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North American Vegetation Patterns Observed with the NOAA-7 Advanced Very High Resolution Radiometer

Samuel N. Goward*, Compton J. Tucker**, & Dennis G. Dye*

*Department of Geography, University of Maryland, College Park, MD 20742 USA

**Earth Resources Branch,
NASA/Goddard Space Flight Center, Greenbelt, MD 20771 USA

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ABSTRACT

Spectral vegetation index measurements derived from remotely sensed observations show great promise as a means to improve knowledge of land vegetation patterns. The daily, global observations acquired by the Advanced Very High Resolution Radiometer, a sensor on the current series of U.S. National Oceanic and Atmospheric Administration meteorological satellites, may be particularly well suited for global studies of vegetation. Preliminary results from analysis of North American observations, extending from April to November 1982, show that the vegetation index patterns observed correspond to the known seasonality of North American natural and cultivated vegetation. Integration of the observations over the growing season produced measurements that are related to net primary productivity patterns of the major North American natural vegetation formations. Regions of intense cultivation were observed as anomalous areas in the integrated growing season measurements. These anomalies can be explained by contrasts between cultivation practices and natural vegetation phenology. Major new information on seasonality, annual extent and interannual variability of vegetation photosynthetic activity at continental and global scales can be derived from these satellite observations.

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INTRODUCTION

Vegetation is a key element in the environment and ecology of the Earth. Full understanding of global climate, biospheric productivity, human impact on environment and related biophysical phenomena requires detailed knowledge of the geographic and seasonal patterns of terrestrial vegetation (Shukla & Mintz 1982, Hansen et al. 1981, Woodwell et al. 1978, Sharpe 1975, Thomas 1959). Currently, information concerning the distribution and seasonality of global vegetation are derived from a wide range of information sources, such as maps, atlases, and field reports, which are of varying reliability and usually compiled from observations taken at different times. Recent efforts to estimate the global extent of selected vegetation types have produced results which differ by more than a factor of two for comparable vegetation types (Ajtay, Ketner & Duigneand 1979, Olson & Watts 1982, Matthews 1983). Much less information is available on the global patterns of vegetation seasonality (Junge & Czeplak 1968, Lieth 1974, Fung, Prentice, Matthews, Learner & Russell 1983). There is a need for consistant, timely and reliable information sources to facilitate analysis of global vegetation patterns. Remotely sensed spectral measurements of reflected solar radiation may contribute such an information source (Shay 1969, NASA/HQ 1983). This report discusses preliminary results from a study of North American vegetation patterns observed with visible and near-infrared measurements from the NOAA-7 Advanced Very High Resolution Radiometer (AVHRR).

BACKGROUND

Spectral Vegetation Indices

Research carried out since the 1940's has shown that photosynthetically active "green" vegetation displays a unique spectral reflectance pattern in the visible and near-infrared spectral regions when compared to other earth surface materials (Krinov 1947, Colwell 1956, Gates, Keegan, Schleter & Weidner 1965,

Knipling 1970, Colwell 1974). The spectral reflectance of rocks, soils, dormant vegetation and woody plant materials, although variable in overall brightness, generally increases monotonically with increasing wavelength in the 0.4-1.0 μm wavelength region. Photosynthetically active plant components, primarily leaves, produce a stepped reflectance pattern with low reflectance in the visible and high reflectance in the near infrared. This green vegetation spectral reflectance pattern results from strong absorption of visible light by chlorophylls and related pigments and scattering, because of leaf structural properties, but minimal absorption of light in the near infrared. Researchers have proposed a number of spectral vegetation indices premised on the contrasts in spectral reflectance between green vegetation and background materials (Rouse, Hass, Deering & Schell 1974, Kauth & Thomas 1976, Richardson & Wiegand 1977, Tucker 1979, Jackson 1983). All of the indices are computed, at least in part, by calculating a difference or ratio of visible to near infrared measurements. This calculation minimizes the effects of variable background brightness while emphasizing variations in the measurements that occur because of varying green vegetation density. The normalized difference vegetation index (NDVI) is representative of the various spectral vegetation indices (Rouse, Hass, Deering & Schell 1974). It is computed;

$$NDVI = (NIR-VIS)/(NIR+VIS)$$

where NIR = near infrared spectral measurement
VIS = visible spectral measurement

In theory NDVI measurements range between -1.0 and +1.0. However, in practice the measurements generally range between -0.1 and +0.7. Clouds, water, snow and ice give negative NDVI values. Bare soils and other background materials produce NDVI values between -0.1 and +0.1. Larger NDVI values occur as the amount of green vegetation in the observed area increases. The relative merits of the various spectral vegetation indices is still subject to discussion

(Tucker 1979, Jackson 1983, Hatfield 1983). However, analytical evaluation has shown that the various indices are functional equivalents (Perry Jr. & Lautenschlager 1984).

The physical significance of spectral vegetation indices is under intensive investigation. Field studies, predominantly for agricultural crops and grasslands, have shown that the spectral vegetation indices correlate, in a nonlinear manner, with the green leaf area index and green biomass in the canopy (Dethier 1974, Deering, Rouse, Hass & Schell 1974, Blair & Baumgardner 1977, Holben, Tucker & Fan 1980, Bauer, Daughtry & Vanderbilt 1981, Curran 1983). These relations however are species-specific and saturate at high LAI and green leaf biomass levels. Theoretical studies of vegetation canopy radiance characteristics show that at a minimum the leaf area index, leaf angle distribution and leaf optical properties of the canopy must be known to predict observed canopy reflectance patterns (Idso & de Wit 1970, Suits 1973, Bunnik 1978). Parallel research on photosynthesis has shown that calculation of intercepted photosynthetically active radiation (IPAR) requires equivalent specification of canopy attributes (Wienman & Guetter 1972, Lemur & Blad 1974, Monteith 1977, Hesketh & Jones 1980). Recent field studies of several different agricultural crops have shown a strong linear relation between IPAR and the spectral vegetation indices (Kumar & Monteith 1981, Daughtry, Gallo & Bauer 1983, Asrar, Fuchs, Kanemasu & Hatfield 1984). This IPAR-spectral vegetation index relation provides a physical link between the indices and plant productivity which is supported by studies of crops and grasslands which show a direct relation between the integrated value of spectral vegetation index measurements, acquired several times through the ground season, and the seasonal accumulation of biomass (Tucker, Holben, Elgin Jr. & McMurtrey 1981, Daughtry, Gallo & Bauer 1982, Hatfield 1983, Steven, Biscoe & Jaggard 1983, Tucker, Vanpraet,

Boerwinkle & Gaston 1984). This research suggests that periodic visible and near-infrared observations of the Earth may be used to characterize the current status, seasonal dynamics and integrated seasonal magnitude of vegetation photosynthetic activity.

Advanced Very High Resolution Radiometer

Satellite-based remotely sensed observations have provided major impetus to vegetation studies based on spectral measurements. Satellites conveniently provide consistent, repeated coverage of all land areas. Much attention has been given to Landsat multispectral scanner (MSS) observations and selected studies have successfully used these measurements to analyze the regional extent, seasonality and productivity of natural and cultivated vegetation (Dethier 1974, Deering, Rouse, Hass & Schell 1974, NASA/JSC 1979, Thompson & Wehemenan 1979). However Landsat data are not well suited for global scale studies. The MSS 80 meter ground resolution produces a large data volume--over 6,000 MSS scenes are required for one observation of the Earth's total land area--and in cloudy regions of the globe, the 18 day repeat cycle produces too few cloud-free observations to record vegetation seasonal dynamics. The AVHRR sensor on the TIROS-N series of meteorological satellites, beginning with NOAA-6 launched in 1979, provides an alternate source of satellite visible and near-infrared measurements. With a 1.1 km nadir ground resolution and a daily repeat cycle, the AVHRR observations are well suited for large area studies. Several researchers have begun to use this new source of spectral measurements in vegetation studies and the results are encouraging (Townshend & Tucker 1981, Gatlin, Tucker & Schneider 1981, Gray & McCrary 1981, Greegor & Norwine 1981, Ormsby 1982, Justice 1983, Tucker & Townshend & Goff 1984).

The AVHRR is a multispectral imaging sensor that was designed to permit detection and discrimination between clouds, land, water, snow and ice (Schneider & McGinnis 1977). Spectral measurements are acquired in the visible, near infrared, middle infrared and thermal infrared regions, with four channels on the earlier AVHRR instruments on TIROS-N and NOAA-6 satellites and five channels on NOAA-7 and NOAA-8 (Table 1). AVHRR observations are available from the U.S. National Oceanic and Atmospheric Administration (NOAA) in several forms including High Resolution Picture Transmission (HRPT), Local Area Coverage (LAC), Global Area Coverage (GAC) and Global Vegetation Index (GVI) (Kidwell 1979). The HRPT data are direct transmission data to ground receiving stations. The LAC data are the original 1.1 km observations, which are only recorded and placed in archives on special request. The GAC data, which are regularly recorded and stored, are partially resampled LAC observations. GAC data are produced by calculating the average value of the first four pixels in a 3 x 5 array of LAC observations. The average value is then used to represent the 3 x 5 pixel area. The Global Vegetation Index data are weekly summaries of channel 1 and channel 2 GAC data which have been geographically registered on a polar stereographic map projection and processed to minimize cloud cover and atmospheric haze (Tarpley, Schneider & Morey 1983). One grid cell of the GVI data represents approximately a 15 x 15 km ground area at the equator and increases in size with latitude to approximately a 30 x 30 km ground area at the poles. For each day of observations one GAC data value is randomly selected from the 10 to 60 GAC pixels present within each of the GVI grid cells to represent that GVI cell. The normalized difference vegetation index is computed for each of the selected seven days measurements. Measurements from the day with the largest NDVI value are selected to represent the composite weekly value. The NDVI value for that day is recorded, along with the associated

channel 1 and channel 2 data, as the NDVI data. Selection of the maximum NDVI value minimizes the effects of clouds and haze and tends to emphasize near nadir rather than off nadir observations (Holben & Frazer 1983).

DATA AND METHODS

Two aspects of the North American AVHRR NDVI measurements are examined in this study; 1) seasonal variability and 2) the area under the curve (integral) defined by the temporal variation of the measurements over the growing season. Given current knowledge of spectral vegetation index measurements, the seasonal variations should be related to the phenology of vegetation green leaf display and hence absorbed photosynthetically active radiation and the integral of measurements over the growing season is expected to be related to annual net primary productivity (Monteith 1977). However these relations have not previously been examined at a continental scale, across the diversity of vegetation types encountered in North America. The degree to which spectral vegetation index measurements provide a general indicator of vegetation activity, independent of the species or species composition observed, is unknown.

AVHRR Global Vegetation Index data were selected for this study for convenience since considerable data processing is already accomplished and observations of the entire North American continent are contained in a 1024 x 1024 geographically registered grid. Observations from NOAA-7 are used because the nominal daylight overpass time is 1430 hours compared to 0730 hours for NOAA-6 and NOAA-8. The afternoon solar illumination conditions provide more uniform and intense radiance measurements than the low zenith angle solar radiation observed in the early morning overpasses. A disadvantage of the afternoon observations is that cloud cover is usually greater at this time because of daytime atmospheric convection. The analysis presented in this report examines observations from April to November in 1982. Preliminary

inspection of the winter (November to March) North American observations has revealed that low irradiance measurements near the polar terminator produce anomalous NDVI values. Restricting the current analysis to April through November avoids much of this problem while capturing the majority of the North American growing season north of 35°N latitude, with the exception of the central west coast (i.e., California, Oregon, and Washington). All processing of the data was carried out on the HP-1000 minicomputer of the Sensor Evaluation Branch at the Goddard Space Flight Center.

Three-week Composites

Seasonal variations in the spectral vegetation measurements were extracted from the data by forming three-week composites of the observations. Experience gained in analysis of NOAA-7 AVHRR data for the African continent has shown that at least three weeks of AVHRR observations must be composited to effectively remove cloud observations in cloudy regions of the continent (Tucker, Townshend & Goff 1984). The compositing follows procedures previously described for the NOAA Global Vegetation Index data; that is, for each grid cell in the data, the week with the highest NDVI value is selected to represent the three-week interval. The resultant composite map is taken to represent the state of spectral vegetation index measurements across the continent during that three week interval.

Thirty GVI weekly composites, extending from 12 April 1982 to 7 November 1982, were processed to form ten three-week composites. Examples of the three-week composites for April, June, August and October are provided in Figure 1. The NDVI value at each grid cell location is color-coded, dependent on its magnitude, as shown by the color bar in Fig. 1. The same color code is used for all the maps to permit interseasonal comparisons. A latitude-longitude coordinate grid, national boundaries and state boundaries in the United States are

superimposed on the image to aid interpretation.

Integrated NDVI Measurements

The area under the temporal curve was computed by trapezoidal integration of the three-week interval composite values at each grid cell location on the map. This resultant measurements are displayed in Fig. 2. The same color code used in Fig. 1 is used here with the exception that each value is multiplied by ten. These measurements are referred to as integrated NDVI ('NDVI) values.

RESULTS AND DISCUSSION

Seasonal NDVI Patterns

The three-week composites (Fig. 1) show that in general the NDVI measurements increase to a maximum in late August and thereafter decline. This seasonality is in agreement with the phenology of North American vegetation (Lieth 1974). High NDVI values move northward across the continent in the spring and summer and shift to the south in the fall. This green-wave and brown-wave phenomenon has previously been studied for selected regions of the continent with Landsat observations where it has been related to the seasonal pulse of photosynthetic activity in the vegetation present (Dethier 1974, Deering, Rouse Jr., Haas & Schell 1974, Blair & Baumgardner 1977).

The seasonal variations of NDVI measurements for regions of selected natural and cultivated vegetation types are presented in figure 3. These plots are the average of a 3 x 3 array of GVI three-week composite measurements, centered on the locations given. The observations are primarily from land dominated by natural vegetation although the effects of human activities in these locations cannot be entirely overlooked (e.g., irrigated agriculture). The plots in figure 3a are for locations where the seven months of AVHRR observations cover

the majority of the growing season. The Lovelock, Nevada observations of desert conditions are provided for comparison. As previously noted the measurements increase in the spring and decline in the fall. The magnitude of the summer measurements in general decreases with increasing latitude. Also, the duration of high summer values decreases to the north. However the grassland observations from Nebraska peak at lower summer values than the boreal coniferous forest but with a longer duration of elevated values. These trends in the NDVI measurements correspond with the observed phenological patterns of these vegetation formations (Lieth 1974).

The plots in figure 3b are for regions of the continent where the full growing season is not observed in this seven month period. The NDVI plots for both Oregon and California show high NDVI measurements in April suggesting a continuation of vegetation activity from the winter months. The California observations steadily decline throughout the observation period which agrees with the increased vegetation dormancy observed in this region through the arid summer. The Oregon observations remain at high values until September and thereafter decline, reflecting the more humid character of this region as well as the physiology of these coniferous forests (Waring & Franklin 1979). The South Carolina observations, from a region of pine forests, show a spring increase in the NDVI measurements and a small decline in the fall suggesting continued photosynthetic activity in the winter. No simple explanation of the mid-summer decline in NDVI values in South Carolina can be given. Several possibilities, including drought conditions in this region during 1982, cloud cover contamination, and atmospheric water vapor effects, may explain or contribute to an explanation of this pattern.

Representative temporal plots of NDVI measurements from prime agricultural regions are presented in Figure 3c. Both the corn-soybeans and spring wheat

regions green up later and senesce (and/or are harvested) earlier than local natural vegetation. The winter wheat observations show high values in April with a peak in June and declining values thereafter. The California Central Valley observations are high in April and decline until early July when they again increase to a maximum in late August. These temporal patterns are related to the calendar of cultivation and growth of crops which differs from natural vegetation phenology. This differential timing between cultivated and natural vegetation growth can be also be observed in the three-week composites where the prime cropland areas display distinctive patterns in the images. For example the winter wheat region, extending from north central Texas through central Oklahoma and Kansas, stands out as an island of high NDVI values in the April image whereas the cornbelt shows up as an area of low values in this same image.

The NDVI measurements and climatic conditions should be related if the NDVI measurements are a sensitive indication of vegetation activity (Holdridge 1947, Mather & Yashioka 1968, Odum 1971, Box 1981). The NDVI measurements, precipitation and temperature records fo Point Barrow, Alaska and Phoenix, Arizona for the seven month period are ploted in Figure 4. At Point Barrow the NDVI measurements only increase above 0.0 after mid-June, when the temperatures rise above 0°C, a condition essential for vegetation growth. In the Phoenix, Arizona region temperatures are always above freezing but moisture limits vegetation growth. NDVI measurements for Phoenix follow moisture seasonality, showing lower values in the dry season from April to July and an increase in late summer when rainfall increases. This interaction between the NDVI measurements and climatic conditions is suggestive of the value of spectral vegetation index measurements in regional- to global-scale vegetation phenology research.

Integration over the Growing Season

The map of integrated normalized difference vegetation index (∫NDVI) measurements (Fig. 2) displays a pattern of marked familiarity. The highest values occur in the southeastern and central west coast regions of the continent. The integrated measurements generally decrease to the north and west across North America but display more heterogeneity in the western one third of the continent. The north-south gradient of ∫NDVI measurements corresponds to the major temperature ecocline of North America, whereas the east-west gradient corresponds to the major precipitation ecocline of the continent (Whittaker 1970). The geographic complexity of the measurements in western North America is related to the mountainous terrain of the region. Note that elevation affects the measurements differentially dependent on latitude. North of 50°N latitude the ∫NDVI measurements decrease with increasing elevation. South of 40°N latitude the measurements increase with increasing elevation. This geography of ∫NDVI measurements compares well with the known patterns of North American natural vegetation activity (Shelford 1963, Kuchler 1966, Whittaker 1970, Odum 1971, Rodin, Bazilevich & Razov 1975, Lieth 1978).

The pattern of ∫NDVI values in certain areas of the continent, particularly in the United States, appear "anomalous" considering the natural vegetation and terrain of these locations. A region in the midwestern United States, extending from central Ohio to Iowa and including much of Indiana and Illinois, as well as portions of Wisconsin and Michigan, produce ∫NDVI values that are lower than might at first be expected. A similar area of relatively low ∫NDVI values extends north-south in the Mississippi River Valley from extreme southeastern Missouri through Arkansas and Tennessee to northwestern Mississippi. Conversely selected regions in the western United States, including the Columbia and Snake river basins in the Northwest, the Central and Imperial valleys in California

and several locations in the Great Plains, exhibit higher than expected ∫NDVI values. These locations correspond to the prime croplands in the United States (Fig. 5). The relatively low ∫NDVI values in the U.S. Midwest occur because this region produces low NDVI values both early and late in the growing season, prior to planting and following harvest. Most agriculture in the western portion of the U.S. depends upon irrigation to sustain plant growth which produces greater plant cover and thus higher ∫NDVI values than observed from natural vegetation of this semiarid region. These patterns correspond to the observed impact of agriculture on regional net primary productivity (Whittaker & Likens 1975).

∫NDVI Measurements and Net Primary Productivity

The relation between ∫NDVI measurements and net primary productivity (NPP) was examined by computing the mean ∫NDVI value for each of the major vegetation biomes of the continent and comparing these figures to net primary productivity figures reported in the literature. The North American biome map (Fig. 6) from Odum (1971) was used as a means to identify the natural vegetation formations. ∫NDVI samples were selected from sites within each formation based on the location of world weather observing stations used by World Meteorological Organization for global studies (NOAA 1982). These sites were selected since they are uniformly distributed, approximately every 5° of latitude and longitude, across the continent. There are an average ten stations within each major biome. For each station the mean of a 3 x 3 pixel array of ∫NDVI measurements, centered on the station location, was computed. The mean of all sites within each biome was then computed. These biome-averaged NDVI measurements were compared to net primary productivity figures provided by Whittaker & Likens (1975) supplemented by NPP figures for subclimax pine and pine/oak forests from Whittaker (1970) and values for the ecotones from Lieth (1978) and Rodin,

Bazilevich & Razov (1975). The results (Fig. 7) show a strong direct relation between the NDVI measurements and net primary productivity. Excluding agriculture the explained variance (r^2) of the relation is 0.94. With agriculture included the r^2 value drops to 0.89. Further investigation is required before these results are fully understood. However the correspondence between these two variables is sufficient to suggest that satellite-derived spectral vegetation index measurements will significantly improve global studies of vegetation productivity.

CONCLUSIONS

The results from this analysis of NOAA-7 AVHRR observations of the North American continent show that these high temporal frequency, large area spectral measurements of the Earth provide a major new source of information for investigations of terrestrial vegetation characteristics. Seasonal variations in the NDVI measurements agree with the known phenological patterns for natural and cultivated vegetation and, for natural vegetation, these temporal patterns vary in concert with climate conditions which limit plant growth. Annually integrated patterns of NDVI measurements correspond to known continental patterns of net primary productivity. The effects of human cultivation are clearly noted and these patterns agree with the known effects of agriculture on regional vegetation activity. Similar results have been derived other continents (Tucker, Townshend & Goff 1984, Justice, Townshend, Holben & Tucker 1984). Use of AVHRR observations in macroscale studies of vegetation should significantly improve knowledge of global vegetation dynamics. Availablity of several years of these high temporal frequency, globally consistant measurements will permit studies of interregional, interannual and seasonal vegetation phenomena not previously possible.

Much remains to be accomplished before the full value of the observations is realized. For example, interannual analysis of the data is needed and the effects of atmospheric conditions and sensor configuration on these measurements requires further investigation. However, even at this early stage of investigation, the results suggest that spectral vegetation index measurements provide a consistent and generalized means to conduct global vegetation studies. The AVHRR observations represent a major advance in realization of the promise of remotely sensed spectral observations for vegetation research because they provide the global overview of terrestrial conditions needed in multistage analysis of land conditions. An ability to observe the global distribution and dynamics of vegetation activity opens numerous new avenues of research for geographers, ecologists, climatologists and other earth scientists. Improved understanding of the earth's biosphere should result and at a time when concern is growing about human impact on the biosphere this new source of information is a welcome addition to the limited means available to study global biospheric activity.

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Table 1. Characteristics of the NOAA/AVHRR System

TIROS-N - launched Oct. 1978 - Protoflight NASA funded
NOAA-6 - launched June 1979 - NOAA funded
NOAA-7 - launched June 1981 - NOAA funded
NOAA-8 - launched March 1983 - NOAA funded

Coverage Cycle	9 days	Orbit Inclination	102°
Scan Angle Range	+ 56°	Orbital Flight	850 km
Ground Coverage	2700 km	Orbital Period	102 mins

IFOV	1.39-1.51 mr	Equatorial Crossing	Des. / Asc. 0730 / 1930 (NOAA 6 & 8) 1430 / 0230 (NOAA 7)
Ground Resolution	1.1 km (nadir) 3.5 km (max off angle)		
Quantization	10 bit		

Spectral Channels	1	2	3	4	5
Spectral Range (μm)	0.58-0.68*	0.725-1.1	3.55-3.93	10.3-11.3	11.5-12.5**

* Channel 1 range on TIROS-N 0.55-0.90
** NOT ON NOAA 6

FIGURE CAPTIONS

Fig. 1. Three-week composite maps of North American normalized difference vegetation index measurements for April, June, August and October 1982. The measurements are color-coded dependent on magnitude as displayed on the color bar in the center of the figure.

Fig. 2. Map of NDVI measurements integrated over the April to November 1982 observation period. The integration was computed by trapezoidal approximation of the area under the curve subtended by the ten three-week composite NDVI measurements. The ∫NDVI measurements are displayed with a color code equivalent to that used in Fig. 1 except that the numerical valves are ten times larger.

Fig. 3. Temporal variations of the normalized difference vegetation index measurements for selected sites of natural and cultivated vegetation types. Vegetation-type identification was by means of maps presented in Fig. 5 and Fig. 6. The ploted measurements are the mean of a 3 x 3 array of NDVI measurements centered on the cited locations. (a) Natural vegetation observed over the growing season, (b) natural vegetation with a growing season extending into winter months (c) cultivated vegetation.

Fig. 4. Comparison of normalized difference vegetation index measurements and climate data for Point Barrow, Alaska and Phoenix, Arizona. The NDVI measurements were computed in the same manner as those presented in Fig. 3. The climate observations are thirty-year averages from the NOAA world weather station records (NOAA 1982).

Fig. 5. Percentage of land in cultivation for the United States. This map helped to explain the "anomalous" areas observed in the integrated NDVI map (Fig. 2). From World Atlas of Agriculture (1968). Authorized reproduction by Istituto Geografico De Agostini, Novara, Italy.

Fig. 6. Distribution of major biomes in North America. This map was used to determine the natural vegetation types on the continent for the ∫NDVI-net primary productivity analysis. The detailed western vegetation subregions were grouped to form the woodland and scrub category (sage subclimax, sagebrush, coastal chaparrel and pinon-juniper) and the desert category (desert scrub and creosote-bush desert). From Fundamentals of Ecology, 3rd ed. by Eugene P. Odum. Copywright (c) 1971 by Saunders College Publishing. Reprinted by permission of CBS College Publishing.

Fig. 7. Plot of biome-averaged ∫NDVI measurements versus published mean biome net primary productivity rates. For each biome a well-distributed sampled of ∫NDVI measurements (~90 per biome) were used to compute the biome average. The net primary productivity figures are predominantly from Whittaker and Likens (1975), supplemented with values from Whittaker (1970), Rodin, Bazilevich and Razov (1975) and Lieth (1978). The explained variance (r^2) of the relation is 0.89. Excluding agricylture raises the r^2 value to 0.94.

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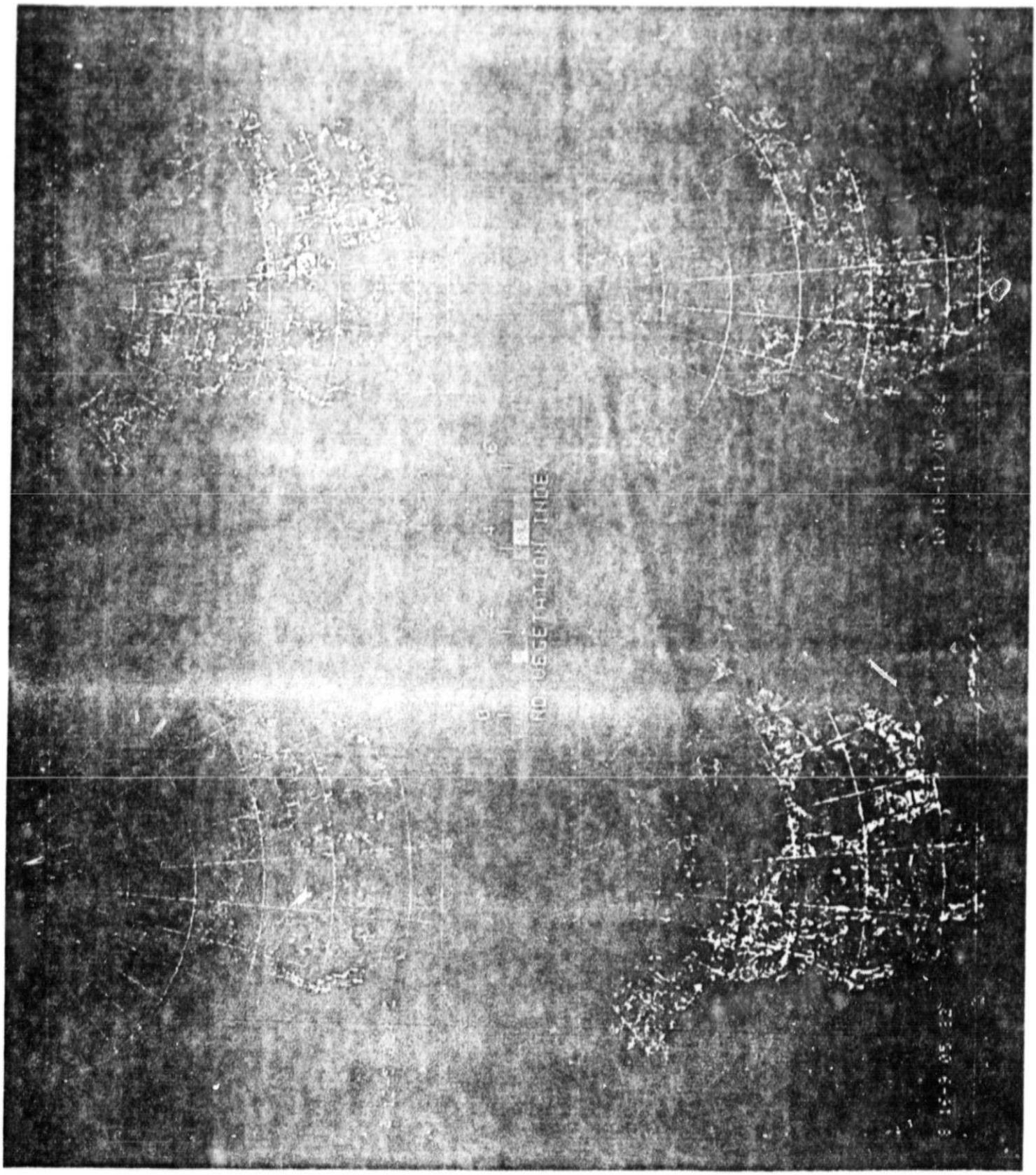

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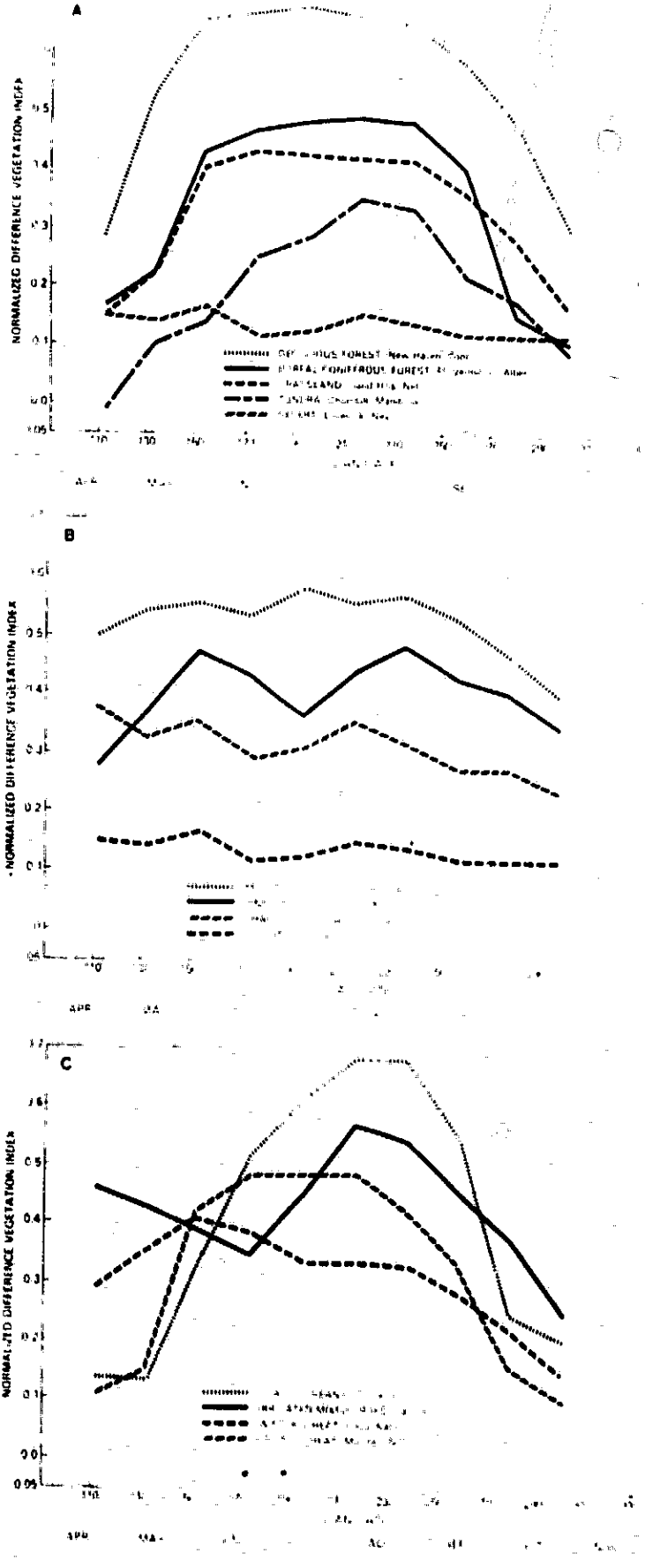
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B
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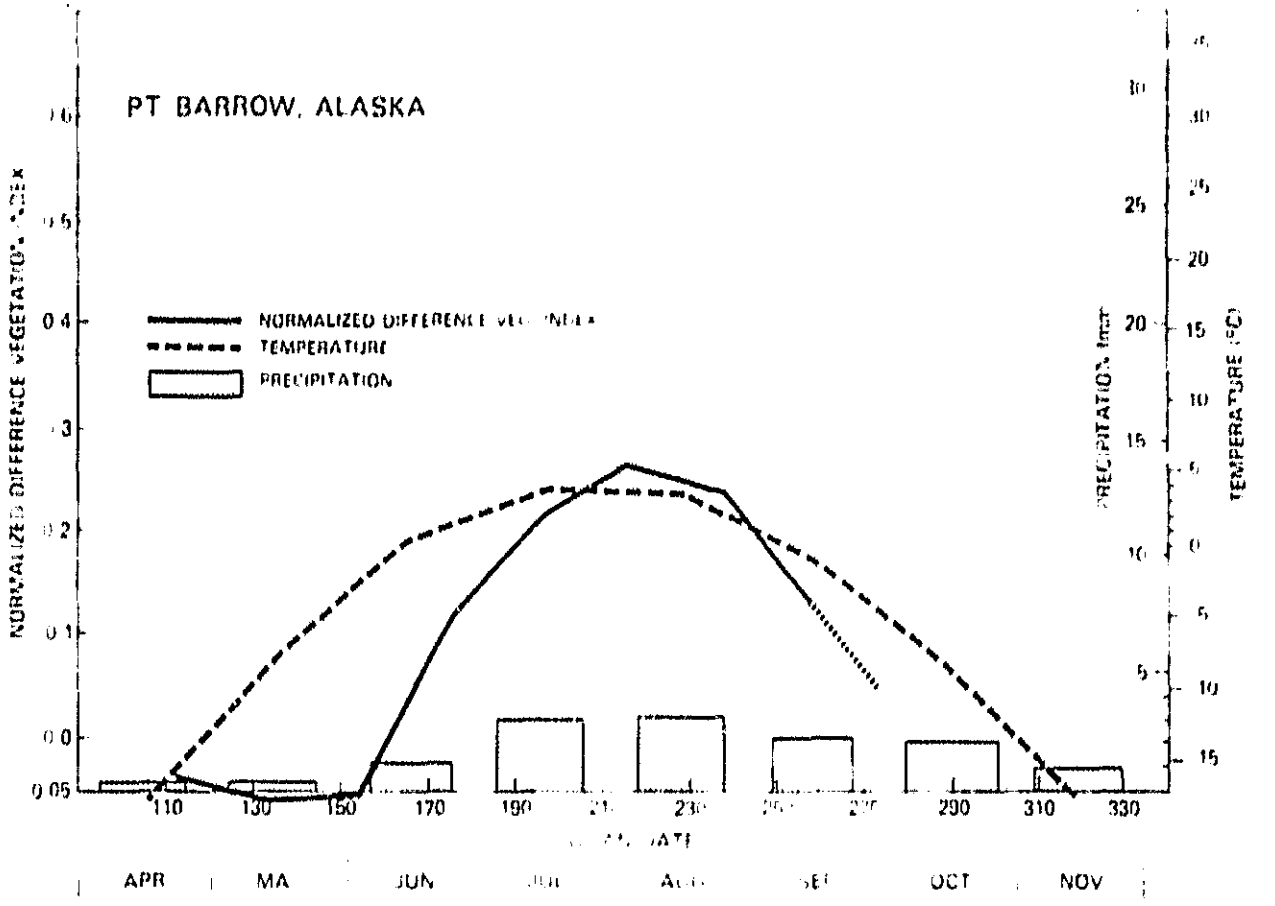
NORMALIZED DIFFERENCE VEGETATION INDEX
NORMALIZED DIFFERENCE VEGETATION INDEX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NORMALIZED DIFFERENCE VEG INDEX
TEMPERATURE
PRECIPITATION
PRECIPITATION (mm)
TEMPERATURE (°C)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.05
30
25
20
15
10
5
0
5
10
15
110
130
150
170
190
210
230
250
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290
310
330
JULIAN DATE
APR
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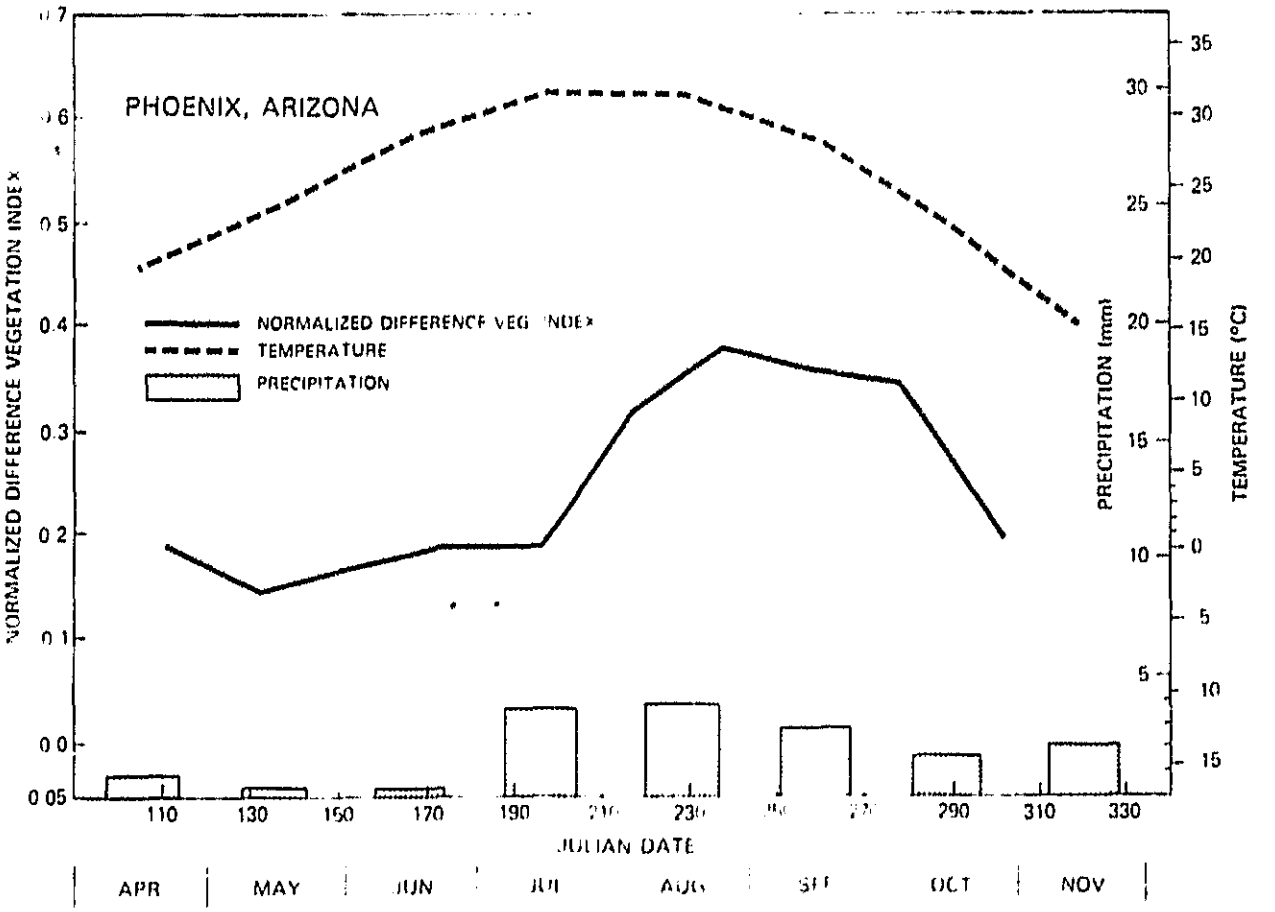
PHOENIX, ARIZONA
NORMALIZED DIFFERENCE VEGETATION INDEX
NORMALIZED DIFFERENCE VEG INDEX
TEMPERATURE
PRECIPITATION
PRECIPITATION (mm)
TEMPERATURE (°C)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.05
35
30
25
20
15
10
5
0
5
10
15
110
130
150
170
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APR
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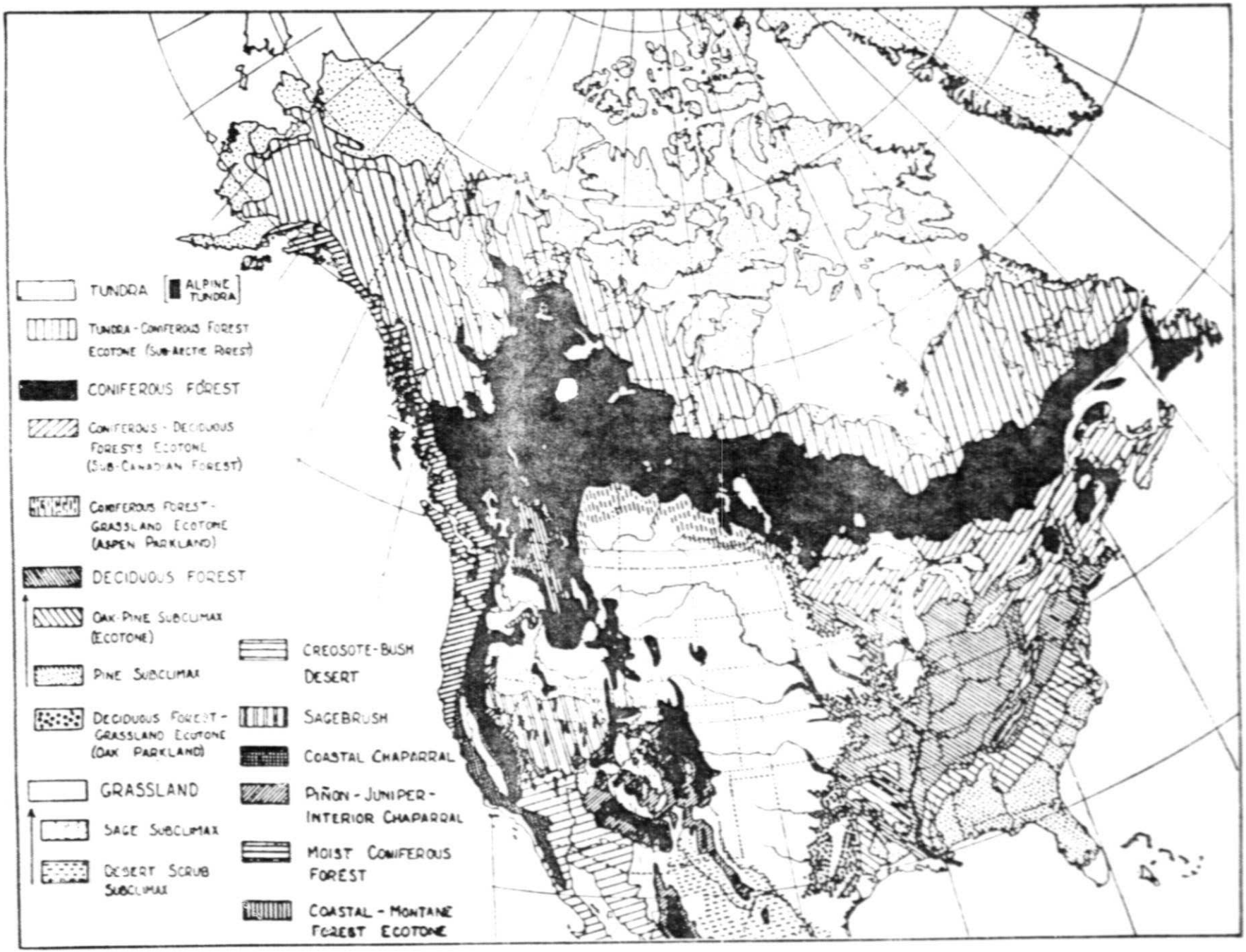

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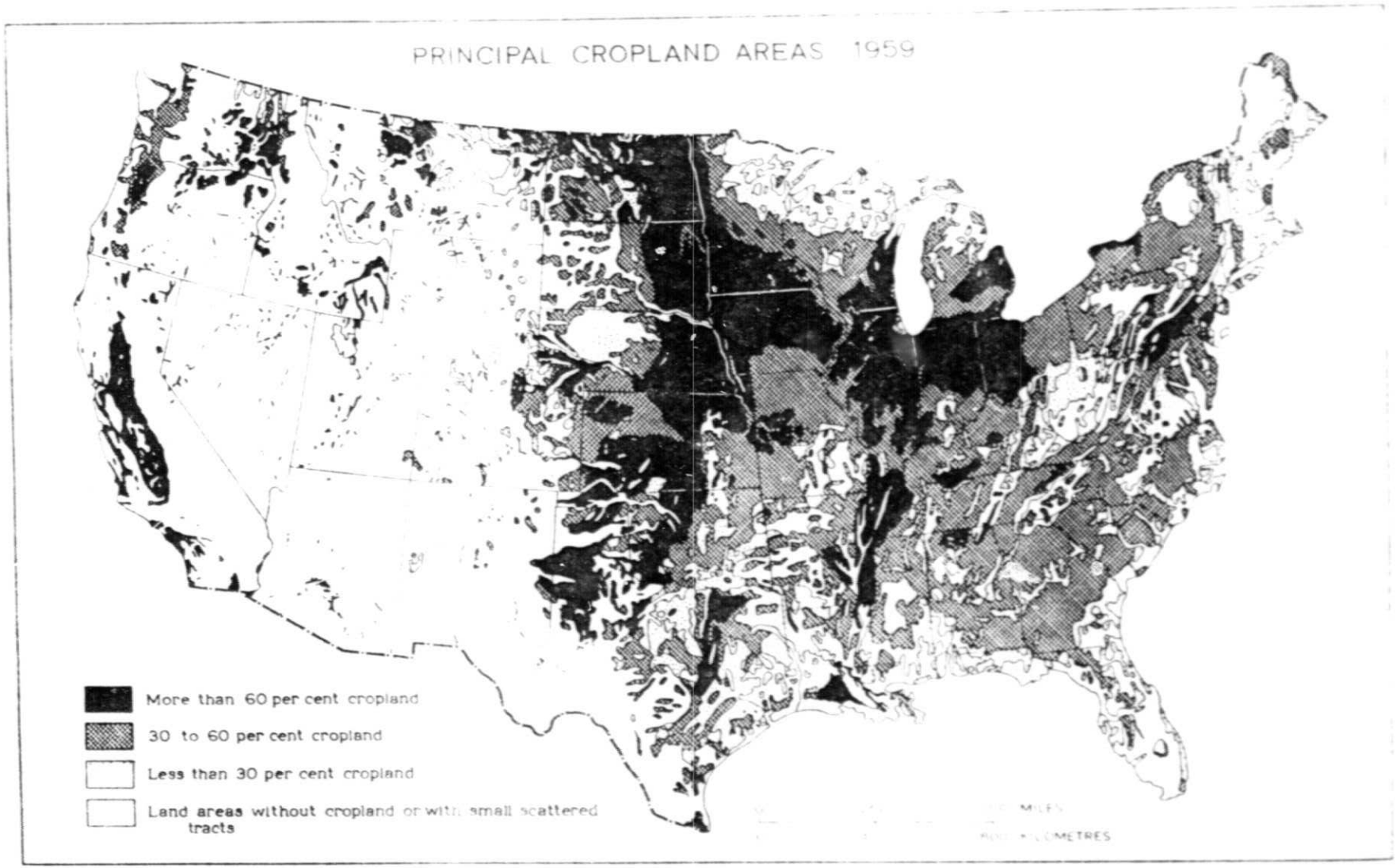

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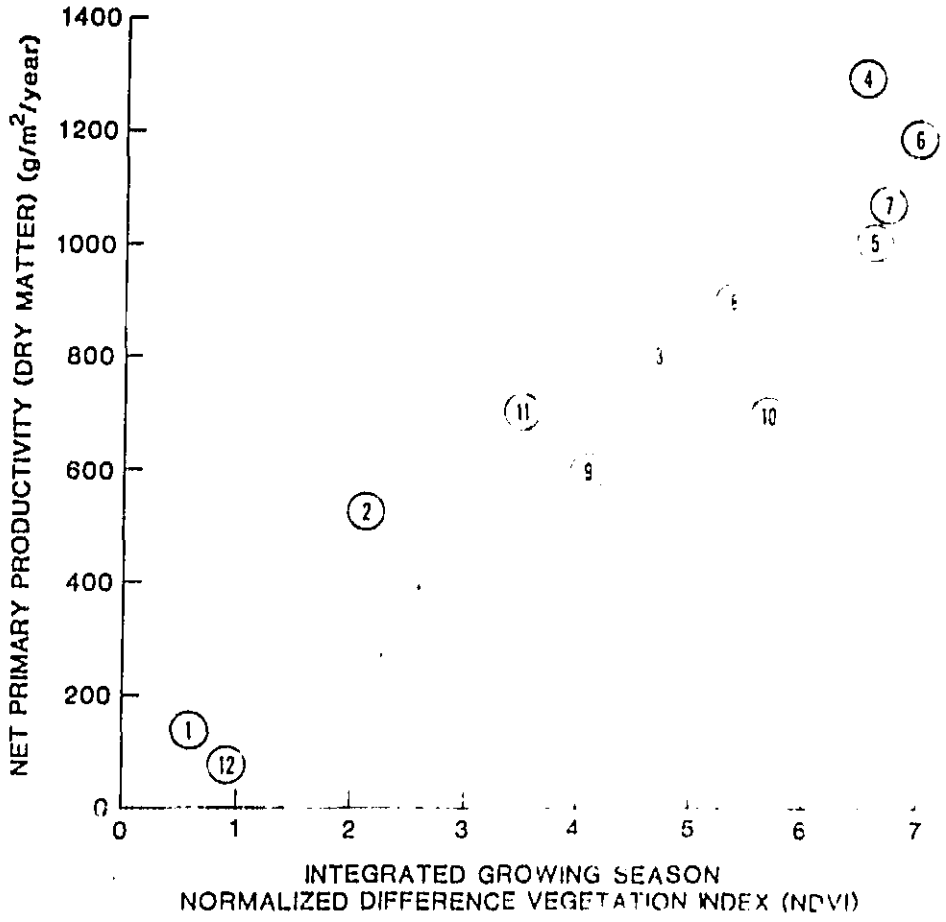

(1) TUNDRA
(2) TUNDRA-CONIFEROUS ECOTONE
(3) BOREAL CONIFEROUS
(4) TEMPERATE MOIST CONIFEROUS
(5) CONIFEROUS-DECIDIOUS ECOTONE
(6) DECIDIOUS
(7) OAK-PINE SUBCLIMAX
(8) PINE SUBCLIMAX
(9) GRASSLAND
(10) CULTIVATED
(11) WOODLAND & SCRUB
(12) DESERT