879	---
Grassland	4	600	200-1000	551	348-835
Agriculture	5	650	100-4000	435	243-592
Scrub-Woodland	4	700	250-1200	309	127-566
Desert	2	90	10-250	68	7-129

*data not available
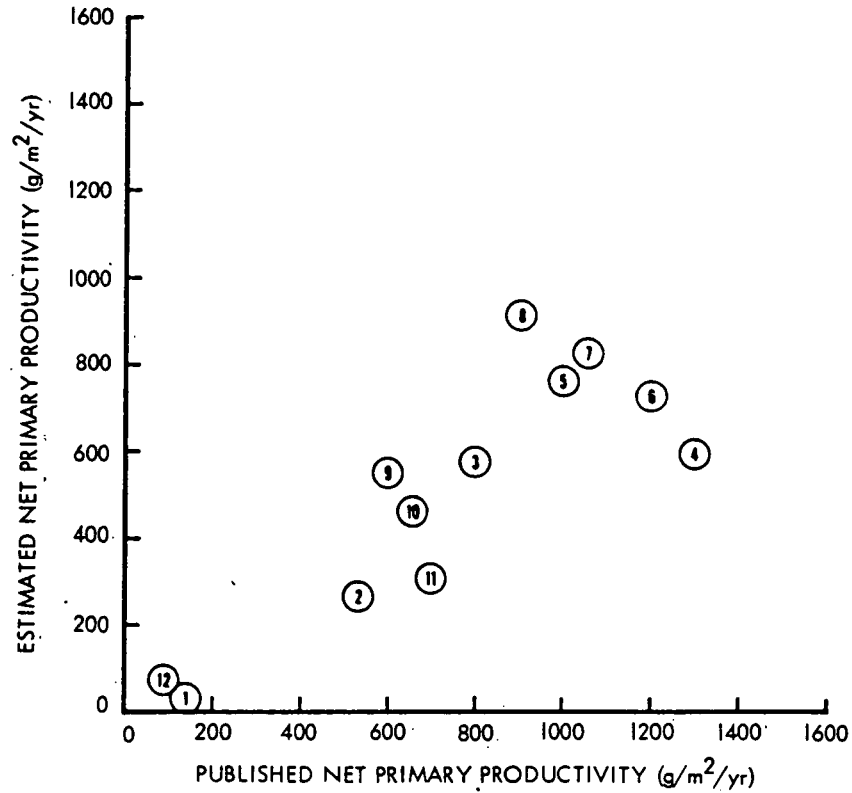
Figure 11. Relationship between reported and model-estimated
net primary productivity.

Several factors may be considered to account for the
inaccuracies of the model. Some of these factors are directly
related to simplifications or generalizations inherent in the
model, and others are related to the reliability of the various
data involved.

The first factor to consider is the success of

the data sampling strategy. The number of sample stations for each biome varied from only one station for pine subclimax forest, to as many as eight for the tundra-coniferous forest ecotone (Table 1, Appendix H). Poor representation of the spatial variability of productivity which may exist within the biome regions could possibly produce biased results.

Because the model was constructed for general application across a variety of plant environments, it addresses only the most fundamental and universal factors governing plant growth. Therefore, the unique eco-physiological attributes of any single biome may not be properly accounted for at the level of generalization in which the model operates. This circumstance may, for instance, contribute to error associated with the NPP estimate for the Moist Coniferous Forest. According to Waring and Franklin (1979), the evergreen trees in this environment may have a higher proportion of photosynthesis occur outside of the summer "growing season". This was not observed to be the case in the results generated by the model for this biome.

Plants in warm, arid environments often have specific physiological adaptations, such as crussulacean acid metabolism (CAM) photosynthesis systems or deep, widespread root systems, which enable them to survive exposure to high temperature and low moisture conditions. The model was not designed to account for these adaptations, and therefore, may incorrectly calculate moisture stress in the vegetation. This is one possible explanation for low NPP estimates for the desert and scrub-woodland biomes.

The accuracy with which the Terjung photosynthetic
response curves describe the actual behavior of each of the
plant environments cannot be overlooked as a source of error.
Because they have been derived from empirical data representing
a limited number of sites, and then extrapolated to represent
entire regions (Figure 4), a large chance of error may be
expected.

Two broad generalizations concerning the structural and
spatial characteristics of the biome vegetation were made, and
these should be considered as additional sources of error. As
explained in Chapter 3, a constant value of 0.6 was used in the
photosynthesis model to represent the structure of the
vegetation canopy (variable "s") for all biomes. There is
great variation in the architecture of the biomes. For
instance, leaves in a deciduous forest canopy are generally
horizontal in relation to the incident rays of sunlight. This
leaf orientation would produce a smaller value for "s" than
that appropriate for desert, or scrub-woodland. In these
biomes, leaves may be oriented less horizontally so as to
minimize exposure to extreme radiation intensities. A single,
constant value cannot be expected to represent correctly all
types of plant canopies.

The second generalization was made with regard to the
ground coverage of the vegetation. For sound application of
the Thornthwaite procedure in estimating PE and AE, it was
necessary to assume that the ground is fully vegetated. This
is not always so in all the biomes, particulary desert, tundra, a
scrub-woodland. The evapotranspiration estimates, and

therefore the moisture stress corrections, may in these cases be innappropriate. Moreover, many vegetation types have root systems which supply adequate moisture to the plant for transpiration during periods when the soil surface may be relatively dry. In such cases, the moisture stress computed from AE/PE would be innappropriately high. This could in part account for low estimates of NPP observed in the model results.

The assumption that photosynthesis which occurs from light energy which is transmitted through leaves is another possible reason for consistently low NPP estimates from the model. In dense vegetation environments, much of the understory photosynthesis must occur with transmitted light, and this portion of the total canopy photosynthesis is not represented in the NPP estimates from the model.

In the case of the tundra and tundra-coniferous forest ecotone biomes, an additional factor can be identified as contributing to underestimation. Lichens are a significant and often dominant part of the vegetation landscape in these biomes. Measurements of the spectral reflectance of a variety of subarctic lichens were collected in the field by Goward et al. (1985). Their data revealed patterns of reflectance in the visible wavelengths which differ distinctly from the typical reflectance pattern of green leaf vegetation. In general, lichens appear to absorb less radiation in the visible part of the spectrum, particulary red light, than do green leaf vegetation. This spectral characteristic of lichens may

produce misleading results, because, an NDVI value computed from lichen reflectances would be lower than what might be expected for the amount of photosynthetically active biomass present. The NPP estimates from the model would be low accordingly.

Another possible explanation for the model's tendency to understimate NPP lies in the fact that much of the vegetation of the continent is not in a natural state. From the vantage provided by an aircraft, one can observe clearly the widespread extent to which human activities have caused disturbance to natural vegetation systems. In the Oak-Pine forest of the Eastern United States, for instance, one would observe that the natural vegetation cover is not continuous nor necessarily dominant. Rather, agricultural fields, urban and suburban settlements, and roads compose a significant portion of the landscape. Since the satellite data samples used in this investigation represent areas on the ground of at least 2025 km (3x3 pixel array, maximum 15 km resolution), then it is expected that observations made in the highly settled regions of the continent represent disturbed, not natural vegetation. Areas of naturally high vegetation productivity which have been disturbed and replaced by less productive or non-productive elements can be assumed to exhibit a decreased productivity compared to that of its natural state. The NPP figures reported in the literature are associated with pure, homogeneous stands of biome vegetation. Thus, NPP estimates derived from observations of disturbed environments would be lower than the reported figures for similar biomes. The

obvious exception to this is when irrigated agriculture is introduced into areas which have a naturally low vegetation productivity, such as the desert and scrub-woodland biomes.

With the exception of the long-term average solar radiation data for a limited number of stations, the NPP estimates from the model were produced using data which represent a single, specific 12 month period in 1982 and 1983. Because meteorlogical conditions through the course of a year may not be replicated exactly from one year to the next, the productivity of vegetation at any given location may be expected to fluctuate with these interannual variations. This variation could then be represented in the NPP estimates from the model. This is one other factor which can help account for differences between the reported and model estimated values.

CHAPTER 7

CONCLUSIONS

Notwithstanding possible estimation errors associated with any eco-physiological generalizations or oversights, the basic results obtained from this modelling effort are positive and encouraging. The estimated values exhibit sensitivity to NPP of the biomes in relation to one another. Pending more detailed consideration of the model assumptions and parameters, the results of this research suggest potential for further improvement of a remote sensing/ecological modelling approach to the estimation of terrestrial vegetation on continental and global scales. The major difficulty faced with the ecological model was specification of the various parameters required. The difficulties and errors associated with attempts to quantify such a wide variety of variables can be expected to continue to be a major problem in this approach. This circumstance provides reason to consider whether there exists a simpler modelling approach which requires fewer variables, and therefore involves fewer sources of error.

A key element in this research is the NDVI-IPAR relationship since it provides the scientific basis for use of satellite observations. Based on preliminary results of an investigation begun near the completion of this research, it appears that the relationship between the NDVI and IPAR alone may provide significant information on vegetation productivity.

The NDVI measurements from any given time represent an
integrated response of vegetation to all factors determining
vegetation growth.   Attempts to account for environmental
factors such as moisture stress may actually be "double
counting" the effects already represented in the NDVI.

On the basis of concepts and equations presented by
Monteith (1981), the integrated amount of "effective" PAR
intercepted by a plant canopy was estimated from the same NDVI
data used in the ecological model. Effective IPAR is that
portion of the total intercepted radiation which is at or below
the light saturation intensity of the plant. It is a measure
of the amount of incident radiation which can be utilized for
photosynthesis. With knowledge of the quantum efficiency of
photosynthesis, this can be directly converted to units of dry
matter production. A strong relationship (correlation
coefficient of .92) was found to exist between annual
integrals of effective IPAR and reported annual NPP figures
(figure 12).

The effective IPAR estimates alone, then, may provide a
more simplified and manageable approach to evaluating net
primary productivity of vegetation and should be investigated
further. To support this, a strengthening of the theoretical
foundations is needed for research in this area. This can, in
part, be achieved through an improved and experimentally
supported understanding of the NDVI-IPAR relationship for all
types of vegetation canopies.

This research has demonstrated that course spatial
resolution spectral satellite data from the AVHRR holds promise
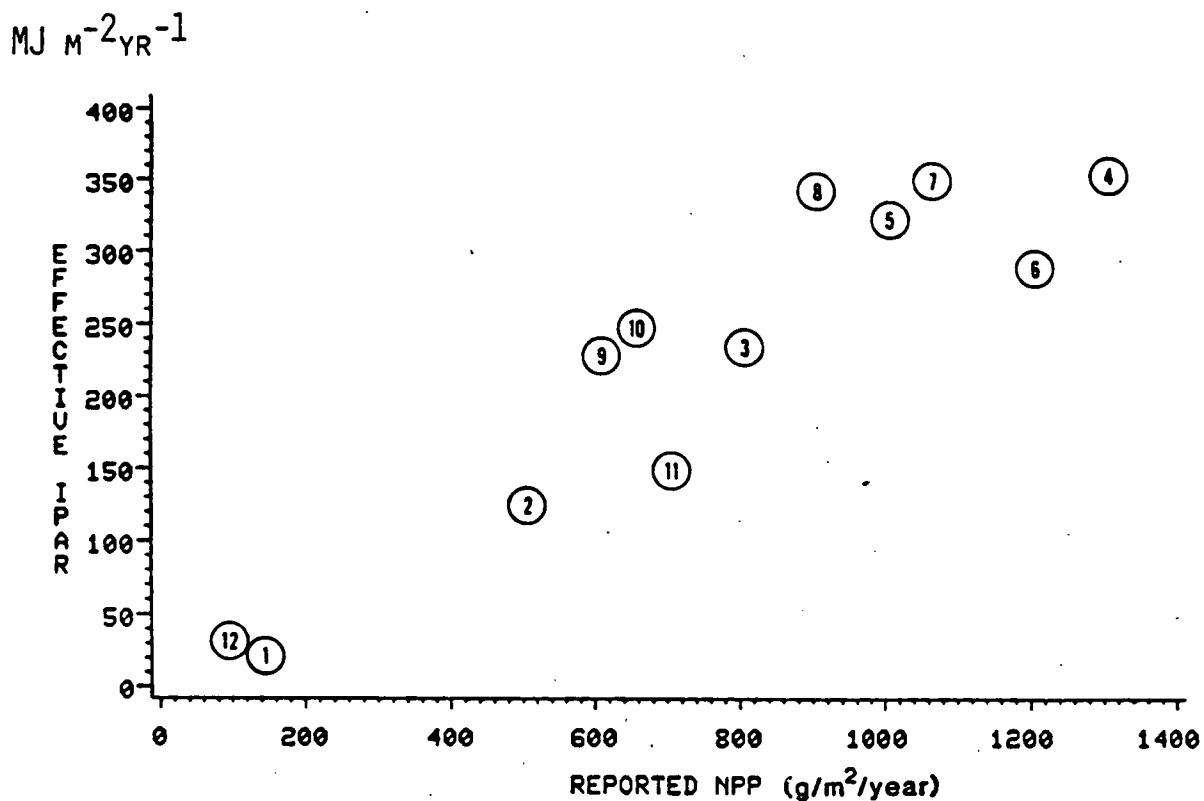
MJ M^{-2}YR^{-1}

① TUNDRA   ⑦ OAK-PINE SUBCLIMAX
② TUNDRA-CONIFEROUS ECOTONE   ⑧ PINE SUBCLIMAX
③ BOREAL CONIFEROUS   ⑨ GRASSLAND
④ TEMPERATE MOIST CONIFEROUS   ⑩ CULTIVATED
⑤ CONIFEROUS-DECIDIOUS ECOTONE   ⑪ WOODLAND & SCRUB
⑥ DECIDIOUS   ⑫ DESERT

Figure 12. Relationship between annual integral of effective
IPAR and reported NPP for North American biomes.

as a source of information on net primary productivity of

vegetation at the biome scale. Although the ecological model

developed and evaluated in this research consistently

underestimates NPP in comparison to reported figures, several potential sources contributing to the innaccuracies of the have been identified. If such errors are minimized and more consideration is given to unique eco-physiological charateristics of the biomes, then improved results might be realized using an ecological modelling approach. The NDVI-IPHR relationship should be further evaluated to better understand its information content and utility with regard to estimating, monitoring and modelling vegetation net primary productivity.

On the basis of this research and other continental vegetation studies currently underway involving AVHRR data, further refinements and improved results may be expected over the next several years. The fields of biogeography and global plant ecology appear now to be on the threshold of a new era in research and understanding of the distribution and functioning of terrestrial vegetation on the planet.

APPENDIX A

LIST OF BIOME SAMPLE STATIONS

AND THEIR GEOGRAPHIC LOCATIONS

A. Tundra

1.	Cambridge Bay	69.06N	105.07W
2.	Hall Beach	68.47N	81.15W
3.	Baker Lake	64.18N	96.00W
4.	Frobisher Bay	63.45N	68.33W
5.	Barrow	71.18N	156.47W

B. Tundra-Conifer Ecotone

1.	Inuvik	66.18N	133.29W
2.	Norman Wells	65.17N	110.22W
3.	Whitehorse	60.43N	135.04W
4.	Churchill	58.45N	94.04W
5.	Nitchequon	53.12N	70.54W
6.	Moosenee	51.16N	80.39W
7.	Goose	53.19N	60.25W
8.	Trout Lake	53.50N	89.52W

C. Coniferous (Boreal) Forest

1.	Fort Smith	60.01N	111.58W
2.	Prince George	53.53N	122.40W
3.	Kapukasing	49.25N	82.28W
4.	Sept-Isles	50.13N	66.16W
5.	Rapid City	44.03N	103.04W

D. Moist Coniferous Forest

1.	Sandspit	53.15N	131.49W
2.	Port Hardy	50.41N	127.22W
3.	Vancouver	49.15N	123.15W
4.	Olympia	46.58N	122.54W
5.	Medford	42.22N	122.52W

E. Coniferous-Deciduous Forest Ecotone

1.	Toronto	43.41N	79.38W
2.	Montreal	45.28N	73.35W
3.	Sault Ste. Marie	46.31N	84.20W
4.	Caribou	46.52N	68.01W
5.	Boston	42.22N	71.02W

F. Deciduous Forest

1.	New York	40.46N	73.54W
2.	Little Rock	34.50N	92.14W

G. Oak-Pine Forest Subclimax

1.	Atlanta	33.39N	84.26W
2.	Rockville	39.10N	77.10W

H. Pine Subclimax

    1. Charleston   32.54N   80.02W

I. Grassland

    1. Bismarck   46.46N 100.45W
    2. Great Falls   47.29N 111.22W
    3. Oklahoma City   35.24N   97.36W
    4. San Antonio   29.25N   98.30W

J. Agriculture

    1. Edmonton   53.34N 113.31W
    2. Winnepeg   49.54N   97.14W
    3. Lethbridge   49.38N 112.48W
    4. Spokane   47.38N 117.32W
    5. Boise   43.34N 116.13W

K. Scrub Woodland

    1. Grand Junction   39.07N 108.32W
    2. Albuquerque   35.03N 106.37W
    3. Ely   39.17N 114.51W
    4. Salt Lake City   40.46N 111.58W

L. Desert

    1. Las Vegas   36.05N 115.10W
    2. El Paso   31.48N 106.24W

APPENDIX B

SUMMARIES OF MODEL RESULTS

FOR INDIVIDUAL SAMPLE LOCATIONS

SUMMARY OF RESULTS FOR SITE CAMBRIDGE BAY
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.00	0.00
MAY 1982	0.00	0.00	0.00
JUN 1982	0.00	0.86	0.00
JUL 1982	0.00	0.60	0.00
AUG 1982	20.94	0.42	8.82
SEP 1982	0.00	0.00	0.00
OCT 1982	0.00	0.00	0.00
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
	20.94		

Annual Total Estimated Net Photosynthesis= 8.82

SUMMARY OF RESULTS FOR SITE HALL BEACH
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.00	0.00
MAY 1982	0.00	0.00	0.00
JUN 1982	0.00	1.00	0.00
JUL 1982	0.00	0.55	0.00
AUG 1982	0.00	0.48	0.00
SEP 1982	0.00	0.00	0.00
OCT 1982	0.00	0.00	0.00
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
	0.00		

Annual Total Estimated Net Photosynthesis= 0.00

SUMMARY OF RESULTS FOR SITE BAKER LAKE
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.00	0.00
MAY 1982	0.00	0.00	0.00
JUN 1982	0.00	0.79	0.00
JUL 1982	27.11	0.64	17.34
AUG 1982	71.32	0.55	39.05
SEP 1982	13.97	1.00	13.97
OCT 1982	0.00	0.00	0.00
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
	112.40		

Annual Total Estimated Net Photosynthesis= 70.36

TUNDRH, cont.

SUMMARY OF RESULTS FOR SITE FROBISHER BAY

(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.00	0.00
MAY 1982	0.00	0.00	0.00
JUN 1982	0.00	0.84	0.00
JUL 1982	0.00	0.92	0.00
AUG 1982	27.61	0.68	18.83
SEP 1982	0.00	0.00	0.00
OCT 1982	0.00	0.00	0.00
NCV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
	27.61		

Annual Total Estimated Net Photosynthesis=   18.83

SUMMARY OF RESULTS FOR SITE BARROW

(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.00	0.00
MAY 1982	0.00	0.00	0.00
JUN 1982	0.00	0.86	0.00
JUL 1982	0.00	0.87	0.00
AUG 1982	16.96	0.97	16.39
SEP 1982	0.00	0.00	0.00
OCT 1982	0.00	0.00	0.00
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
	16.96		

Annual Total Estimated Net Photosynthesis=   16.39

SUMMARY OF RESULTS FOR SITE INUVIK
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.00	0.00
MAY 1982	0.00	0.00	0.00
JUN 1982	98.89	0.77	76.46
JUL 1982	105.49	0.35	36.46
AUG 1982	108.27	0.48	51.43
SEP 1982	31.93	0.48	15.41
OCT 1982	0.00	0.00	0.00
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
	344.57		

Annual Total Estimated Net Photosynthesis= 179.76

SUMMARY OF RESULTS FOR SITE NORMAN WELLS
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.00	0.00
MAY 1982	0.00	1.00	0.00
JUN 1982	0.00	0.80	0.00
JUL 1982	54.97	0.60	33.22
AUG 1982	68.75	0.66	45.71
SEP 1982	31.90	0.58	18.62
OCT 1982	0.00	0.00	0.00
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
	155.62		

Annual Total Estimated Net Photosynthesis= 97.55

SUMMARY OF RESULTS FOR SITE WHITEHORSE
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.00	0.00
MAY 1982	0.00	0.56	0.00
JUN 1982	76.85	0.28	21.30
JUL 1982	140.92	0.32	45.13
AUG 1982	137.33	0.64	88.15
SEP 1982	44.63	0.63	28.01
OCT 1982	0.00	0.00	0.00
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
	399.72		

Annual Total Estimated Net Photosynthesis= 182.59

SUMMARY OF RESULTS FOR SITE CHURCHILL
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.00	0.00
MAY 1982	0.00	1.00	0.00
JUN 1982	0.00	1.00	0.00
JUL 1982	12.42	0.99	12.25
AUG 1982	80.50	0.89	71.89
SEP 1982	23.21	1.00	23.21
OCT 1982	0.00	1.00	0.00
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
	116.12		

Annual Total Estimated Net Photosynthesis= 107.35

SUMMARY OF RESULTS FOR SITE NITCHEQUON
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.00	0.00
MAY 1982	0.00	1.00	0.00
JUN 1982	51.80	1.00	51.80
JUL 1982	71.24	1.00	71.24
AUG 1982	57.03	1.00	57.03
SEP 1982	55.98	1.00	55.98
OCT 1982	2.94	1.00	2.94
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
	238.99		

Annual Total Estimated Net Photosynthesis= 238.99

SUMMARY OF RESULTS FOR SITE MOOSENEE
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.00	0.00
MAY 1982	49.57	0.98	48.35
JUN 1982	81.87	0.99	81.16
JUL 1982	167.79	1.00	167.79
AUG 1982	140.94	1.00	140.94
SEP 1982	78.16	1.00	78.16
OCT 1982	21.59	1.00	21.59
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
	539.92		

Annual Total Estimated Net Photosynthesis= 537.99

SUMMARY OF RESULTS FOR SITE GOOSE
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.00	0.00
MAY 1982	0.00	1.00	0.00
JUN 1982	72.65	1.00	72.65
JUL 1982	99.58	0.98	97.62
AUG 1982	111.66	1.00	111.66
SEP 1982	61.68	1.00	61.68
OCT 1982	3.51	1.00	3.51
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
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	349.08		

Annual Total Estimated Net Photosynthesis= 347.11

SUMMARY OF RESULTS FOR SITE TROUT LAKE
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.00	0.00
MAY 1982	51.24	0.94	47.97
JUN 1982	34.33	1.00	34.33
JUL 1982	139.76	1.00	139.76
AUG 1982	119.01	1.00	119.01
SEP 1982	55.02	0.95	52.27
OCT 1982	0.00	1.00	0.00
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
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	399.36		

Annual Total Estimated Net Photosynthesis= 393.34

SUMMARY OF RESULTS FOR SITE FORT SMITH

(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.00	0.00
MAY 1982	12.45	0.97	12.08
JUN 1982	113.81	0.49	56.22
JUL 1982	164.71	0.47	77.79
AUG 1982	147.98	0.46	68.18
SEP 1982	55.05	1.00	55.05
OCT 1982	0.00	1.00	0.00
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
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	494.00		

Annual Total Estimated Net Photosynthesis= 269.32

SUMMARY OF RESULTS FOR SITE PRINCE GEORGE

(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	1.00	0.00
MAY 1982	86.71	1.00	86.71
JUN 1982	222.16	0.42	92.60
JUL 1982	227.44	1.00	227.44
AUG 1982	214.00	1.00	214.00
SEP 1982	128.34	1.00	128.34
OCT 1982	24.66	1.00	24.66
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.35	1.00	0.35
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	903.65		

Annual Total Estimated Net Photosynthesis= 774.09

SUMMARY OF RESULTS FOR SITE KAPUKASING

(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.00	0.00
MAY 1982	78.60	0.97	76.08
JUN 1982	179.02	0.89	159.90
JUL 1982	246.01	1.00	246.01
AUG 1982	173.89	1.00	173.89
SEP 1982	96.86	1.00	96.86
OCT 1982	12.93	1.00	12.93
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
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	787.30		

Annual Total Estimated Net Photosynthesis= 765.67

SUMMARY OF RESULTS FOR SITE SEPT ISLES

(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.00	0.00
MAY 1982	42.53	1.00	42.53
JUN 1982	71.85	1.00	71.85
JUL 1982	92.77	0.95	88.03
AUG 1982	69.14	1.00	69.14
SEP 1982	61.49	1.00	61.49
OCT 1982	11.85	1.00	11.85
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
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	349.62		

Annual Total Estimated Net Photosynthesis= 344.88

SUMMARY OF RESULTS FOR SITE RAPID CITY

(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	16.06	0.91	14.63
MAY 1982	79.94	1.00	79.94
JUN 1982	160.24	1.00	160.10
JUL 1982	158.98	0.73	116.10
AUG 1982	171.97	1.00	171.97
SEP 1982	114.21	0.99	113.09
OCT 1982	42.07	1.00	42.07
NOV 1982	1.61	1.00	1.61
DEC 1982	0.00	0.00	0.00
JAN 1983	0.11	1.00	0.11
FEB 1983	5.48	1.00	5.48
MAR 1983	4.49	1.00	4.49
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	755.16		

Annual Total Estimated Net Photosynthesis= 709.60

SUMMARY OF RESULTS FOR SITE SANDSPIT

(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	3.18	1.00	3.18
MAY 1982	94.32	1.00	94.32
JUN 1982	136.72	0.78	106.88
JUL 1982	131.25	0.80	104.68
AUG 1982	133.10	0.88	117.26
SEP 1982	98.16	0.56	55.12
OCT 1982	29.45	1.00	29.45
NOV 1982	12.23	1.00	12.23
DEC 1982	2.58	1.00	2.58
JAN 1983	9.81	1.00	9.81
FEB 1983	13.28	1.00	13.28
MAR 1983	54.50	1.00	54.50
	718.57		

Annual Total Estimated Net Photosynthesis= 603.28

SUMMARY OF RESULTS FOR SITE PORT HARDY

(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	45.35	1.00	45.35
MAY 1982	90.42	1.00	90.42
JUN 1982	121.46	0.80	96.89
JUL 1982	69.03	0.92	63.42
AUG 1982	149.21	0.76	113.47
SEP 1982	93.79	1.00	93.79
OCT 1982	42.44	1.00	42.44
NOV 1982	6.32	1.00	6.32
DEC 1982	1.28	1.00	1.28
JAN 1983	5.29	1.00	5.29
FEB 1983	11.32	1.00	11.32
MAR 1983	44.36	1.00	44.36
	680.26		

Annual Total Estimated Net Photosynthesis= 614.34

SUMMARY OF RESULTS FOR SITE VANCOUVER

(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	4.10	1.00	4.10
MAY 1982	75.16	0.89	67.25
JUN 1982	84.57	0.62	52.75
JUL 1982	99.02	0.79	78.17
AUG 1982	131.28	0.50	65.75
SEP 1982	80.67	0.66	53.12
OCT 1982	46.29	1.00	46.29
NOV 1982	9.16	1.00	9.16
DEC 1982	0.00	1.00	0.00
JAN 1983	0.00	1.00	0.00
FEB 1983	6.99	1.00	6.99
MAR 1983	37.59	1.00	37.59
	574.84		

Annual Total Estimated Net Photosynthesis= 421.16

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              SUMMARY OF RESULTS FOR SITE SEATTLE/TAKOMA
                   (NPP in grams per square meter)

                        Estimated         Wtr Balance
                        Potential         Adjustment      Estimated
        Month/Year      Monthly NPP        Factor        Monthly NPP
        APR   1982         96.58            1.00            96.58
        MAY   1982        217.15            0.83           179.88
        JUN   1982        231.13            0.58           134.04
        JUL   1982        259.71            0.30            76.78
        AUG   1982        235.12            0.20            47.05
        SEP   1982        161.33            0.66           119.74
        OCT   1982         97.17            1.00            97.17
        NOV   1982         21.60            1.00            21.60
        DEC   1982          6.47            1.00             6.47
        JAN   1983          6.92            1.00             6.92
        FEB   1983         21.06            1.00            21.06
        MAR   1983         74.80            1.00            74.80
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                         1449.04

        Annual Total Estimated Net Photosynthesis=  882.09

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                 SUMMARY OF RESULTS FOR SITE MEDFORD
                   (NPP in grams per square meter)

                        Estimated         Wtr Balance
                        Potential         Adjustment      Estimated
        Month/Year      Monthly NPP        Factor        Monthly NPP
        APR   1982        102.60            0.78            80.48
        MAY   1982        166.29            0.27            45.73
        JUN   1982        178.05            0.29            51.41
        JUL   1982        186.40            0.04             7.73
        AUG   1982        177.84            0.01             2.54
        SEP   1982        139.47            0.34            47.28
        OCT   1982         84.67            0.83            70.58
        NOV   1982         28.32            1.00            28.32
        DEC   1982         10.46            1.00            10.46
        JAN   1983         14.04            1.00            14.04
        FEB   1983         28.50            1.00            28.50
        MAR   1983         56.29            1.00            56.29
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                         1172.92

        Annual Total Estimated Net Photosynthesis=  443.33

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SUMMARY OF RESULTS FOR SITE TORONTO
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	8.35	1.00	8.35
MAY 1982	125.94	0.85	107.58
JUN 1982	153.19	1.00	153.19
JUL 1982	198.07	0.61	120.90
AUG 1982	154.18	1.00	154.18
SEP 1982	109.81	1.00	109.81
OCT 1982	54.40	1.00	54.40
NOV 1982	5.75	1.00	5.75
DEC 1982	0.00	1.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.45	1.00	0.45
	810.13		

Annual Total Estimated Net Photosynthesis= 714.60

SUMMARY OF RESULTS FOR SITE MONTREAL
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	7.19	1.00	7.19
MAY 1982	129.92	0.62	80.51
JUN 1982	158.90	0.88	139.04
JUL 1982	172.80	0.63	108.43
AUG 1982	160.12	1.00	160.12
SEP 1982	127.95	1.00	127.95
OCT 1982	54.56	1.00	54.56
NOV 1982	0.00	1.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
	811.43		

Annual Total Estimated Net Photosynthesis= 677.80

SUMMARY OF RESULTS FOR SITE SAULT STE. MARIE
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.00	0.00
MAY 1982	127.31	0.90	115.21
JUN 1982	175.35	0.85	149.76
JUL 1982	206.96	0.64	131.62
AUG 1982	209.87	1.00	209.87
SEP 1982	136.39	1.00	136.39
OCT 1982	35.96	1.00	35.96
NOV 1982	0.15	1.00	0.15
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
	891.99		

Annual Total Estimated Net Photosynthesis= 778.96

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SUMMARY OF RESULTS FOR SITE CARIBOU
(NPP in grams per square meter)
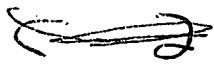
Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	3.68	1.00	3.68
MAY 1982	124.03	0.80	98.97
JUN 1982	191.78	0.90	172.44
JUL 1982	173.18	0.98	169.76
AUG 1982	182.12	1.00	182.12
SEP 1982	138.99	1.00	138.99
OCT 1982	32.25	1.00	32.25
NOV 1982	0.00	1.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
	846.02		

Annual Total Estimated Net Photosynthesis= 798.20

SUMMARY OF RESULTS FOR SITE BOSTON
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	25.27	1.00	25.27
MAY 1982	155.33	1.00	155.33
JUN 1982	157.92	1.00	157.92
JUL 1982	186.54	0.97	181.56
AUG 1982	164.50	0.76	124.90
SEP 1982	134.22	0.64	85.95
OCT 1982	48.85	1.00	48.85
NOV 1982	0.00	1.00	0.00
DEC 1982	0.00	1.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	1.00	0.00
MAR 1983	12.79	1.00	12.79
	885.42		

Annual Total Estimated Net Photosynthesis= 792.58

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                SUMMARY OF RESULTS FOR SITE NEW YORK
                 (NPP in grams per square meter)

                      Estimated        Wtr Balance
                      Potential        Adjustment        Estimated
    Month/Year        Monthly NPP        Factor         Monthly NPP
    APR   1982           8.78             1.00              8.78
    MAY   1982         116.93             0.96            112.57
    JUN   1982         114.44             1.00            114.44
    JUL   1982         110.48             0.83             91.75
    AUG   1982         136.34             0.78            106.66
    SEP   1982         104.31             0.53             55.32
    OCT   1982          40.98             0.84             34.50
    NOV   1982           0.00             1.00              0.00
    DEC   1982           0.00             1.00              0.00
    JAN   1983           0.00             1.00              0.00
    FEB   1983           0.00             1.00              0.00
    MAR   1983           0.00             1.00              0.00
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                        632.25

        Annual Total Estimated Net Photosynthesis=   524.02
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                SUMMARY OF RESULTS FOR SITE LITTLE ROCK
                 (NPP in grams per square meter)

                      Estimated        Wtr Balance
                      Potential        Adjustment        Estimated
    Month/Year        Monthly NPP        Factor         Monthly NPP
    APR   1982          57.47             1.00             57.47
    MAY   1982         163.65             1.00            163.65
    JUN   1982         162.25             1.00            162.22
    JUL   1982         117.78             0.95            111.68
    AUG   1982         157.41             0.97            153.29
    SEP   1982         142.03             0.58             82.97
    OCT   1982          62.45             1.00             62.45
    NOV   1982          21.15             1.00             21.15
    DEC   1982           5.72             1.00              5.72
    JAN   1983           6.99             1.00              6.99
    FEB   1983           5.30             1.00              5.30
    MAR   1983          34.20             1.00             34.20
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                        936.41

        Annual Total Estimated Net Photosynthesis=   867.10

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SUMMARY OF RESULTS FOR SITE ATLANTA
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	85.06	1.00	85.06
MAY 1982	157.04	0.93	145.45
JUN 1982	158.81	1.00	158.81
JUL 1982	132.89	1.00	132.89
AUG 1982	122.41	0.63	77.03
SEP 1982	109.94	0.85	93.42
OCT 1982	62.66	1.00	62.66
NOV 1982	34.00	1.00	34.00
DEC 1982	9.68	1.00	9.68
JAN 1983	8.52	1.00	8.52
FEB 1983	10.90	1.00	10.90
MAR 1983	39.31	1.00	39.31
	931.23		

Annual Total Estimated Net Photosynthesis= 857.74

SUMMARY OF RESULTS FOR SITE ROCKVILLE
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	75.52	1.00	75.52
MAY 1982	148.67	1.00	148.67
JUN 1982	168.75	1.00	168.75
JUL 1982	155.25	0.82	127.99
AUG 1982	166.30	0.66	110.02
SEP 1982	122.96	0.52	64.08
OCT 1982	71.99	0.81	58.05
NOV 1982	9.80	1.00	9.80
DEC 1982	0.00	1.00	0.00
JAN 1983	0.00	1.00	0.00
FEB 1983	3.34	1.00	3.34
MAR 1983	19.41	1.00	19.41
	941.99		

Annual Total Estimated Net Photosynthesis= 785.63

PINE SUBCLIMAX FOREST

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              SUMMARY OF RESULTS FOR SITE CHARLESTON
                (NPP in grams per square meter)

                       Estimated      Wtr Balance
                       Potential      Adjustment      Estimated
        Month/Year     Monthly NPP      Factor       Monthly NPP
        APR  1982        121.04          1.00          121.04
        MAY  1982        125.54          0.95          119.46
        JUN  1982        131.15          1.00          131.15
        JUL  1982        117.15          0.98          115.02
        AUG  1982        107.45          0.86           92.39
        SEP  1982         91.74          0.95           86.97
        OCT  1982         72.74          0.98           71.31
        NOV  1982         41.81          0.77           32.39
        DEC  1982         18.95          1.00           16.95
        JAN  1983         15.01          1.00           15.01
        FEB  1983         26.65          1.00           26.65
        MAR  1983         48.45          1.00           48.45
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                         917.69

        Annual Total Estimated Net Photosynthesis=  878.80

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GRASSLAND

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            SUMMARY OF RESULTS FOR SITE BISMARCK
               (NPP in grams per square meter)
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	Estimated Potential	Wtr Balance Adjustment	Estimated
Month/Year	Monthly NPP	Factor	Monthly NPP
APR 1982	0.00	1.00	0.00
MAY 1982	96.14	1.00	96.14
JUN 1982	156.26	0.85	132.11
JUL 1982	156.12	0.64	100.13
AUG 1982	130.50	0.46	59.89
SEP 1982	80.19	0.24	19.11
OCT 1982	2.86	1.00	2.86
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
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	622.08		

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      Annual Total Estimated Net Photosynthesis=   410.25
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          SUMMARY OF RESULTS FOR SITE GREAT FALLS
               (NPP in grams per square meter)
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	Estimated Potential	Wtr Balance Adjustment	Estimated
Month/Year	Monthly NPP	Factor	Monthly NPP
APR 1982	0.00	1.00	0.00
MAY 1982	30.39	1.00	30.39
JUN 1982	118.30	1.00	117.90
JUL 1982	171.73	0.59	101.87
AUG 1982	111.99	0.26	29.60
SEP 1982	62.91	1.00	62.91
OCT 1982	9.82	0.59	5.83
NOV 1982	0.00	1.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	1.00	0.00
FEB 1983	0.00	0.64	0.00
MAR 1983	0.00	1.00	0.00
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	505.14		

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      Annual Total Estimated Net Photosynthesis=   348.50
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          SUMMARY OF RESULTS FOR SITE OKLAHOMA CITY
               (NPP in grams per square meter)
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	Estimated Potential	Wtr Balance Adjustment	Estimated
Month/Year	Monthly NPP	Factor	Monthly NPP
APR 1982	115.62	1.00	115.62
MAY 1982	193.58	1.00	193.58
JUN 1982	141.42	0.99	140.41
JUL 1982	155.96	0.65	101.31
AUG 1982	135.53	0.26	34.87
SEP 1982	104.04	0.67	69.65
OCT 1982	85.30	0.46	39.16
NOV 1982	28.46	1.00	28.46
DEC 1982	14.30	1.00	14.30
JAN 1983	10.33	1.00	10.33
FEB 1983	10.61	1.00	10.61
MAR 1983	76.82	1.00	76.82
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	1071.97		

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      Annual Total Estimated Net Photosynthesis=   835.11
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GRASSLAND, cont.

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                SUMMARY OF RESULTS FOR SITE SAN ANTONIO
                   (NPP in grams per square meter)

                        Estimated      Wtr Balance
                        Potential      Adjustment      Estimated
         Month/Year     Monthly NPP      Factor      Monthly NPP
         APR  1982        72.04          0.66          47.44
         MAY  1982       107.23          1.00         107.23
         JUN  1982       112.83          0.56          63.26
         JUL  1982       103.18          0.08           7.92
         AUG  1982        89.40          0.08           7.34
         SEP  1982        77.22          0.17          13.29
         OCT  1982        59.15          1.00          59.15
         NOV  1982        42.35          1.00          42.35
         DEC  1982        42.25          1.00          42.25
         JAN  1983        50.21          1.00          50.21
         FEB  1983        59.22          1.00          59.22
         MAR  1983       109.72          1.00         109.72
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                         924.79

            Annual Total Estimated Net Photosynthesis=  609.37

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SUMMARY OF RESULTS FOR SITE EDMONTON
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	1.00	0.00
MAY 1982	76.81	0.72	55.55
JUN 1982	145.19	0.33	48.32
JUL 1982	199.26	1.00	199.26
AUG 1982	191.76	0.89	171.04
SEP 1982	132.97	0.71	94.81
OCT 1982	31.02	0.75	23.35
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
	777.01		

Annual Total Estimated Net Photosynthesis= 592.34

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SUMMARY OF RESULTS FOR SITE WINNEPEG
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	1.00	0.00
MAY 1982	54.50	0.56	30.37
JUN 1982	114.72	0.73	83.67
JUL 1982	211.55	0.93	197.64
AUG 1982	160.32	0.66	105.57
SEP 1982	56.21	0.93	52.16
OCT 1982	0.00	1.00	0.00
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	0.00	0.00
MAR 1983	0.00	0.00	0.00
	597.30		

Annual Total Estimated Net Photosynthesis= 469.41

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SUMMARY OF RESULTS FOR SITE LETHBRIDGE
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.93	0.00
MAY 1982	26.66	0.71	18.92
JUN 1982	87.08	0.70	61.38
JUL 1982	201.63	0.87	175.66
AUG 1982	169.10	0.31	52.73
SEP 1982	67.99	0.90	61.04
OCT 1982	6.10	0.22	1.34
NOV 1982	0.00	1.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.00	0.00	0.00
FEB 1983	0.00	1.00	0.00
MAR 1983	0.00	0.00	0.00
	558.57		

Annual Total Estimated Net Photosynthesis= 371.08

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SUMMARY OF RESULTS FOR SITE SPOKANE
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	28.61	1.00	28.61
MAY 1982	77.63	0.59	46.15
JUN 1982	143.00	0.39	56.25
JUL 1982	111.09	0.31	34.49
AUG 1982	81.38	0.07	5.89
SEP 1982	52.14	0.62	32.14
OCT 1982	15.57	1.00	15.57
NOV 1982	0.00	0.00	0.00
DEC 1982	0.00	0.00	0.00
JAN 1983	0.91	1.00	0.91
FEB 1983	1.42	1.00	1.42
MAR 1983	21.34	1.00	21.34
	533.08		

Annual Total Estimated Net Photosynthesis= 242.77

SUMMARY OF RESULTS FOR SITE BOISE
(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	72.69	0.86	62.68
MAY 1982	164.44	0.45	73.42
JUN 1982	208.18	0.21	43.82
JUL 1982	245.10	0.38	94.21
AUG 1982	223.20	0.04	9.80
SEP 1982	186.19	0.50	93.67
OCT 1982	67.64	1.00	67.64
NOV 1982	4.67	1.00	4.67
DEC 1982	0.00	0.00	0.00
JAN 1983	1.45	1.00	1.45
FEB 1983	2.91	1.00	2.91
MAR 1983	43.51	1.00	43.51
	1219.97		

Annual Total Estimated Net Photosynthesis= 497.78

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                 SUMMARY OF RESULTS FOR SITE GRAND JUNCTION
                      (NPP in grams per square meter)

                          Estimated        Wtr Balance
                          Potential        Adjustment      Estimated
            Month/Year    Monthly NPP       Factor        Monthly NPP
            APR  1982        33.38            0.43           14.36
            MAY  1982        90.22            0.43           39.06
            JUN  1982       135.56            0.11           14.70
            JUL  1982       196.51            0.07           13.15
            AUG  1982       227.04            0.17           38.84
            SEP  1982       211.11            0.78          165.71
            OCT  1982        87.69            0.58           50.50
            NOV  1982         3.62            1.00            3.62
            DEC  1982         0.00            1.00            0.00
            JAN  1983         0.00            1.00            0.00
            FEB  1983         0.00            1.00            0.00
            MAR  1983         0.00            0.93            0.00
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                            985.14

            Annual Total Estimated Net Photosynthesis=   339.94
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                 SUMMARY OF RESULTS FOR SITE ALBUQUFRQUE
                      (NPP in grams per square meter)

                          Estimated        Wtr Balance
                          Potential        Adjustment      Estimated
            Month/Year    Monthly NPP       Factor        Monthly NPP
            APR  1982         0.00            0.38            0.00
            MAY  1982        34.17            0.34           11.67
            JUN  1982        31.79            0.06            2.05
            JUL  1982        35.78            0.23            8.40
            AUG  1982       171.98            0.20           34.80
            SEP  1982       154.87            0.37           57.29
            OCT  1982        64.58            0.20           13.04
            NOV  1982         0.00            1.00            0.00
            DEC  1982         0.00            1.00            0.00
            JAN  1983         0.00            1.00            0.00
            FEB  1983         0.00            1.00            0.00
            MAR  1983         0.00            0.91            0.00
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                            493.17

            Annual Total Estimated Net Photosynthesis=   127.25
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                 SUMMARY OF RESULTS FOR SITE ELY, NEVADA
                      (NPP in grams per square meter)

                          Estimated        Wtr Balance
                          Potential        Adjustment      Estimated
            Month/Year    Monthly NPP       Factor        Monthly NPP
            APR  1982         8.32            0.98            8.14
            MAY  1982        54.29            0.87           47.33
            JUN  1982        43.75            0.24           10.40
            JUL  1982        72.00            0.21           14.88
            AUG  1982       114.13            0.34           38.72
            SEP  1982        70.35            1.00           70.35
            OCT  1982        14.06            1.00           14.06
            NOV  1982         0.00            1.00            0.00
            DEC  1982         0.00            0.00            0.00
            JAN  1983         0.00            0.00            0.00
            FEB  1983         0.00            0.00            0.00
            MAR  1983         0.00            1.00            0.00
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                            376.90

            Annual Total Estimated Net Photosynthesis=   203.87
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SCRUB-WOODLAND, cont.

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                   SUMMARY OF RESULTS FOR SITE SALT LAKE CITY
                        (NPP in grams per square meter)

                        Estimated        Wtr Balance
                        Potential        Adjustment        Estimated
        Month/Year      Monthly NPP      Factor            Monthly NPP
        APR   1982         35.38            1.00              35.38
        MAY   1982        114.28            0.91             103.45
        JUN   1982        148.67            0.39              57.50
        JUL   1982        127.70            0.53              67.42
        AUG   1982        233.42            0.11              26.02
        SEP   1982        206.02            1.00             206.02
        OCT   1982         53.95            1.00              53.95
        NOV   1982          6.76            1.00               6.76
        DEC   1982          0.00            0.00               0.00
        JAN   1983          0.00            1.00               0.00
        FEB   1983          0.00            1.00               0.00
        MAR   1983          9.56            1.00               9.56
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                          935.74                                       

        Annual Total Estimated Net Photosynthesis=  566.07
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SUMMARY OF RESULTS FOR SITE LAS VEGAS

(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	9.91	0.35	3.46
MAY 1982	11.48	0.21	2.36
JUN 1982	11.36	0.01	0.14
JUL 1982	10.81	0.00	0.00
AUG 1982	0.00	0.10	0.00
SEP 1982	20.01	0.03	0.66
OCT 1982	0.00	0.07	0.00
NOV 1982	0.00	1.00	0.00
DEC 1982	0.00	1.00	0.00
JAN 1983	0.00	1.00	0.00
FEB 1983	0.00	0.61	0.00
MAR 1983	0.00	0.78	0.00
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	63.57		

Annual Total Estimated Net Photosynthesis=   6.61

SUMMARY OF RESULTS FOR SITE EL PASO

(NPP in grams per square meter)

Month/Year	Estimated Potential Monthly NPP	Wtr Balance Adjustment Factor	Estimated Monthly NPP
APR 1982	0.00	0.34	0.00
MAY 1982	23.30	0.19	4.40
JUN 1982	0.00	0.04	0.00
JUL 1982	0.00	0.14	0.00
AUG 1982	66.06	0.07	4.48
SEP 1982	113.33	1.00	113.33
OCT 1982	64.30	0.11	7.08
NOV 1982	0.00	0.38	0.00
DEC 1982	0.00	1.00	0.00
JAN 1983	0.00	1.00	0.00
FEB 1983	0.00	1.00	0.00
MAR 1983	0.00	0.75	0.00
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	266.99		

Annual Total Estimated Net Photosynthesis=   129.30

REFERENCES

Atjay, G.L., Ketner, P. and Duvigneaud, P. 1979.
Terrestrial Primary Production and Phytomass. In: The
Global Carbon Cycle, Q B. Bolin, E.T. Degens, S. Kempe and
P. Ketner, eds. New York: J. Wiley and Sons.

Bacastow, R.B., Keeling, C.D. and Whorf, T.P. 1985. Seasonal
Amplitude Increase in Atmospheric CO_2 Concentration at
Mauna Loa, Hawaii. J. Geophys. Res., in press, 1985.

Barbour, M.G., Burk, J.H. and Pitts, W.D. 1980. Terrestrial
Plant Ecology. Menlo Park: Benjamin/Cummings. 604 pp.

Bolin, B., and Cook, R.B., eds. 1982. The Biogeochemical
Cycles and their Interactions. New York: J. Wiley and
Sons.

Botkin, D.B. 1982. Habitability of the Earth: Land-Air
Interactions, World Food Production and Net Primary
Productivity. A Report Prepared for NASA from a Conference
held at Santa Barbara in May, 1982.

Boyer, J.S. 1976. Water Deficit and Photosynthesis. In:
Water Deficits and Plant Growth, Vol. IV. T. Kozlowski,
ed., pp. 153-190.

CAST. 1975. Land Resources Use and Protection. Council
for Agricultural Science and Technology, Ames, Iowa,
Report no. 38.

Chang, J. 1968. The Agricultural Potential of the Humid
Tropics. The Geographical Review, 58:3,333-361.

Chartier, P. 1970. A Model of CO2 Assimilation in the Leaf.
In: Prediction and Measurement of Photosynthetic
Productivity. Proceedings of the IBP/PP Technical Meeting,
Trebon, 14-21 Sept. 1969. Wageningen: Center for
Agricultural Publishing and Documentation, pp. 307-315.

Cicone, R.C., and Metzler, D. 1982. Comparison of Landsat MSS,
Nimbus 7 CZCS, and NOAA6/7 AVHRR Features for Land Use
Analysis. Proceedings, Machine Processing of Remotely
Sensed Data Symposium, Ann Arbor, MI: Env. Res. Inst.
Michigan.

Committee for World Atlas of Agriculture. 1968. World Atlas of
Agriculture. Instituto Geografico de Agostini, Novara,
Italy.

Daubenmire, R. 1978. Plant Geography, with Special Reference
to North America. New York: Academic Press. 338 pp.

Eyre, S.R. 1963. Vegetation and Soils: A World Picture.
Edward Arnold.

Gaastra, P. 1959. Photosynthesis of Crop Plants as Influenced
by Light, Carbon Dioxide, Temperature, and Stomatal
Diffusion Resistance. Mededelingen van de
Landbouwhogeschool te Wageningen, Nederland. 59:13, 1-68.

Gates, D.M. 1976. Energy Exchange and Transpiration. In: Water
and Plant Life: Problems and Modern Approaches. O.L.
Lange, L. Kappen, and E.-D. Schulze, eds. New York:
Springer-Verlag.

Gatlin, J.A., Tucker, C.J., and Schneider, S.R. 1981. Use of
NOAA-6 Channels One and Two for Monitoring Vegetation.
In: IEEE Proceedings Int. Geoscience and Remote Sensing
Symposium, Wash. D.C., June 8-11, 1981.

Goward, S.N, Tucker, C.J. and Dye, D.G. 1985. North American
Vegetation Patterns Observed by NOAA-7 AVHRR. Vegetatio,
in press.

_____, Petzold, D.E., and Dye, D.G. 1985. Reflectance Spectra
of Subarctic Lichens. In preparation, August 1985.

Greegor, D.H., and Norwine, J. 1981. A Gradient Model of
Vegetation and Climate Utilizing NOAA Satellite Imagery,
Phase I: Texas Transect. AgRISTARS report no. FC-J1-04176.
NASA Johnson Space Center, Houston, Texas.

Hatfield, J.L., Asrar, G. and Kanemasu, E.T. 1984. Intercepted
Photosynthetically Active Radiation Estimated by Spectral
Reflectance. Remote Sensing of Environment, 14:65-75.

Hesketh, J.D. 1980. Predicting Canopy Photosynthesis from Gas
Exchange Studies in Controlled Environments. In:
Predicting Photosynthesis for Ecosystem Models, Vol. 1,
J.D. Hesketh and J.W. Jones, eds. Boca Raton, Fla.: CRC
Press, pp. 37-50.

_____, and Musgrave, R.B. 1962. Light Studies with Individual
Corn Leaves. Crop Science, 2:311-315.

_____, and Moss, D.N. 1963. Variations in the Response of
Photosynthesis to Light. Crop Science, 3.

Holben, B. and Fraser, R.S. 1984. Red and Near-Infrared Sensor
Response to Off-Nadir Viewing. Int. J. Remote Sensing,
5,1:145-160.

Hsio, T.C. 1973. Plant Response to Water Stress. Ann. Rev. Pl.
Physiol., 24:519-570.

ITT. 1981. Alignment and Calibration Data Book, AVHRR/2 Protoflight Model (PFM). Report produced by ITT Aerospace/Optical Division for NASA Goddard Space Flight Center, Greenbelt, Maryland. Contract NAS-5-23400.

Justice, C.O., Townshend, J.R.G., Holben, B.N., and Tucker, C.J. 1984. Phenology of Global Vegetation Using Meteorlogical Satellite Data. Int. J. Remote Sensing, in press.

Kuchler, A.W. 1966. Potential Natural Vegetation of the Conterminous United States. Am. Geogr. Soc. Spec. Publ. No. 36, New York.

Larcher, W. 1965. The Influence of Water Stress on the Relationship between CO2 Uptake and Transpiration. In: Water STress in Plants, B. Slavik, ed., The Hague: Dr. W. Junk Publ., pp. 184-193.

Lof, G.O.G., Duffie, J.A., and Smith, C.O. 1966. World Distribution of Solar Radiation. Report No. 21, Solar Energy Laboratory, University of Wisconsin.

Kidwell, K.B. 1984. NOAA Polar-Orbiter Data (TIROS-N, NOAA-6, NOAA-7, and NOAA-8) Users Guide. U.S. Dept. of Commerce, NOAA/NESDIS, Washington, D.C., 140 pp.

Kormondy, E.J. and McCormick, J.F. 1981. Handbook of Contemporary Developments in World Ecology. Westport, Conn.: Greenwood Press.

Knipling, E.B. 1970. Physical and Physiological Basis for the Reflectance of Visible and Near-Infrared Radiation from Vegetation. Remote Sensing of Environment, 1:155-159.

Lemon, E. 1967. Aerodynamic Studies of CO2 Exchange between Atmosphere and the Plant. In: Harvesting the Sun: Photosynthesis in Plant Life. A. San Pietro, F.A. Greer, and T.J. Army, eds. New York: Academy Press, pp. 263-290.

Lieth, H. 1972. Modelling the Primary Productivity of the World. 10 pp. (offset), Deciduous Forest Biome Memo Rep. 72-9, March 1972.

_____, and Box, E. 1972. Evapotranspiration and Primary Productivity; C.W. Thornthwaite Memorial Model. Publications in Climatology, v. 25(2):37-46, Centerton/Elmer, N.J.: C.W. Thorntwaite Associates.

_____. 1973. Primary Production: Terrestrial Ecosystems. Human Ecology, 1:303-332.

_____. 1975. Primary Production of the Major Vegetation Units of the World. In: Primary Productivity of the Biosphere, New York: Springer-Verlag, 339 pp.

_____, and Whittaker, R.H., eds. 1975. _Primary Productivity of the Biosphere_, New York: Springer-Verlag, 339 pp.

Long, S.P. 1982. Measurement of Photosynthetic Gas Exchange. In: _Techniques in Bioproductivity and Photosynthesis_, J. Coombs and D.O. Hall, eds. New York: Pergammon Press, 171 pp.

Malingreau, J.-P. 1985. Global Vegetation Dynamics: Satellite Observations over Asia. In preparation, July, 1985. NASA Goddard Space Flight Center, Code 623, Greenbelt MD 20771.

Milner, C. and Hughes, R.E. 1968. _Methods for the Measurement of the Primary Production of Grassland_. IBP Handbook No. 6. Abingdon, Berkshire: Burgess and Son, 70 pp.

Monteith, J.L. 1962. Measurement and Interpretation of Carbon Dioxide Fluxes in the Field. _Netherland J. Agr. Sci._, 10:334-346.

_____. 1965. Light Distribution and Photosynthesis in Field Crops. _Annals of Botany_, 29:113, 17-37.

_____. 1981. Climatic Variation and the Growth of Crops. _Quart. J. R. Met Soc._, 107:749-774.

NAS. 1982. _A Strategy for Earth Science from Space in the 1980's, part I: Solid Earth and Oceans_. National Academy of Science, Space Science Board Subcommittee Report (Committee on Earth Sciences), Wash. D.C.: National Academy Press.

NASA. 1983. _Global Biology Research Program_. NASA Technical Memorandum 85629. National Aeronautics and Space Administration, Office of Space Science and Applications, Wash., D.C., 112 pp.

_____. 1984. _Global Change: Impacts on Habitability; A Scientific Basis for Assessment_. A Report by the Executive Committee of a Workshop held at Woods Hole, Mass., June 21-26, 1982. JPLD-95. Nationanal Aeronautics and Space Administration, Jet Propulsion Laboratory, Pasadena, Calif., 15 pp.

_____. 1983. _Land-Related Global Habitability Science Issues_. NASA Technical Memorandum 85841. National Aeronautics and Space Administration, Office of Space Science and Applications, Washington, D.C., 112 pp.

Newbold, P.J. 1967. _Methods for Estimating the Primary Production of Forests_. IBP Handbook No. 2. Oxford: Blackwell Scientific Publications, 62 pp.

NOAA. 1985. Hydraulic and Land Sciences Applications of NOAA Polar-Orbiting Satellite Data. United States Dept. of Commerce, Natl. Oceanic and Atmospheric Admin., Natl. Envtl. Satellite, Data and Information Service. Wash. D.C., January 1985.

NRC. 1983a. Toward an International Geosphere-Biosphere Program: A Study of Global Change. Report of a National Research Council Workshop, Woods Hole, Mass., July 25-29, 1983. Washington, D.C.: National Acadamy Press.

_____. 1983b. Changing Climate: Report of the Carbon Dioxide Assessment Committee, National Research Council. Washington, D.C.: National Acadamy Press.

Norwine, J. and Greegor, D.H. 1983. Vegetation Classification Based on AVHRR Satellite Imagery. Remote Sensing of Environment, 13:69-87.

Odum, E.P. 1975. Fundamentals of Ecology. 3rd edition. Philadelphia: W.B. Saunders Co., 574 pp.

Olson, J.S. 1971. Primary Productivity: Temperate Forests, Especially American Deciduous Types. In: Productivity of Forest Ecosystems, Proc. Brussels Symp., 1969, UNESCO.

_____, and Watts, J.A. 1982. Major World Ecosystem Complexes, (Map scale 1:30 m). In: Carbon Dioxide Review 1982, Oxford University Press.

Ormsby, J.P. 1982. Classification of Simulated and Actual NOAA-6 AVHRR Data for Hydraulic and Land-Surface Feature Definition. Geoscience and Remote Sensing, GE-20:262-267.

Pelton, W.L., King, K.M., and Tanner, C.B. 1960. An Evaulation of the Thornthwaite and Mean Temperature Methods for Determining Potential Evapotranspiration. Agronomy Journal, 52:387-395.

Penman, H.L. 1956. Estimating Evaporation. Trans. Am. Geophys. Union, 37:43-50.

Robinson, H. 1972. Biogeography. London: McDonald and Evans, Ltd., 541 pp.

Reichle, D.L. 1970. Geographic Index of World Ecosystems. In: Analysis of Temperate Forest Ecosystems, D.L. Reichle, ed. New York: Springer-Verlag.

Revelle, R., and Munk, W. 1977. The Global Carbon Dioxide Cycle and the Biosphere. In: Energy and Climate, National Academy of Science, pp. 243-280.

Rodin, L.E., Bazilevich, N.I., and Rozov, N.N. 1975. Productivity of the World's Main Ecosystems. In:

Productivity of World Ecosystems, Wash., D.C.: National
Academy of Sciences.

Satoo, T. 1970. A Synthesis of Studies by the Harvest Method:
Primary Production in the Temperate Deciduous Forests of
Japan. In: Analysis of Temperate Forest Ecosystems, D.E.
Reichle, ed., pp. 55-72.

SCEP. 1971. Man's Impact on the Global Environment: Assessment
and Recommendations for Action. Report of the Study of
Critical Environmental Problems (SCEP). Cambridge, Mass.:
MIT Press.

Seidel, S. and Keyes, D. 1983. Can We Delay a Greenhouse
Warming? U.S. Environmental Protection Agency, Office of
Policy and Resources Management, Washington, D.C.

Sellers, W.D. 1965. Physical Climatology. Chicago: University
of Chicago Press, 272 pp.

Slater, P.N. 1980. Remote Sensing, Optics and Optical Systems.
Reading, Mass.: Addison-Wesley.

Slatyr, R.O. 1963. Climatic Control of Plant Water Relations.
In: Environmental Control of Plant Growth, L.T. Evans, ed.
New York: Academic Press.

Steven, M.D., Biscoe, P.V., Jaggard, K.W. 1983. Estimation of
Sugar Beet Productivity from Reflection in Red and Near
Infrared Spectral Bands. Int. J. Remote Sensing, 4:325-
334.

Tarpley, J.D., Schneider, S.R. and Morey, R.L. 1983. Global
Vegetation Indices from NOAA-7 Meteorological Satellite.
J. Climate and Appl. Meteor., 23: 491-493.

Terjung, W.H., Louie, S.S.-F., and O'Rourke, P.A. 1976. Toward
an Energy Budget Model of Photosynthesis Predicting World
Productivity. Vegetatio, 32:1,31-53.

Thornthwaite, C.W. 1948. An Approach Toward a Rational
Classification of Climate. Geographical Review, Vol.
XXXVIII, No. 1, pp. 55-94.

_____, and Mather, J.R. 1957. Instructions and
Tables for Computing Potential Evapotranspiration and the
Water Balance. Publications in Climatology, vol. X, no. 3.
Centerton, New Jersey: Drexel Institute of Technology,
Laboratory of Climatology.

Townshend, J.R.G., and Tucker, C.J. 1981. Utility of AVHRR of
NOAA-6 and NOAA-7 for Vegetation Mapping. In: Matching
Remote Sensing Technologies and Applications Proceedings.
London: Remote Sensing Society, pp. 97-107.

Tucker, C.J. 1979. Red and Photographic Infrared Linear
    Combinations for Monitoring Vegetation. Remote Sensing of
    Environment, 8:127-150.

_____, and Holben, B.N. 1980. Relationship of Spectral Data to
    Grain Yield Variation. Photogrammetric Engineering and
    Remote Sensing, 46,5:657-666.

_____, Holben, B.N., Elgin, J.A. and McMurtrey, J.E. 1981.
    Remote Sensing of Total Dry-Matter Accumulation in Winter
    Wheat. Remote Sensing of Environment, 11:171-189.

_____, Gatlin, J.A., Schneider, S.R. and Kuchinos, M.A. 1982.
    Measuring Vegetation in the Nile Delta with NOAA-6 and
    NOAA-7 Data. In: Proceedings, Int. Symp. Remote Sensing of
    Arid and Semiarid Lands, Cairo. Envtl. Res. Inst. of
    Michigan.

_____, Townshend, J.R.G. and Goff, T.E. 1985a. African Land-
    Cover Classification Using Satellite Data. Science,
    227,4685:369-375.

_____, Vanpraet, C.L., Sharman, M.J., and Van Ittersum, G.
    1985b. Satellite Remote Sensing of Total Herbacious
    Biomass Production in the Senegalese Sahel: 1980-1984.

USDA. 1980. Descriptions of the Ecoregions of the United
    States. United States Dept. of Agriculture, Forest
    Service, Misc. Publ. no. 1391., Wasington, D.C.

Vankat, J. 1979. The Natural Vegetation of North America. New
    York: Wiley and Sons, 261 pp.

Walter, H. 1979. Vegetation of the Earth and Ecological
    Systems of the Biosphere. New York: Springer-Verlag, 247
    pp.

Waring, R.H. and Franklin, J.F. 1979. Evergreen Coniferous
    Forests of the Pacific Northwest. Science, 204,29:1380-
    1385.

Whittaker, R.H., and Likens, G.E. 1975. The Biosphere and Man.
    In: Primary Productivity of the Biosphere, H. Lieth and
    R.H. Whittaker, eds. New York: Springer-Verlag.

_____, and Marks, P.L. 1975. Methods of Assessing Terrestrial
    Productivity. In: Primary Productivity of the Biosphere,
    H. Lieth and R.H. Whittaker, eds. New York: Springer-
    Verlag.

Woodwell, G.M. and Whittaker, R.H. 1968. Primary Production in
    Terrestrial Ecosystems. Am. Zoologist, 8:19-30.

_____, and Botkin, D.B. 1970. Metabolism of Terrestrial Ecosystems by Gas Exchange Techniques: The Brookhaven Approach. In: Analysis of Temperate Forest Ecosystems, D.E. Reichle, ed. New York: Springer-Verlag.

_____, Whittaker, R.H., Reiners, W.A., Likens, G.E., Delwiche, C.C., and Botkin, D.B. 1978. The Biota and the World Carbon Budget. Science, 199:141-145.