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# Correlation between atmospheric $CO_2$ concentration and vegetation greenness in North America: $CO_2$ fertilization effect

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ABSTRACT: The possibility that rising atmospheric $CO_2$ concentrations are influencing plant growth in contemporary ecosystems has received little attention, and the studies that exist have been done on a small spatial scale. We correlated the monthly rate of relative change in normalized differenced vegetation index (NDVI) from advanced very high resolution radiometer (AVHRR) data to the rate of change in atmospheric $CO_2$ concentration during the natural vegetation growing season for evidence of a possible $CO_2$ fertilization effect on vegetation development. The study addressed seasonal and annual patterns in spatially averaged NDVI for 3 different ecological regions in North America from 1982 to 1992. Correlations between $CO_2$ and NDVI were calculated for 3 different lag conditions. Relatively high and positive correlation coefficients were found when the monthly rate of change in NDVI was 1 mo lagged to that for $CO_2$, which suggests, but does not prove, a $CO_2$ fertilization effect on natural vegetation development. Generally, the correlation coefficients changed from relatively high and positive correlations when NDVI was lagged 1 mo behind $CO_2$ to relatively high and negative correlations when $CO_2$ was lagged 1 mo behind NDVI. A general increase in the annual maximum greenness of the vegetation was also found in most of the regions studied from 1982 to 2001. The desert and humid temperate regions in the eastern part of North America showed an increase in the annual minimum vegetation greenness, while the southern humid temperate regions showed relatively high correlations between the minimum NDVI and atmospheric $CO_2$ concentration in interannual comparisons. The results of this study are generally consistent with the notion of a contemporary $CO_2$ fertilization effect, but they also demonstrate how remotely sensed data can be used to explore the effects of global change at large scales in order to complement experimental results obtained on smaller temporal and spatial scales.

KEY WORDS: Global change · Climate change · $CO_2$ fertilization effect · NDVI · Remote sensing · Vegetation

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## 1. INTRODUCTION

The atmospheric $CO_2$ concentration has been increasing since the end of the 18th century, but at a rate that is substantially lower than the rate of new carbon inputs to the atmosphere from fossil fuel combustion and deforestation (Schlesinger 1997). The increase rate of atmospheric $CO_2$ has been slowed by an increase in the sink function of oceans and perhaps terrestrial ecosystems. Efforts to balance the global atmospheric $CO_2$ budget indicate that there is an enhanced terrestrial sink of $1.4 \pm 1.5$ Gt $yr^{-1}$ (90% confidence interval) in the Northern Hemisphere due to forest regrowth (Lambers et al. 1998, Chen et al. 1999, Schimel et al. 2000). An increase in net primary productivity (NPP) in North America has also been suggested by remote sensing data sets and carbon cycle models (Keeling et al. 1996, Myneni et al. 2001, Hicke 2002).

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One of the causes of enhanced terrestrial uptake of $CO_2$ may be a stimulation of photosynthesis by elevated atmospheric $CO_2$ concentration (Melillo et al. 1993). There is substantial evidence from controlled experiments that elevated $CO_2$ will stimulate future terrestrial photosynthesis (Curtis 1996, Körner 2000). In such experiments, net primary production often increases by 30% or more in response to a doubling of the atmospheric $CO_2$ concentration (DeLucia et al. 1999). However, it is far less certain whether the so-called '$CO_2$ fertilization' will persist or diminish over time due to nutrient limitation (Oren et al. 2001, Hungate et al. 2003), or whether the enhancements last only a short period of time (Oren et al. 2001). Another uncertainty is whether rising $CO_2$ has already influenced the metabolism of contemporary terrestrial ecosystems (e.g. Gill et al. 2002).

Unlike a controlled experiment, it is difficult to establish a direct relationship between contemporary changes in atmospheric $CO_2$ concentration and vegetation growth through observation because of the simultaneous influence of many other climatic, geographical and anthropogenic factors. However, contemporary observations offer means to investigate such relationships at large scales using the normalized difference vegetation index (NDVI) derived from the advanced very high resolution radiometers (AVHRR). NDVI/AVHRR is a reliable index for describing the surface vegetation greenness, which reflects the condition of the biomass in a given area (Asrar & Myneni 1991). Using $CO_2$ and NDVI data sets, the relationship between changes in atmospheric $CO_2$ concentration and vegetation development can be examined in natural environments. The goal of our study was to complement investigations on the influence of atmospheric $CO_2$ content on vegetation growth in controlled experimental environments to contemporary natural environments at regional and global scales using remote sensing data sets.

## 2. THEORETICAL BASIS

One of the difficulties in investigating the influence of atmospheric $CO_2$ on vegetation development is the strong seasonal oscillation in both time series (Fig. 1). $CO_2$ and NDVI oscillations are both driven by photosynthetic $CO_2$ consumption (Keeling et al. 1996), such that the correlation between the vegetation development and atmospheric $CO_2$ concentration is negative. Thus, a direct correlation of NDVI and atmospheric $CO_2$ concentration does not provide a proper criterion to understand how changes in atmospheric $CO_2$ concentration may or may not influence vegetation foliage development.

Examining the interannual variation in NDVI and atmospheric $CO_2$ concentration for the same month (i.e. performing a climatology analysis) alone does not clarify how atmospheric $CO_2$ concentration influences vegetation development, as vegetation growth also depends on interannual climate anomalies in tempera-

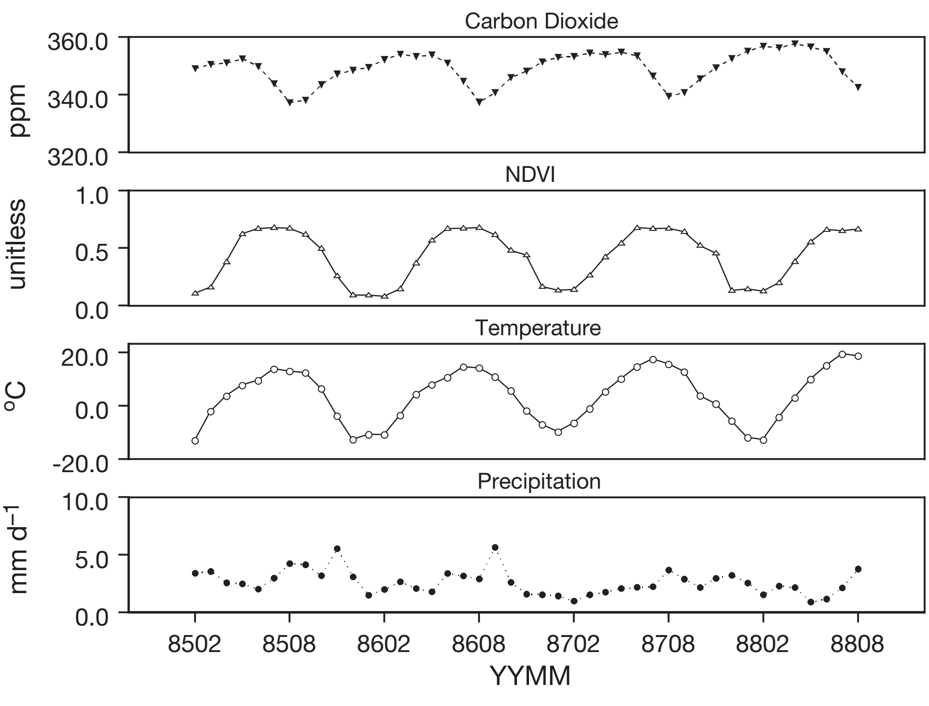


Fig. 1. Annual and seasonal trends in precipitation (mm $d^{-1}$), surface temperature (°C) and normalized difference vegetation index (NDVI) for Region H3, and $CO_2$ concentration at Point Barrow, Alaska, from February 1985 to August 1988. YYMM: year and month

ture, precipitation, and the El Niño Southern Oscillation (ENSO) (Myneni et al. 1996, Lambers et al. 1998, Lim & Kafatos 2002, Gurgel & Ferreira 2003). Thus, it is desirable to examine the correlation between the atmospheric $CO_2$ concentration and NDVI within the same year, as well as inter-annually.

Both atmospheric $CO_2$ concentration and NDVI are time-dependent variables. As the vegetation assimilates $CO_2$ from the atmosphere, the rate of change in the atmospheric $CO_2$ concentration should track the rate of change in the amount of foliage (Keeling et al. 1996, Idso et al. 2000). When there is a large increase in foliage, the vegetation will consume more $CO_2$ from the atmosphere, and a relatively large decrease in atmospheric $CO_2$ concentration will follow. Hence, changes in $CO_2$ concentration driven by changes in vegetation growth are expected to produce a negative correlation between NDVI change in a given month and $CO_2$ concentration change in the following month. Such a correlation can be interpreted as the influence of vegetation development on the atmospheric $CO_2$ concentration. On the other hand, if a change in atmospheric $CO_2$ in a given month precedes a change in NDVI the following month, and the correlation is positive, this will suggest (but not prove) a possible $CO_2$ fertilization effect.

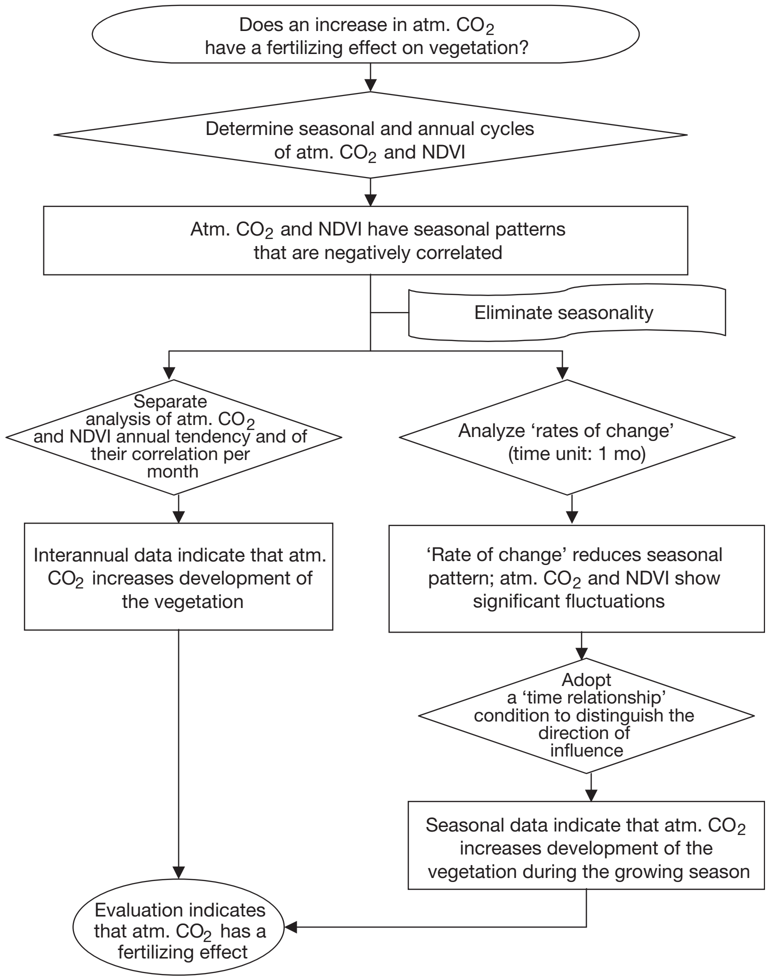


Fig. 2. Approach to investigate the relation between changes in atmospheric $CO_2$ and changes in vegetation greenness

The increase or decrease in the values of variables such as NDVI and atmospheric $CO_2$ concentration can be expressed as a rate of change, which is a measurement of the variables' fluctuation (Kent 1960). We examined the correlations between the rates of change in NDVI and atmospheric $CO_2$ concentration to investigate a possible $CO_2$ fertilization effect (Fig. 2). The overall study period was from 1982 to 1992, based on data availability.

To simplify the relationship between atmospheric $CO_2$ and plant growth we assumed a 1-way influence at a time between atmospheric $CO_2$ and plant growth only, without considering how this relationship changes year-to-year due to specific climate anomalies. Finally, we compared how temperature, precipitation, and atmospheric $CO_2$ correlate with vegetation canopy condition interannually for each month, including the annual minimum vegetation greenness indicated by the original NDVI values (not the rate of change).

## 3. METHODS

### 3.1. Data

Correlations were calculated between NDVI, atmospheric $CO_2$ concentration, and temperature and precipitation in a time-delayed or time-advanced order over the growing season. Time lag conditions have been used for examining relationships between vegetation and climate factors such as precipitation (Gurgel & Ferreira 2003) or climate anomalies such as ENSO (Lim & Kafatos 2002).

NDVI is an index describing relative vegetation greenness based on the fact that the first AVHRR channel is in a part of the spectrum where chlorophyll causes considerable absorption of incoming radiation, and the second channel is in a spectral region where spongy mesophyll leaf structure leads to considerable reflectance. NDVI is (Ch2 R – Ch1 R)/(Ch2 R + Ch1 R), where R is reflectance

(Asrar & Myneni 1991, ftp://eosdata.gsfc.nasa.gov/data/avhrr/Readme.pal). To minimize influences of atmospheric particles on the reflectance from the ground to the instrument, atmospheric correction is applied after reflectance is calibrated. NDVI can be lower than the true vegetation greenness when there is continuous snow cover during a month. However, the monthly NDVI composites use the maximum reflectance of the month, and since our study excluded wintertime data and used monthly composites, the possible underestimate is minimal.

We used TIROS Operational Vertical Sounder (TOVS) 1 × 1 degree surface skin temperature data, Global Precipitation Climatology Project (GPCP) 1 × 1 degree global combined precipitation data, Carbon Dioxide Information Analysis Center (CDIAC) Trends ′93 $CO_2$ data measured at Barrow, Alaska, and NDVI/AVHRR (8 × 8 km) data. GPCP data are spatially averaged by weighted mean to quantify the error associated with each pixel; pixels with smaller errors are given more weight using reciprocals of the errors. All the data are in the public domain and available electronically from the National Aeronautics and Space Administration (NASA) Goddard Earth Sciences (GES) Distributed Active Archive Center (DAAC) site (http://daac.gsfc.nasa.gov).

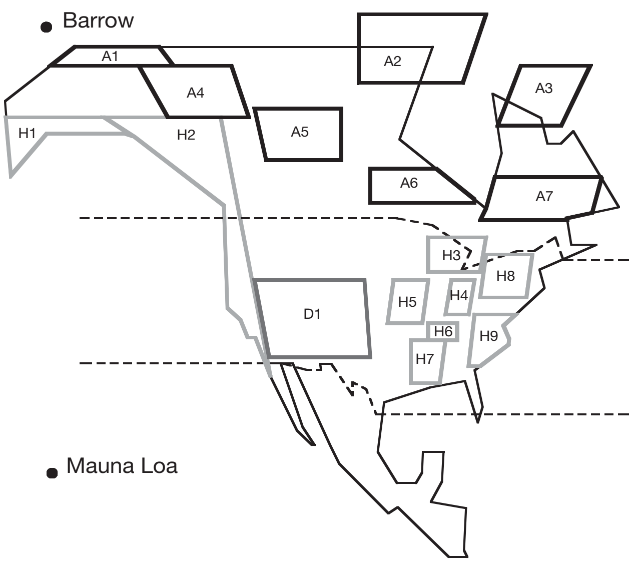


Fig. 3. Subdivisions of 3 ecological regions in North America, and location of 2 $CO_2$ measuring stations (Mauna Loa, Hawaii and Barrow, Alaska). (A) Arctic and Sub-Arctic Zone—Tundra altitudinal zone, polar desert: (A1) Alaska North; tundra province, Arctic Ocean moss-grass tundra: (A2) Hudson Bay North, (A3) Hudson Bay East; sub-arctic altitudinal zone: open woodland and woodland-tundra: (A4) Klondike; sub-arctic province: (A5) Great Slave, (A6) Hudson Bay South, (A7) Mid-Canada East. (H) Humid Temperate Zone—Marine altitudinal zone: (H1) Alaska south, (H2) Pacific coast; moderate continental province: (H3) Great Lakes; warm continental province: (H4) Indiana-Illinois; Prairie province: (H5) Inland Prairie; humid subtropical province: (H6) Southern Appalachia, (H7) Mississippi Delta; warm continental altitudinal zone: (H8) Mid-Atlantic North; humid subtropical province: (H9) Mid-Atlantic South. (D) Dry and Desert Zone: (D1) Temperate desert province

### 3.2. Ecological regions

NDVI values are based upon radiation reflected by the canopy surface (Kidwell 1994). Because different vegetation types have different characteristic leaf area indices (Running & Nemani 1988), the same NDVI value may represent different levels of photosynthetic activity for different vegetation types. Thus, to properly utilize NDVI it is necessary to divide the region investigated into zones of an optimum size that captures the vegetation type. We adopted a zonal division according to Rand McNally Goode's World Atlas Ecoregions (Espenshade 1995), which closely agrees with the USGS-NASA North America Land Cover Characteristics Data Base Version 2.0 (http://lpdaac.usgs.gov/glcc/glcc.asp). The longitude and latitude coordinates were modified to use pixel coordinates of remote sensing data sets (Lim & Kafatos 2002).

We applied a large-scale eco-region classification and divided North America into 3 different zones: Arctic and Sub-Arctic Zone (A), Humid Temperate Zone (H), and Dry and Desert Zone (D).

In the eco-zones in North America, maximum vegetation greenness occurs around August and the minimum is around February. Zones were subdivided according to vegetation types: 7 subdivisions in Zone A, 8 in Zone H, and 1 in Zone D (Fig. 3). There is relatively greater diversity in vegetation types in the Humid Temperate Zone than in the other zones. Although all the sub-regions were studied for relationships of NDVI to CO2, we focused on the Humid Temperate Zone for a more detailed analysis to examine how different vegetation types correlated with $CO_2$.

### 3.3. Vegetation periods in each region

The seasonal pattern of vegetation development depends on the climate and geography of a location (Starr 1994, Miller 1996). Arctic and sub-arctic tundra provinces have a much shorter growing season than forests or grasslands in humid temperate regions, and this must be taken into account when investigating correlations between vegetation growth and atmospheric $CO_2$ concentration. The growing periods of the vegetation were determined for each region on the basis of monthly NDVI time series (Fig. 4). The growing periods in our study include the month of the annual minimum vegetation greenness, because this provides the initial condition of the vegetation growth in that particular growing season.

### 3.4. Correlation coefficient and associated error

We used a Pearson product-moment coefficient of correlation (Hogg & Craig 1978). The calculation of the correlation coefficient incorporates the errors of the 2 measurements, NDVI and atmospheric $CO_2$ concentration. If $\mu_x$ is the mean of a value $x$ and $\mu_y$ is the mean of $y$, $\sigma_x$ is the SD of $x$ and $\sigma_y$ is the SD of $y$, and $E$ is the expected value, the fractional SD of $x$ and $y$, which are $\sigma_x/x$ and $\sigma_y/y$, in general correspond to their errors. We assume that the errors of the variables $x$ and $y$ are known, thus $\sigma_x\sigma_y$ is a constant. The fractional SD of their correlation coefficient $r$, $\sigma_r/r$, is approximately determined by the term $xy$ in $E\,[(x - \mu_x)(y - \mu_y)]$. That is, $(\sigma_r/r)^2 = 1^2(\sigma_x/x)^2 + 1^2(\sigma_y/y)^2$ (Young 1962).

Therefore, the approximate error of $r$ for an assumed 10% error of NDVI and a 10% error of $CO_2$ measurement is $r = (1^2\ 0.1^2 + 1^2\ 0.1^2)^{1/2} = 0.02^{1/2} \approx 0.14 = 14\%$, and for a 10% error of NDVI and a 15% error of $CO_2$ measurement is $r = (1^2\ 0.1^2 + 1^2\ 0.15^2)^{1/2} = 0.0325^{1/2} \approx 0.18 = 18\%$.

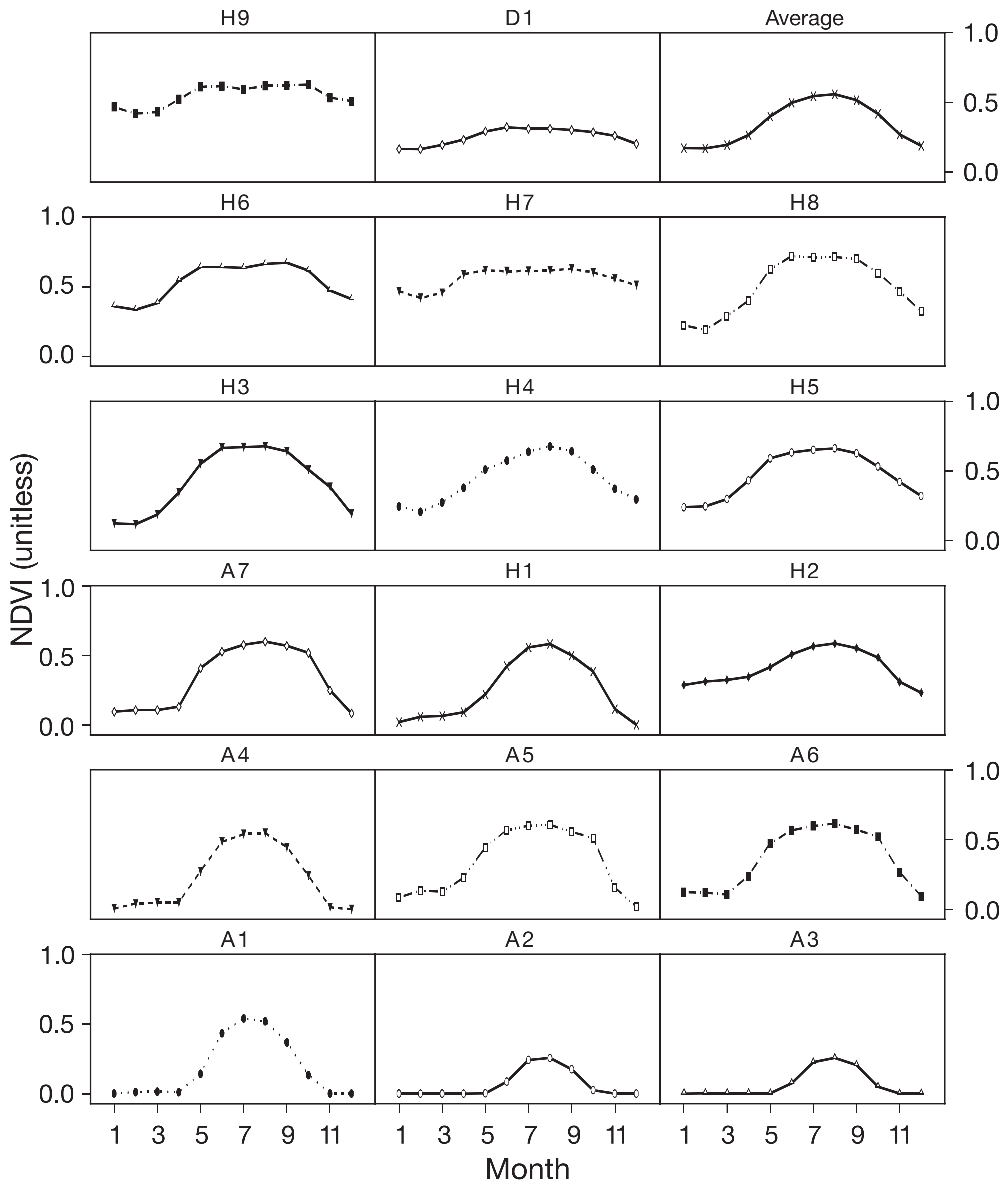


Fig. 4. Monthly vegetation greenness index (NDVI) averaged over 11 yr for January to December 1982–1992. See Fig. 3 for description of regions

## 4. RESULTS

### 4.1. NDVI correlation with temperature, precipitation and atmospheric $CO_2$

Although temperature has a seasonal pattern similar to those of atmospheric $CO_2$ concentration and plant growth, precipitation does not have a regular seasonal pattern in North America (e.g. Fig. 1). Monthly NDVI in Zone H was interannually correlated with precipitation, temperature and atmospheric $CO_2$ concentration during the same month for the 11 yr from 1982 to 1992 (8 yr from 1985 to 1992 for temperature). Correlations were found for all months (Fig. 5). The absolute values required for a significant correlation of n = 11 sample years is >0.52 at the 90% confidence level with a 2-tailed test, and >0.60 at the 95% confidence level (Bendat & Piersol 2000).

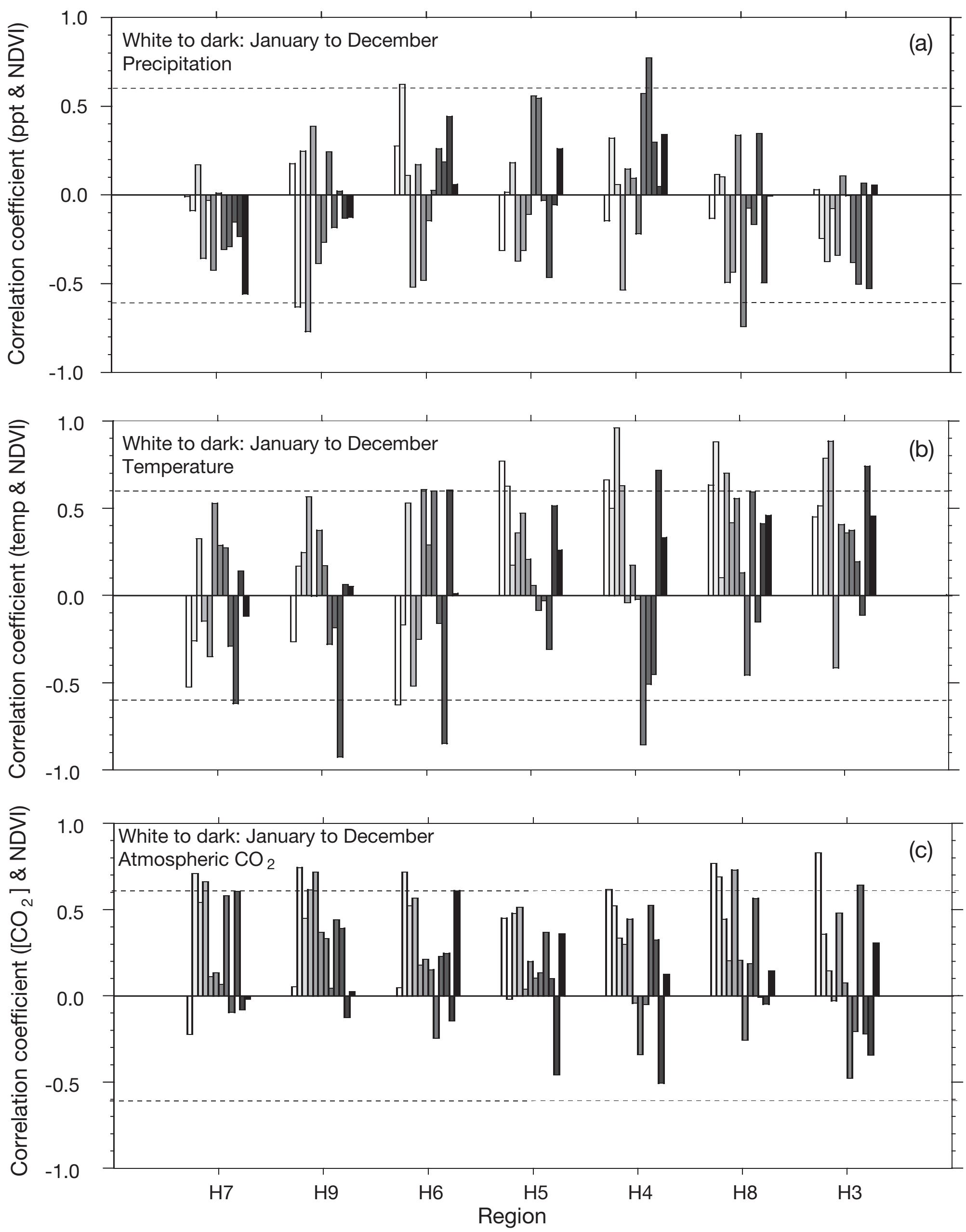


Fig. 5. Correlation coefficients between NDVI and (a) precipitation, (b) surface temperature (°C), and (c) atmospheric $CO_2$ concentration at Point Barrow, Alaska. Data are for 1982–1992 (1985–1992 for temperature). See Fig. 3 for description of regions

4.1.1. Precipitation

Mostly negative correlations were found between monthly precipitation and NDVI for Regions H7, H9, H8 and H3 (Fig. 5a); these regions are adjacent to permanent water bodies (H7 to the Gulf of Mexico, H9 and H8 to the Atlantic Ocean, and H3 to the Great Lakes). The negative correlations were significant at the 95% confidence level for H9 in February and April, and H8 in August.

The inland regions, H4 to H6, have both positive and negative correlations, between monthly precipitation and NDVI. The correlations were positive and significant for H6 in February and H4 in August and September. These mixed (positive and negative) temporal correlations are different from spatial correlations trends between precipitation and vegetation development. For example, Lieth (1975) found a non-linear positive correlation between mean annual precipitation and NPP among different locations, but in that study, variation was between locations, whereas in our study variation was interannual within particular regions.

4.1.2. Temperature

The correlation between temperature and NDVI was mostly positive (Fig. 5b). This agrees with the commonly accepted positive relationship between temperature and NPP (Lieth 1975, Lambers et al. 1998). The positive relationship between temperature and vegetation development was more prominent for northern temperate regions. The correlations were positive and significant at the 95% confidence level for: H5 in January and February; H4 in January, March, April and November; H8 in January, February, April and September; H3 in March, April and November. The correlations were negative and significant for H7 and H9 in October, and H4 in August.

4.1.3. Atmospheric $CO_2$

In the northern temperate regions there was also a positive relationship between atmospheric $CO_2$ and NDVI (Fig. 5c). This relationship was more consistently positive than the correlation between NDVI and temperature. The correlations were positive and significant for: H7 in February and April; H9 in February, April and May; H6 in February and December; H4 in January; H8 in January, February and May; H3 in January and September. There was no a significant negative correlation between $CO_2$ and NDVI.

The positive correlations that dominate Fig. 5c appear to occur independently of the other eco-regions. In paired comparisons among eco-regions, >24% of the pairs have no correlation or negative correlations in monthly NDVI averaged among the regions interannually from 1982 to 1992; 50% had R < 0.31 or negative correlation coefficients. The substantial percentage of low or negative correlations in monthly NDVI average among eco-regions indicates that the positive correlations between atmospheric $CO_2$ and NDVI are not due to correlations in NDVI among the regions.

### 4.2. Case study for the Great Lakes region

We selected the Great Lakes region (H3) for a case study of the relationship between monthly changes in atmospheric $CO_2$ and vegetation development,

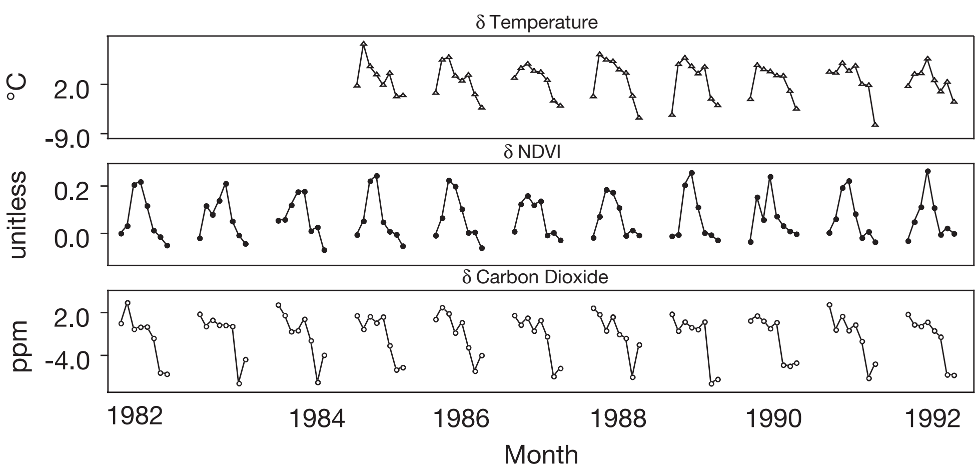


Fig. 6. Annual and seasonal trends in rate of change (δ) per month in surface temperature (°C) and NDVI for Region H3, and in $CO_2$ concentration at Point Barrow, Alaska, during the growing seasons (February) 1982–1992

because it is relatively small and located near several other ecosystems (sub-arctic zone to the north, and prairie to the southwest). The vegetation in this region is composed of mixed coniferous and broadleaf forest.

We examined the correlation between rate of change in NDVI and rate of change in temperature and atmospheric $CO_2$ concentration for 6 intervals within the period between February, when the average NDVI begins to increase, and August, when the average NDVI begins to decrease (Fig. 4). The seasonal patterns (Fig. 1) were largely eliminated by considering the rate of change. Fig. 6 shows the annual and seasonal trends in the rate of change per month for surface temperature (δT) and NDVI (δNDVI), and the rate of change in $CO_2$ concentration ($\delta CO_2$) measured at Point Barrow, Alaska, during the growing season from 1982 to 1992. We used Point Barrow $CO_2$ data to examine relationships between $CO_2$ and vegetation in H3 because Point Barrow is the closest station to H3 that measures atmospheric $CO_2$ concentration on a global scale. We also used the same $CO_2$ data for all other regions in the study, since Point Barrow $CO_2$ data reflect seasonal change of vegetation greenness of these regions better than Mauna Loa, Hawaii, data. $CO_2$ mixes relatively well in the atmosphere; however, the minimum atmospheric $CO_2$ concentration at Mauna Loa occurs 1 or 2 mo after the minimum at Point Barrow, and their seasonal amplitudes are also different. Therefore, $CO_2$ levels at Point Barrow are expected to lag behind those existing in Region H3 less than those at Mauna Loa.

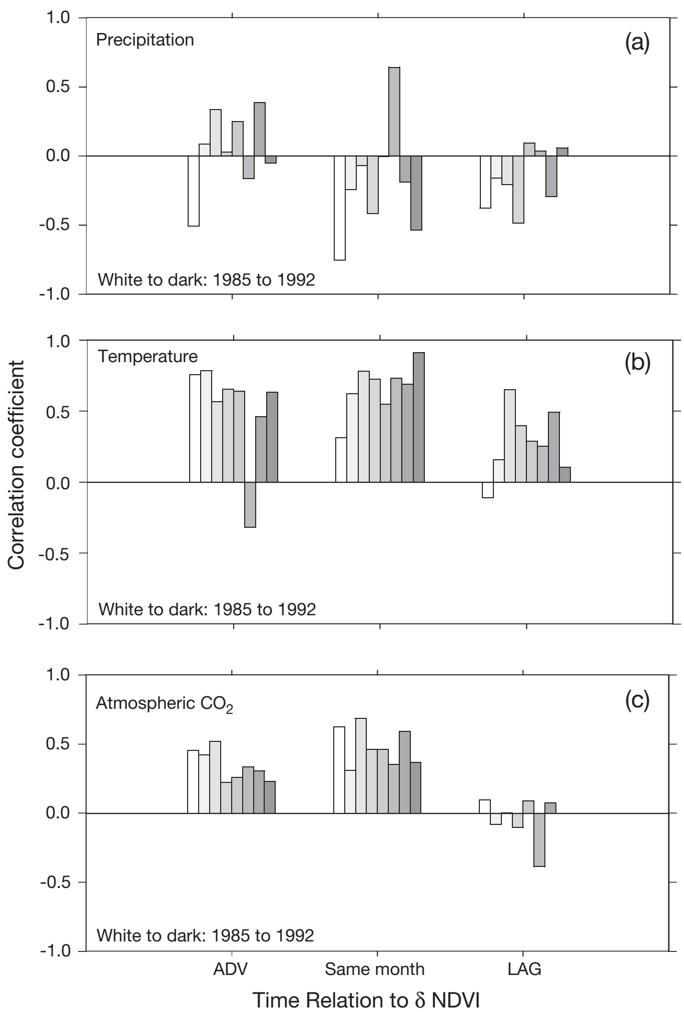


Fig. 7. Correlation coefficients between the rate of change per month in (a) precipitation, (b) surface temperature (°C), and (c) atmospheric $CO_2$ concentration at Point Barrow, Alaska, and the rate of change (δ) per month in NDVI over the growing season for Region H3. ADV: 1 mo advanced; LAG: 1 mo lagged

#### 4.2.1. Precipitation

The rate of change in the precipitation (δP) mostly had a negative correlation with δNDVI of the same month (Fig. 7a, center), as was the case with the interannual relationship of the original values (Fig. 5a). When δNDVI was correlated with δP in the previous month, however, the correlations in the majority of years were positive (Fig. 7a, left). This result is similar to that for a northern region of Brazil, where the vegetation increased in greenness in response to the rainfall during the previous month (Gurgel & Ferreira 2003).

#### 4.2.2. Temperature

δT was positively correlated to the same month's δNDVI (Fig. 7b, center). It also showed positive correlations with the following month's δNDVI (Fig. 7b, right), which may indicate a high correlation in temperatures between the growing months and each previous month (average R = +0.83 for the temperature, and +0.57 for δT).

#### 4.2.3. Atmospheric $CO_2$

δNDVI was positively correlated with $\delta CO_2$ of the same month, and it also had a positive correlation with $\delta CO_2$ of the following month (Fig. 7c, center and left).

The positive correlation between δNDVI and atmospheric $CO_2$ concentration disappears or becomes a negative correlation when the $CO_2$ content is lagged 1 mo. This reflects the negative feedback of $CO_2$ assimilation by the vegetation on the atmospheric $CO_2$ concentration. This change in the correlation indicates that the 'rate of change' approach we adopted to inves-

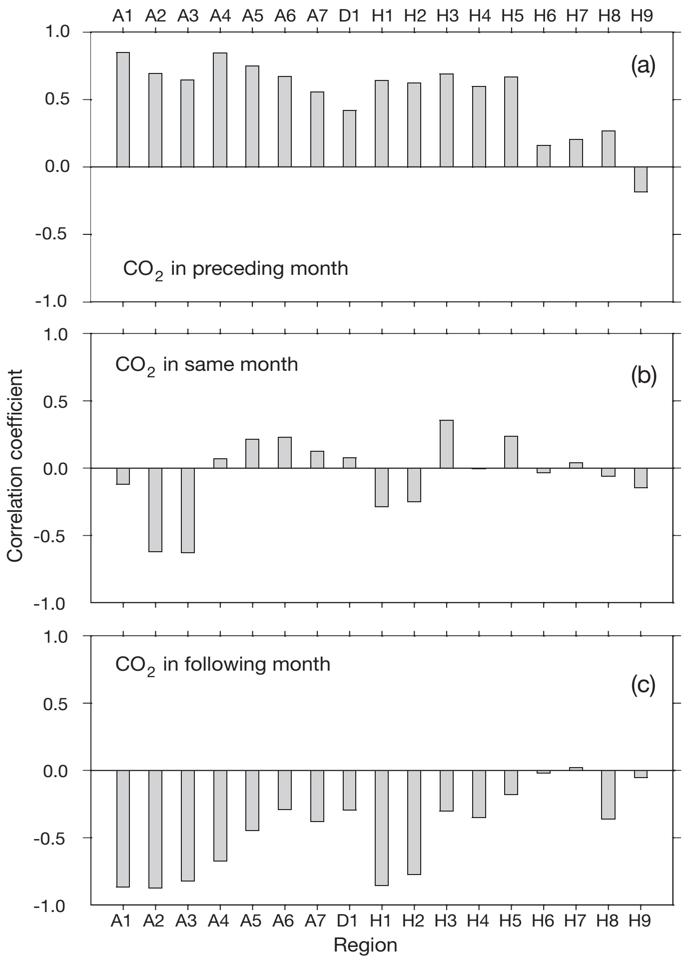


Fig. 8. Correlation coefficients between monthly changes in atmospheric $CO_2$ concentration ($\delta CO_2$) measured at Point Barrow, Alaska, and monthly changes in NDVI (δNDVI). $\delta CO_2$ is (a) 1 mo advanced to δNDVI, (b) the same month as δNDVI, and (c) 1 mo lagged to δNDVI. See Fig. 3 for description of regions

tigate the influence of atmospheric $CO_2$ concentration on vegetation development is reasonable.

### 4.3. Rates of change in NDVI and atmospheric $CO_2$ concentration

$\delta CO_2$ also showed a yearly cyclic pattern, but with much weaker regularity (Fig. 6) than the original $CO_2$ concentration (Fig. 1). Unlike the annual cycle in atmospheric $CO_2$ concentration, the cycle in the rate of change is irregular, and we were thus able to observe patterns that had been obscured by the regular annual pattern of rising and falling atmospheric $CO_2$ concentration.

Fig. 8 shows 11 yr (1982–1992) average coefficients between $\delta CO_2$ concentration and δNDVI during the growing season. For example, for H8 the correlation coefficients shown are for the 7 monthly intervals from February to September (Fig. 4). In all regions except one, $\delta CO_2$ was positively correlated with the rate of change in vegetation greenness in the following month, and most correlations were high. This is consistent with a $CO_2$ fertilization effect. Fig. 8c shows that $\delta CO_2$ was negatively correlated with changes in vegetation greenness of the previous month, which reflects the $CO_2$ assimilation by the vegetation. Fig. 8b shows that there is no clear correlation between simultaneous changes in $CO_2$ levels and greenness.

The positive correlation in the rate of change between atmospheric $CO_2$ and vegetation development is more prominent for the arctic and sub-arctic regions A1 to A7, the west humid temperate regions (H1 and H2) and northwestern regions of the east humid temperate zone (H3 to H5) than in the temperate desert region (D1) and the southern and eastern regions of the east humid temperate zone (H6 to H9). The lack of correlation between NDVI in the SE regions and atmospheric $CO_2$ concentration may be due to their great distance from Point Barrow, and may not necessarily indicate that atmospheric $CO_2$ did not influence vegetation growth in these regions. In fact, all 4 regions (H6, H7, H8 and H9) show high positive correlations between NDVI and atmospheric $CO_2$ concentration interannually in the earliest months of the growing season (Fig. 5).

The approach used in this study cannot identify the cause of the positive correlation between $\delta CO_2$ and δNDVI in the following month, as opposed to experimental manipulations, which can identify cause and effect. However, it is difficult to scale experimental results to large areas and there is always the possibility of experimental artifacts, whereas our approach uses remote sensing data sets that could be extended to a global scale. Our interpretation of the positive correlation between changes in atmospheric $CO_2$ and greenness is consistent with experimental manipulations of atmospheric $CO_2$ (700 to 1000 ppm above ambient) that report a stimulation of photosynthesis and aboveground productivity at high $CO_2$ (Curtis 1996, DeLucia et al. 1999).

### 4.4. Annual minimum NDVI increase

We observed strong positive correlations between interannual variation in NDVI and both temperature and atmospheric $CO_2$ concentration for the early months of the growing season (Fig. 5b,c). This indicates the possibility of annual trends in minimum vegetation greenness, which normally occurs in February in the eastern humid temperate zone. Fig. 9 shows the correlation coefficients between NDVI values (not rate

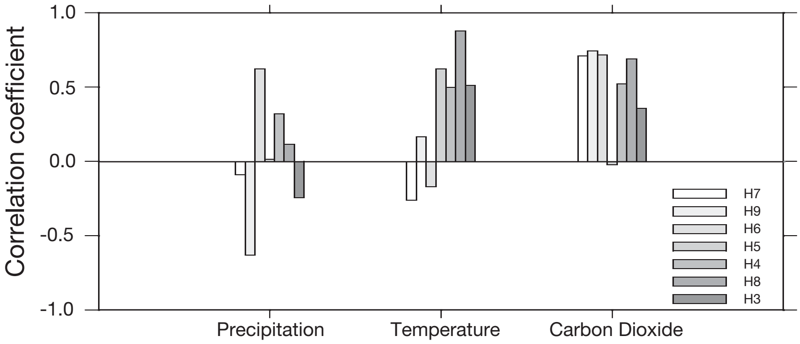


Fig. 9. Correlation coefficients between NDVI and precipitation (mm $d^{-1}$), temperature (°C) and atmospheric $CO_2$ concentration measured at Point Barrow, Alaska, for February 1982–1992 (1985–1992 for temperature). See Fig. 3 for description of regions

of change) and precipitation, temperature and atmospheric $CO_2$ concentration for February 1982–1992 (1985–1992 for temperature).

Precipitation had a positive relationship with the minimum vegetation greenness for Region H6 and a negative one for Region H9. Other regions did not show strong correlations between the annual minimum NDVI and precipitation.

The minimum vegetation greenness in the southern regions H6, H7 and H9 showed a relatively high correlation between atmospheric $CO_2$ increase and minimum vegetation greenness (Fig. 9).

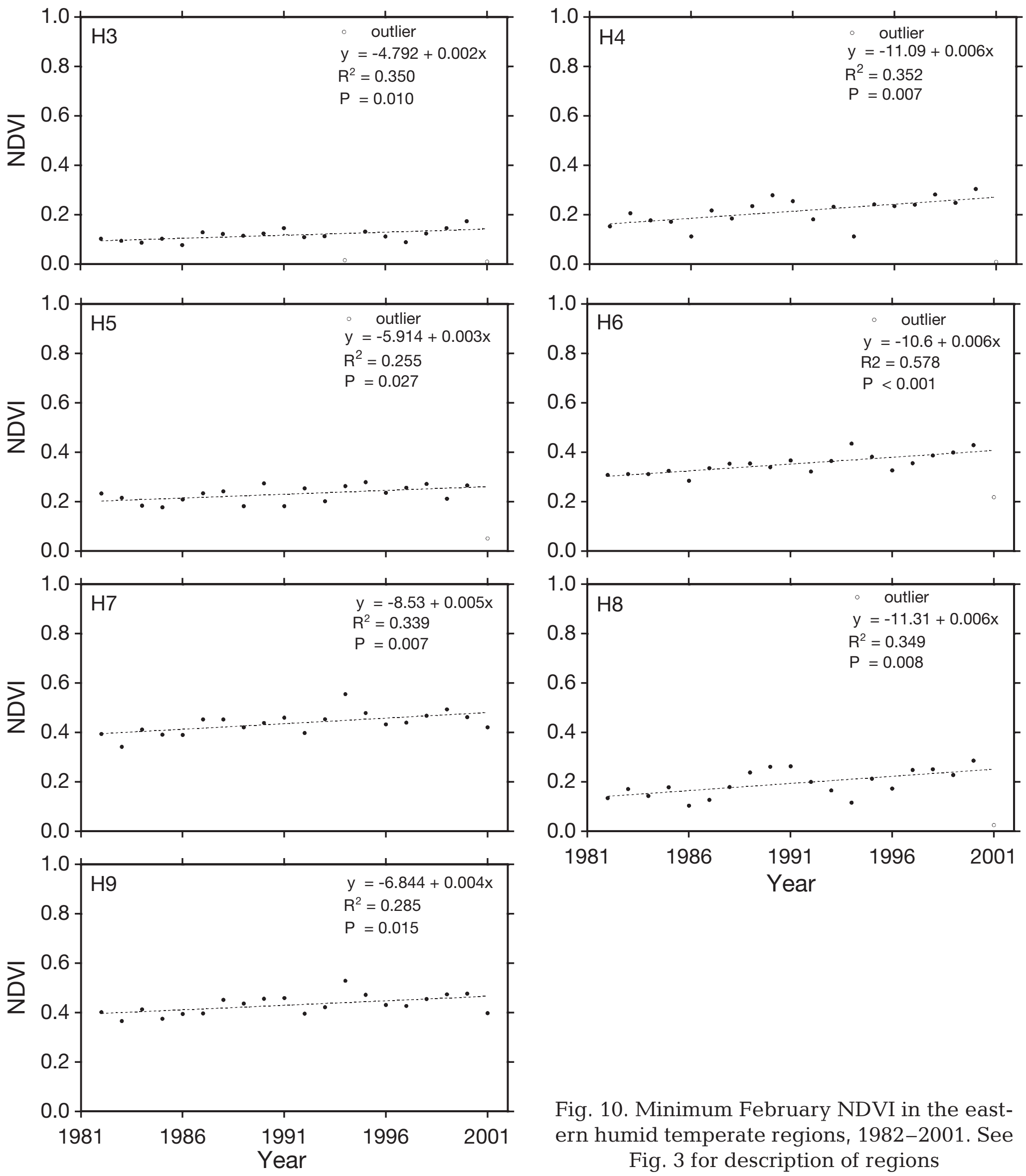


Fig. 10. Minimum February NDVI in the eastern humid temperate regions, 1982–2001. See Fig. 3 for description of regions

The northern temperate regions H4 and H8 also showed a positive correlation between atmospheric $CO_2$ increase and minimum vegetation greenness. The minimum vegetation greenness in Regions H3, H4 and H8 were correlated with temperature as well as atmospheric $CO_2$. In Region H5 the minimum vegetation greenness was positively correlated with temperature, but not with atmospheric $CO_2$. In general, the minimum vegetation greenness increased over the period 1982–2001 for all the regions of the eastern humid temperate zone in North America (Fig. 10).

These correlations are consistent with recent trends in temperature and atmospheric $CO_2$, both of which influence plant productivity. Remote sensing data has been used to show a lengthening of the growing season in North America over roughly the same period of time (Myneni et al. 1997), and this has been ascribed to global warming (Walther et al. 2002). Rising $CO_2$ could also increase minimum greenness by stimulating photosynthesis at the beginning of the growing season (Idso et al. 2000).

## 5. DISCUSSION AND CONCLUSIONS

Over the growing seasons from 1982 to 1992, $\delta CO_2$ was positively correlated with δNDVI in the following month in most eco-regions of North America. Even though it does not constitute proof, these results are consistent with a $CO_2$ fertilization effect and are difficult to explain by other mechanisms. This result is consistent with a recent report of a century-long decline in stomatal conductance in plants across northern Eurasia, which was interpreted as an effect of elevated $CO_2$ (Saurer et al. 2004).

The positive relationship between atmospheric $CO_2$ concentration and NDVI was significant during the early months of the growing season for all the regions examined, and weakened later in the growing season. This is consistent with an experiment showing that atmospheric $CO_2$ enrichment induced a large but transient increase in early spring branch growth (Idso et al. 2000).

All the eastern humid temperate regions generally showed significant increases in minimum vegetation greenness over the period studied, as well as positive correlations with temperature and atmospheric $CO_2$ increase. Unlike atmospheric $CO_2$ and temperature, precipitation did not show a clear positive or negative correlation with vegetation growth, either during the growing season or interannually. Our study is an example of how remotely sensed data can be used to explore the effects of global changes at large scales in order to complement experimental manipulations that are performed on smaller scales of time or space.

## LITERATURE CITED


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