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Geographical distribution of global greening trends and their climatic correlates: 1982–1998

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We examined trends in vegetation activity at the global scale from 1982 to 1998 using a recently developed satellite-based vegetation index in conjunction with a gridded global climate dataset. Vegetation greening trends were observed in the northern high latitudes, the northern middle latitudes, and parts of the tropics and subtropics. Temperature, and in particular spring warming, was the primary climatic factor associated with greening in the northern high latitudes and western Europe. Temperature trends also explained greening in the US Pacific Northwest, tropical and subtropical Africa, and eastern China. Precipitation was a strong correlate of greening in fragmented regions only. Decreases in greenness in southern South America, southern Africa, and central Australia were strongly correlated to both increases in temperature and decreases in precipitation. Over vast areas globally, strong positive trends in greenness exhibited no correlation with trends in either temperature or precipitation. These areas include the eastern United States, the African tropics and subtropics, most of the Indian subcontinent, and south-east Asia. Thus, for large areas of land that are undergoing greening, there appears to be no climatic correlate. Globally, greening trends are a function of both climatic and non-climatic factors, such as forest regrowth, CO_2 enrichment, woody plant proliferation, and trends in agricultural practices.

1. Introduction

The global surface air temperature increased by about 0.5°C between the mid-1970s and the late 1990s (Hansen *et al.* 1999). These changes are geographically stratified. The northern middle and high latitudes have warmed most rapidly, by about 0.8°C since the early 1970s, while the tropics have warmed only moderately (Hansen *et al.* 1999). In addition, global land precipitation increased by about 2% during the 20th century (Jones and Hulme 1996, Hulme *et al.* 1998). Precipitation changes have also exhibited substantial spatial and temporal variability (Karl and Knight 1998, Doherty *et al.* 1999, Mekis and Hogg 1999, Zhai *et al.* 1999).

Increases in temperature and moisture may increase vegetation activity by lengthening the period of carbon uptake (Nemani *et al.* 2002), enhancing photosynthesis (Keeling *et al.* 1996, Randerson *et al.* 1999), and changing nutrient availability by accelerating decomposition or mineralization (Melillo *et al.* 1993). Such processes have important implications for carbon sink/source dynamics,

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changes in the distribution of terrestrial biomes, and food production (Tans *et al.* 1990, Schimel *et al.* 1996).

Several studies have documented greening trends in the northern high latitudes (Tucker *et al.* 2001, Zhou *et al.* 2001, Bogaert *et al.* 2002, Slayback *et al.* 2003) as well as in other large geographical regions (e.g. Kawabata *et al.* 2001, Nemani *et al.* 2003, Xiao and Moody 2004a). However, numerous questions remain regarding the distribution and drivers of trends in vegetation greenness. The focus of this paper is on two questions: (1) what is the geographical distribution of dominant trends in vegetation activity globally? and (2) what are the primary climatic correlates of these trends and patterns? To address these questions, we used a recently developed satellite-measured vegetation index dataset, in conjunction with a gridded global climate dataset, to examine trends in vegetation activity and their associations to climatic drivers in the period 1982–1998. In particular, we emphasize the geographical variability in these bioclimatological associations.

2. Background

The satellite-measured normalized difference vegetation index (NDVI) has been widely used to characterize vegetation activity (Asrar *et al.* 1984, Myneni *et al.* 1995, 1997, Tucker *et al.* 2001, Zhou *et al.* 2001, Xiao and Moody 2004b). NDVI captures the contrast between the visible-red and near-infrared reflectance of vegetation canopies, and is indicative of the abundance and activity of leaf chlorophyll pigments (Asrar *et al.* 1984, Myneni *et al.* 1995). NDVI is closely correlated to the fraction of photosynthetically active radiation (fPAR) absorbed by vegetation canopies, and thus can be used as a proxy for photosynthetic activity of terrestrial vegetation at a global scale (Asrar *et al.* 1984, Myneni *et al.* 1995).

Satellite-based NDVI observations over the past two decades (Myneni *et al.* 1997, Tucker *et al.* 2001, Zhou *et al.* 2001, Bogaert *et al.* 2002, Slayback *et al.* 2003), as well as model predictions based on observed climate data (Lucht *et al.* 2002), have identified a vegetation greening trend in the northern high latitudes (40° N–70° N), especially in Eurasia. The greening trend corresponds to the pronounced warming, particularly during winter and spring over Alaska, northern Canada, and northern Eurasia (Hansen *et al.* 1999). The greening trend is also consistent with ground-based phenological observations (Colombo 1998, Cayan *et al.* 2001, Fitter and Fitter 2002), as well as reports of increased terrestrial carbon stock in woody biomass in these regions (Fan *et al.* 1998, Myneni *et al.* 2001, Schimel *et al.* 2001, Goodale *et al.* 2002). Temperature is thought to be the leading climatic factor controlling the high-latitude greening trend, which has been attributed to an early spring and a delayed autumn (Tucker *et al.* 2001, Zhou *et al.* 2001, Bogaert *et al.* 2002, Lucht *et al.* 2002). Precipitation has been assumed to play a minor role in increasing vegetation activity and has not been fully considered in most studies.

At the global scale, Kawabata *et al.* (2001) and Ichii *et al.* (2002) used the National Oceanic and Atmospheric Administration/National Aeronautics and Space Administration (NOAA/NASA) Pathfinder AVHRR (Advanced Very High Resolution Radiometer) Land (PAL) NDVI dataset (James and Kalluri 1994), combined with gridded climate data, to examine correlations between trends in vegetation activity and climate for the period 1982–1990. Even over this short period, their results illustrated the strong correlation between northern mid-to-high latitude greening and temperature increases. They also identified decreases in greenness in the Southern Hemisphere tropics to mid latitudes. These were correlated with variability in precipitation. Nemani *et al.* (2003) modelled the changes in net primary production (NPP) globally from 1982 to 1999 using both climatic and satellite observations, and indicated that net primary production increased 6%, and the largest increase was in tropical ecosystems. Xiao and Moody (2004a) examined trends in vegetation activity and their climatic correlates in China between 1982 and 1998 using both climatic and satellite data. Temperature was the leading climatic factor controlling greening patterns in China, but trends in agricultural practices, such as increased use of high-yield crops and application of chemical fertilizers, along with land-use changes such as afforestation and reforestation probably have made a greater contribution to the greening trend than temperature (Xiao and Moody 2004a).

Trends in vegetation productivity may indicate changes in terrestrial carbon stock in vegetation biomass, and thus have implications for the global carbon cycle (Goulden *et al.* 1996, Keeling *et al.* 1996, Myneni *et al.* 1997). However, the relative contributions of temperature and precipitation to observed greening trends, and in particular their geographical distribution, patterns and drivers are not resolved. Zhou *et al.* (2001), Tucker *et al.* (2001), Lucht *et al.* (2002) and Ichii *et al.* (2002) argued that temperature is the leading climatic factor in controlling the greening trend in the northern high latitudes. In the conterminous US, by contrast, Nemani *et al.* (2002) showed that increases in precipitation and humidity are the most important factors enhancing vegetation activity.

In this paper we present an analysis of greening trends, bioclimatological patterns and associations at the global scale. Compared to recent studies by Kawabata *et al.* (2001) and Ichii *et al.* (2002) we extend the period of analysis from 1982–1990 (9 years) to 1982–1998 (17 years). This extension is possible due to the recent availability of global, half-degree AVHRR NDVI data (Nemani *et al.* 2003) that has been reprocessed and substantially improved over the earlier, shorter-term version of the PAL dataset (James and Kalluri 1994). This dataset not only allows the evaluation of the longevity and change in the trends reported by Kawabata *et al.* (2001) and Ichii *et al.* (2002), but also permits more statistically conservative and reliable assessment of these trends and relationships.

3. Data and methods

3.1 *Data*

3.1.1 Satellite data. We analysed data for the period 1982–1998 for which we had access to both satellite and climate data. We used a recently developed Version 3 Pathfinder NDVI dataset (Nemani *et al.* 2003) derived from AVHRR on board the NOAA's series of polar-orbiting meteorological satellites (NOAA 7, 9, 11 and 14). This NDVI dataset is the improved version of the NOAA/NASA PAL NDVI dataset (James and Kalluri 1994). The NDVI captures the contrast between the visible-red and near-infrared reflectance of vegetation canopies. It is defined as

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED})/(\mathrm{NIR} + \mathrm{RED}) \qquad (1)$$

where RED and NIR are the visible-red (0.58–0.68 μm) and near-infrared (0.725–1.1 μm) reflectance, respectively. The NDVI is scaled between -1 and $+1$, and typically varies from -0.2 to 0.1 for snow, inland waterbodies, deserts and bare soils, and increases from about 0.1 to 0.75 for progressively increasing amounts of vegetation (Tucker *et al.* 1986).

The Version 3 Pathfinder NDVI dataset was produced by the Dr Ranga Myneni group at Department of Geography, Boston University, and referred to by Nemani *et al*. (2003). In the Version 3 Pathfinder NDVI dataset, remaining noise associated with residual atmospheric effects, orbital drift effects, intersensor variations, and stratospheric aerosol effects (Myneni *et al*. 1998, Kaufmann *et al*. 2000) was further reduced by a series of corrections, including temporal compositing, spatial compositing, orbital correction, and climate correction (Nemani *et al*. 2003). The Version 3 Pathfinder NDVI dataset provides a valuable basis to infer the interannual variability in vegetation activity at a global scale. This dataset is available at two different resolutions, including 16 km and 0.5°. The 0.5° NDVI data were used for this global-scale study.

3.1.2 Climate data. We used a global monthly climatology dataset gridded at 0.5° resolution (New *et al*. 2000). This global climatology dataset includes seven climate variables: precipitation, mean temperature, diurnal temperature range, wet-day frequency, vapour pressure, cloud cover, and ground frost frequency. We used two variables, precipitation and mean temperature. Both variables were interpolated from station observations (New *et al*. 2000). This dataset has higher spatial resolution, longer temporal coverage, and more strict temporal fidelity than other global climatology datasets (New *et al*. 2000).

3.2 *Methods*

We produced spatially averaged time series of annual average NDVI, annual mean temperature, and annual precipitation for all vegetated pixels within the northern high latitudes (40° N–70° N), the northern middle latitudes (23.5° N–40° N) and the tropics (23.5° S–23.5° N). These time series were not analysed for climate zones in the Southern Hemisphere because these zones exhibit no prevalent greening pattern as shown later. Previous studies have shown increasing vegetation activity and carbon stock in the conterminous US (e.g. Pacala *et al*. 2001, Nemani *et al*. 2002) and China (e.g. Goodale *et al*. 2002, Xiao and Moody 2004a). Thus, these time series were also produced for both the US and China. Each time series was standardized by subtracting the mean of the series from the original time series and then dividing by the standard deviation of the series in order to constrain the variance of these time series to the same range and therefore make their intercomparisons more straightforward. The linear trends of spatially averaged NDVI were determined by linearly regressing these variables as a function of time over the period from 1982 to 1998 for each geographical region. We then analysed the correlations between NDVI and climate data to assess the associations between vegetation changes and climate changes on a regional basis.

The trends of spatially averaged NDVI may hide the geographical variability of NDVI trends over space. We thus analysed the spatial patterns of NDVI from 1982 to 1998. We identified the vegetated pixels with linear trends in NDVI that are statistically significant ($p<0.05$) over the 17-year period. For these pixels, we then analysed the correlation between annual average NDVI and annual mean temperature and the correlation between annual mean NDVI and annual precipitation. These analyses were repeated using seasonal mean NDVI, seasonal mean temperature, and seasonal precipitation totals. The relative strength of associations between NDVI and climate variables were mapped and evaluated for different geographical regions.

4. Results

4.1 *Trends of spatially averaged NDVI*

4.1.1 Northern high latitudes. The spatially averaged time series of annual NDVI and annual mean temperature for vegetated areas within the northern high latitudes exhibited upward trends that are statistically significant at 0.01 and 0.05, respectively (figure 1(*a*), table 1). From 1982 to 1998, annual NDVI averages increased by 13.02%, and annual mean temperature increased by 0.74°C (table 1). Annual NDVI averages and annual mean temperature were significantly correlated over the 17-year period within this region ($p<0.05$) (table 2). There is no significant correlation between NDVI and precipitation.

4.1.2 Northern middle latitudes. Within the northern middle latitudes, NDVI exhibited an upward trend between 1982 and 1998 (figure 1(*b*), table 1). This

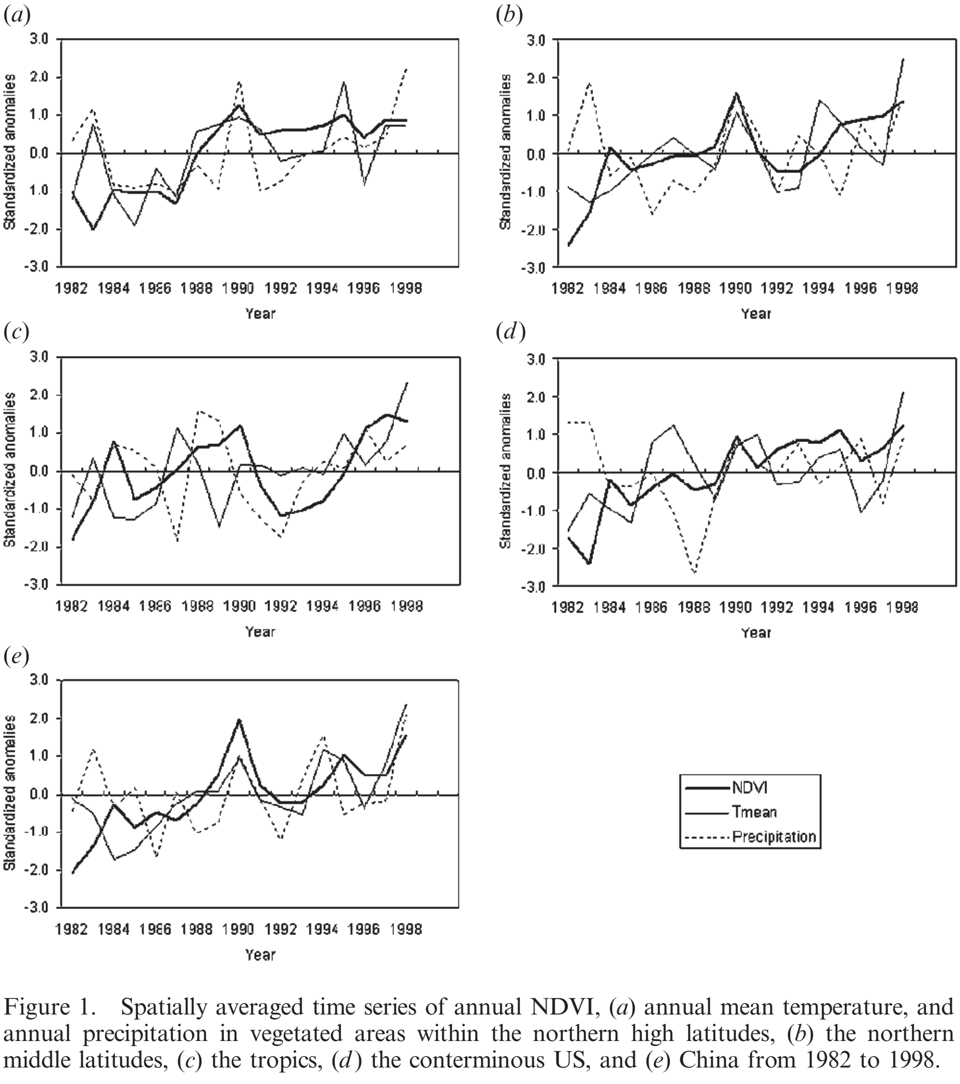


Figure 1. Spatially averaged time series of annual NDVI, (*a*) annual mean temperature, and annual precipitation in vegetated areas within the northern high latitudes, (*b*) the northern middle latitudes, (*c*) the tropics, (*d*) the conterminous US, and (*e*) China from 1982 to 1998.

Table 1. Trends of spatially averaged NDVI, temperature and precipitation for different geographical regions from 1982 to 1998. All the trends are positive.

(*a*) NDVI

	Annual NDVI changes in the 17-year period			
Region	Absolute value	Percentage (%)	R^2	p value
Northern high latitudes	0.043	13.02	0.69	0.00003
Northern middle latitudes	0.028	6.63	0.51	0.001
Tropics	0.020	3.86	0.21	0.07
Conterminous US	0.036	9.14	0.71	0.00002
China	0.030	7.99	0.56	0.0006

(*b*) Temperature

	Annual temperature changes in the 17-year period			
Region	Absolute value (°C)	Percentage (%)	R^2	p value
Northern high latitudes	0.74	83.83	0.24	0.04
Northern middle latitudes	0.56	3.85	0.35	0.01
Tropics	0.48	1.95	0.41	0.006
Conterminous US	0.63	9.04	0.19	0.08
China	0.87	11.13	0.46	0.003

(*c*) Precipitation

	Annual precipitation changes in the 17-year period			
Region	Absolute value (mm)	Percentage (%)	R^2	p value
Northern high latitudes	14.58	2.70	0.12	0.17
Northern middle latitudes	16.44	1.83	0.02	0.59
Tropics	20.07	1.38	0.01	0.65
Conterminous US	4.95	0.69	0.00	0.89
China	40.51	5.27	0.07	0.30

corresponds to an overall greening of 6.63% for the northern middle latitudes as a whole over the 17-year period.

Annual mean temperature increased by 0.56°C from 1982 to 1998 (table 1). Annual NDVI averages are significantly correlated to annual mean temperature (table 2). NDVI is not significantly related to precipitation.

Over the conterminous US, NDVI increased by 9.14% (figure 1(*d*), table 1). The spatially averaged time series of annual NDVI was significantly correlated to annual mean temperature over this area (table 2). There was no significant relationship between annual NDVI averages and annual precipitation.

NDVI increased by 7.99% in China over the study period (figure 1(*e*), table 1). Annual mean temperature increased by about 0.87°C (table 1). The spatially averaged time series of annual NDVI was significantly related to that of annual mean temperature in China (table 2). There was no significant relationship between annual NDVI averages and annual precipitation in China.

4.1.3 Tropical regions. In the tropics, NDVI showed no significant trend from 1982 to 1998, although annual mean temperature increased during this period (table 1). Thus, there is no overall greening trend for the tropics as a whole over the 17-year period.

Table 2. Correlations between spatially averaged NDVI and spatially averaged annual mean temperature and correlations between spatially averaged NDVI and spatially averaged annual precipitation for different geographical regions from 1982 to 1998. All correlations except the correlation between NDVI and precipitation for the conterminous US are positive.

	NDVI versus temperature		NDVI versus precipitation	
Region	R^2	p value	R^2	p value
Northern high latitudes	0.35	0.012	0.09	0.24
Northern middle latitudes	0.44	0.004	0.01	0.66
Tropics	0.14	0.14	0.20	0.07
Conterminous US	0.29	0.027	0.01	0.77
China	0.42	0.005	0.09	0.23

4.2 *Spatial patterns of NDVI trends*

Spatially averaging over large regions conceals the geographical variability of NDVI trends. Thus, we evaluated the spatial patterns of NDVI trends and climatic effects for all the vegetated pixels at a global scale. Figure 2 shows areas where linear trends in NDVI are statistically significant ($p<0.05$).

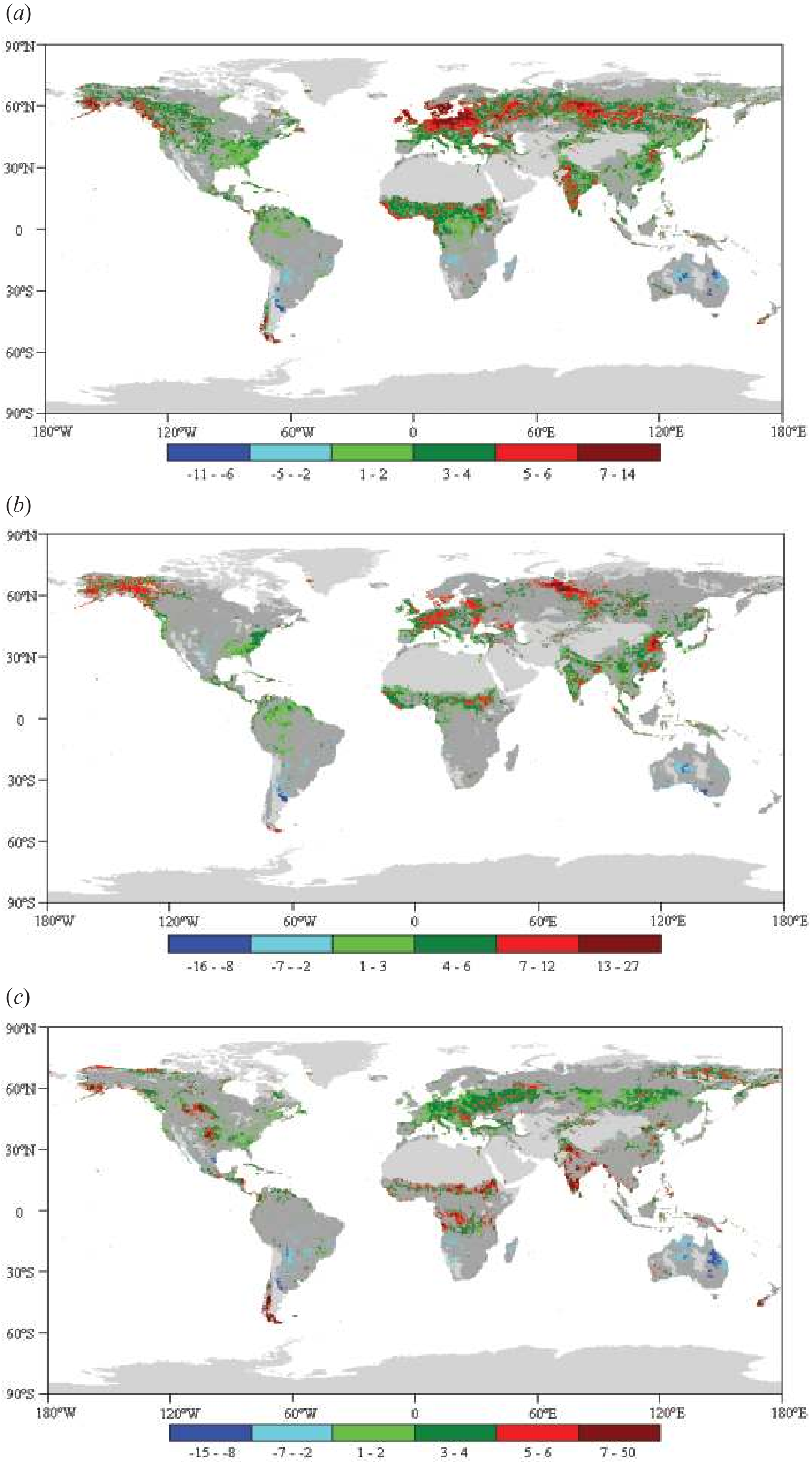
4.2.1 Northern high latitudes. In the northern high latitudes, 52.99% of the vegetated pixels exhibited significant increases in annual NDVI from 1982 to 1998 (figure 2(*a*), table 3). The greening trend was observed over a broad contiguous swath of land from Alaska and Canada, and extending across the Eurasian land mass from central Europe through Russia and north-eastern China (figure 2(*a*)).

The high-latitude greening pattern varied by season (figure 2(*b*)–(*e*), table 3). In March–May, 24.61% of the vegetated pixels showed significant increases in NDVI, mainly in Alaska, western Europe, and much of Russia. In June–August, 33.67% of the vegetated pixels exhibited significant NDVI increases, primarily in northern US and central Canada, central Europe, and Russia. There were 21.96% and 29.73% of the vegetated pixels showing significant NDVI increases over September–November and December–February, respectively. The greening trend over September–November and December–February was mainly observed in Canada, Europe and Russia.

4.2.2 Northern middle latitudes. In the northern middle latitudes, 48.06% of the vegetated pixels showed significant increases in annual NDVI (figure 2(*a*), table 3). The greening trend was observed mainly in the south-eastern US, northern India and south-eastern China.

The greening pattern in the northern middle latitudes also varied by season (figure 2(*b*)–(*e*), table 3). In the conterminous US, the greening trends over March–May, June–August, September–November and December–February were observed in eastern, central and north-western US, respectively. In China, the percentages of the vegetated pixels that showed significant NDVI increases are 48.63% in March–May, 18.00% in June–August, 20.14% in September–November and 16.55% in December–February.

4.2.3 Tropical regions. In the tropics, 32.84% of the vegetated pixels showed significant increases in annual NDVI (figure 2(*a*), table 3). Spatially contiguous greening patterns were observed in parts of tropical Africa, India, the northern portion of South America, and Central America. Spatially fragmented greening patterns were observed in south-east Asia.


(a)
90°N
60°N
30°N
0
30°S
60°S
90°S
180°W
120°W
60°W
0
60°E
120°E
180°E
-11 - -6
-5 - -2
1 - 2
3 - 4
5 - 6
7 - 14
(b)
90°N
60°N
30°N
0
30°S
60°S
90°S
180°W
120°W
60°W
0
60°E
120°E
180°E
-16 - -8
-7 - -2
1 - 3
4 - 6
7 - 12
13 - 27
(c)
90°N
60°N
30°N
0
30°S
60°S
90°S
180°W
120°W
60°W
0
60°E
120°E
180°E
-15 - -8
-7 - -2
1 - 2
3 - 4
5 - 6
7 - 50

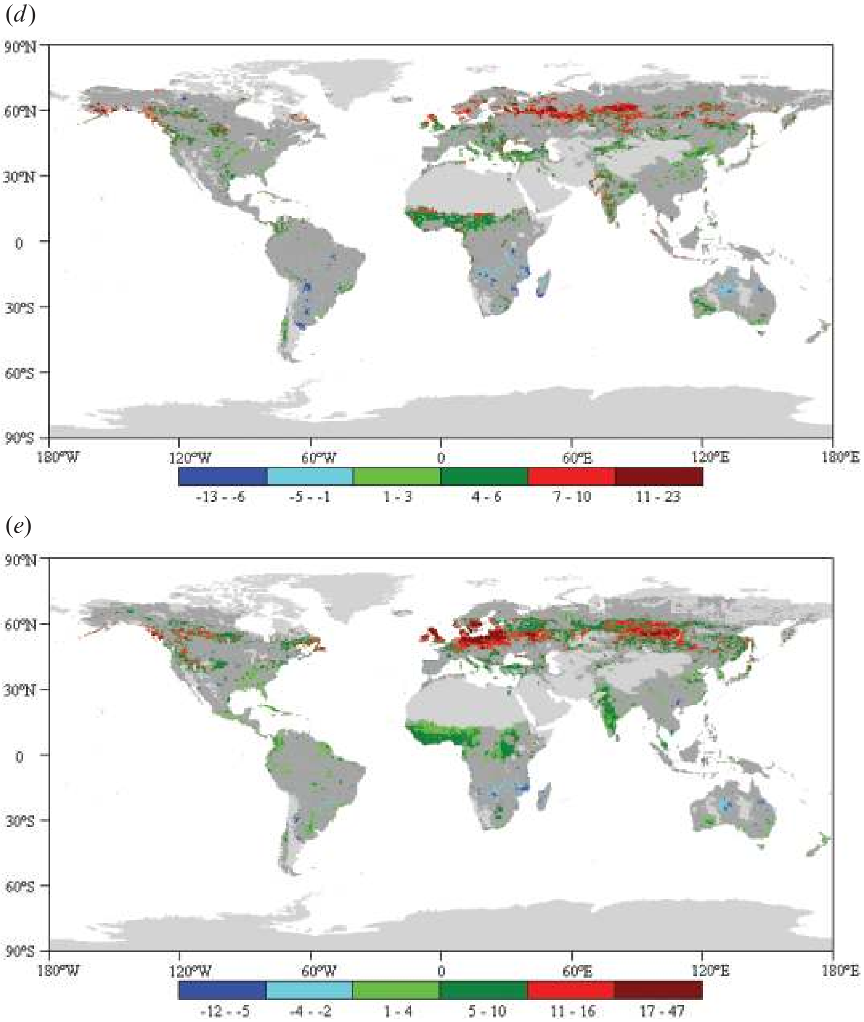


Figure 2. Linear trends of NDVI that are statistically significant ($p<0.05$) from 1982 to 1998 at both annual and seasonal scales pixel by pixel: (*a*) trends of annual NDVI averages; (*b*) trends of NDVI averages over spring (March–May); (*c*) trends of NDVI averages over summer (June–August); (*d*) trends of NDVI averages over autumn (September–November); and (*e*) trends of NDVI averages over winter (December–February). The coloured pixels represent those vegetated pixels with significant NDVI trends; the greyed pixels represent non-vegetated areas; the dark-greyed pixels represent those vegetated pixels without significant NDVI trends. The trends are given in percentages (%).

In the southern middle and high latitudes, a greening trend was observed in the southernmost portion of South America, and south-western Australia. Noticeably, a decreasing NDVI trend was observed in parts of southern Africa, South America (e.g. Argentina), and central Australia (figure 2(*a*)–(*e*)).

4.3 *Climatic correlates of NDVI trends*

4.3.1 Northern high latitudes. In the northern high latitudes, 41.60% of the vegetated pixels with greening trends (figure 2(*a*)) exhibited significant correlations between annual NDVI and annual mean temperature (figure 3(*a*), table 4). These pixels are mainly distributed in Alaska, Canada, Europe, Russia and north-eastern

Table 3. Percentages of pixels with statistically significant ($p<0.05$) linear trends of NDVI over all vegetated pixels for different geographical regions.

Region	Annual	March–May	June–August	September–November	December–February
Northern high latitudes	52.99	24.61	33.67	21.96	29.73
Northern middle latitudes	48.06	42.14	24.57	18.62	18.69
Tropics	32.84	23.48	17.05	12.57	20.13
Conterminous US	51.67	31.07	27.83	15.45	20.30
China	53.39	48.63	18.00	20.14	16.55

China (figure 3(*a*)). By contrast, only 6.44% of the vegetated pixels with greening trends (figure 2(*a*)) showed significant correlations between annual NDVI and annual precipitation (figure 3(*b*), table 5). These pixels are only observed in sparse areas in the northern high latitudes.

In the northern high latitudes, positive NDVI–temperature correlations are most prevalent over March–May (figure 3(*c*), table 4). Positive NDVI–temperature correlations over September–November were only observed in Canada and eastern Russia (figure 3(*g*)). Negative correlations between NDVI and spring precipitation were observed in western Canada and western Europe (figure 3(*d*)).

4.3.2 Northern middle latitudes. In the northern middle latitudes, the positive correlations between annual NDVI averages and annual mean temperature are most prevalent in China (figure 3(*a*), table 4). In contrast, the positive correlations between annual NDVI averages and annual precipitation were only observed in sparse areas in China (figure 3(*b*), table 5). At the seasonal scale, the NDVI–temperature correlation was more prevalent over spring (figure 3(*c*)) and winter (figure 3(*i*)) than over summer (figure 3(*e*)) and autumn (figure 3(*g*), table 4).

NDVI–temperature and NDVI–precipitation correlations show spatially fragmented patterns in the conterminous US (figure 3, tables 4 and 5). Positive NDVI–temperature correlations are mainly observed over March–May (figure 3(*c*)) and winter (figure 3(*i*)). Positive NDVI–precipitation correlations are most prevalent over September–November (figure 3(*h*)).

Northern Mexico shows negative NDVI–temperature and positive NDVI–precipitation correlations (figure 3). However, no prevalent greening trend was observed in northern Mexico (figure 2). Thus, the effects of temperature and precipitation on vegetation activity may be self-cancelling in northern Mexico.

4.3.3 Tropical regions. Positive correlations between annual NDVI averages and annual precipitation were observed in tropical Africa and southern India, although the pattern is spatially fragmented (figure 3, tables 4 and 5). In tropical Africa, positive NDVI–precipitation correlations were primarily observed in the Sahel region (figure 3(*b*)); positive NDVI–temperature correlations were observed in southern tropical Africa to the south of the Sahel (figure 3(*a*)).

Decreasing trends of vegetation activity were observed in some regions in South America (e.g. Argentina), southern Africa, and Australia from 1982 to 1998 (figure 2). These regions show negative correlations between NDVI and temperature and positive correlations between NDVI and precipitation (figure 3).

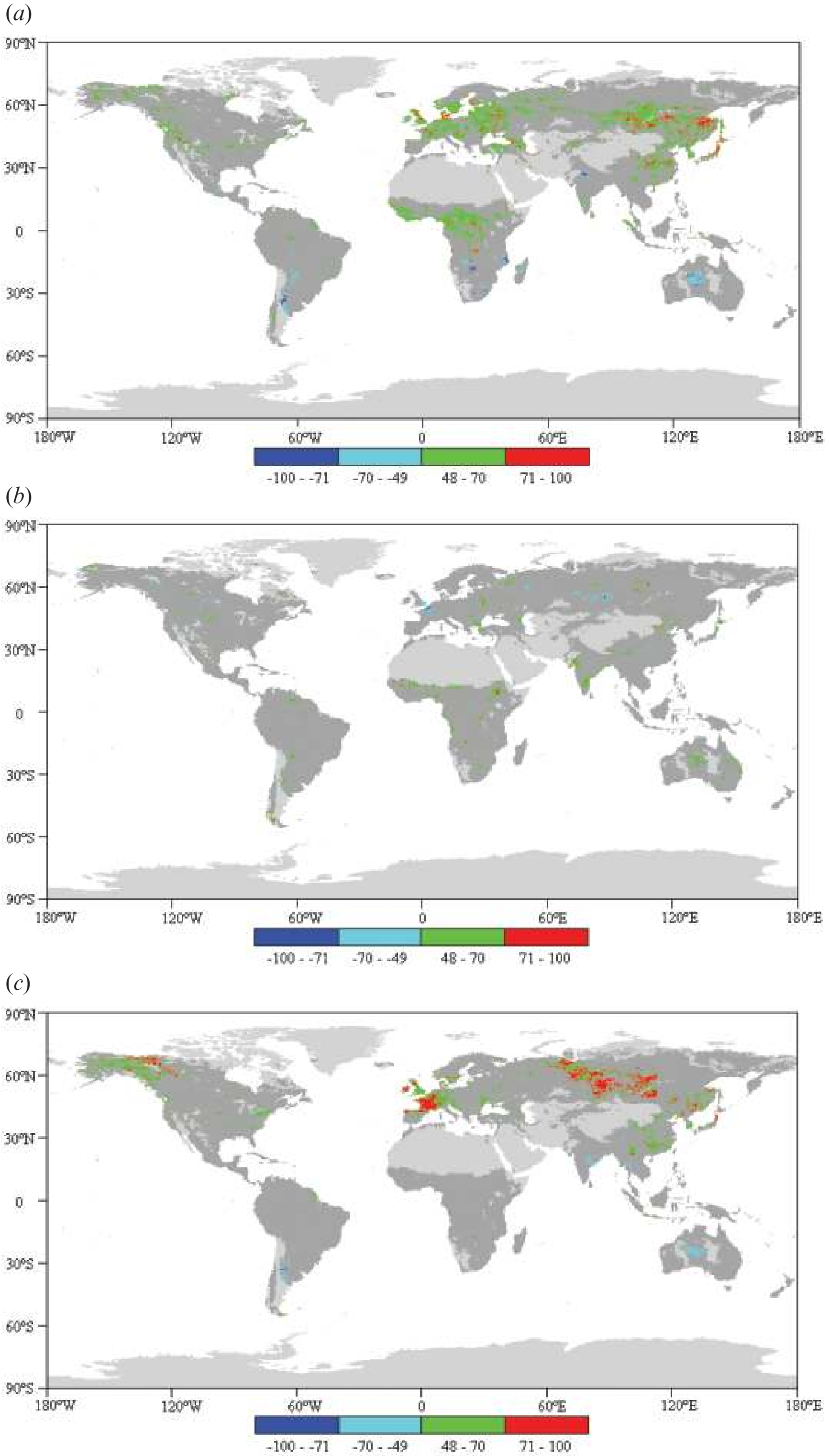


Figure 3. (*Continued overleaf*)

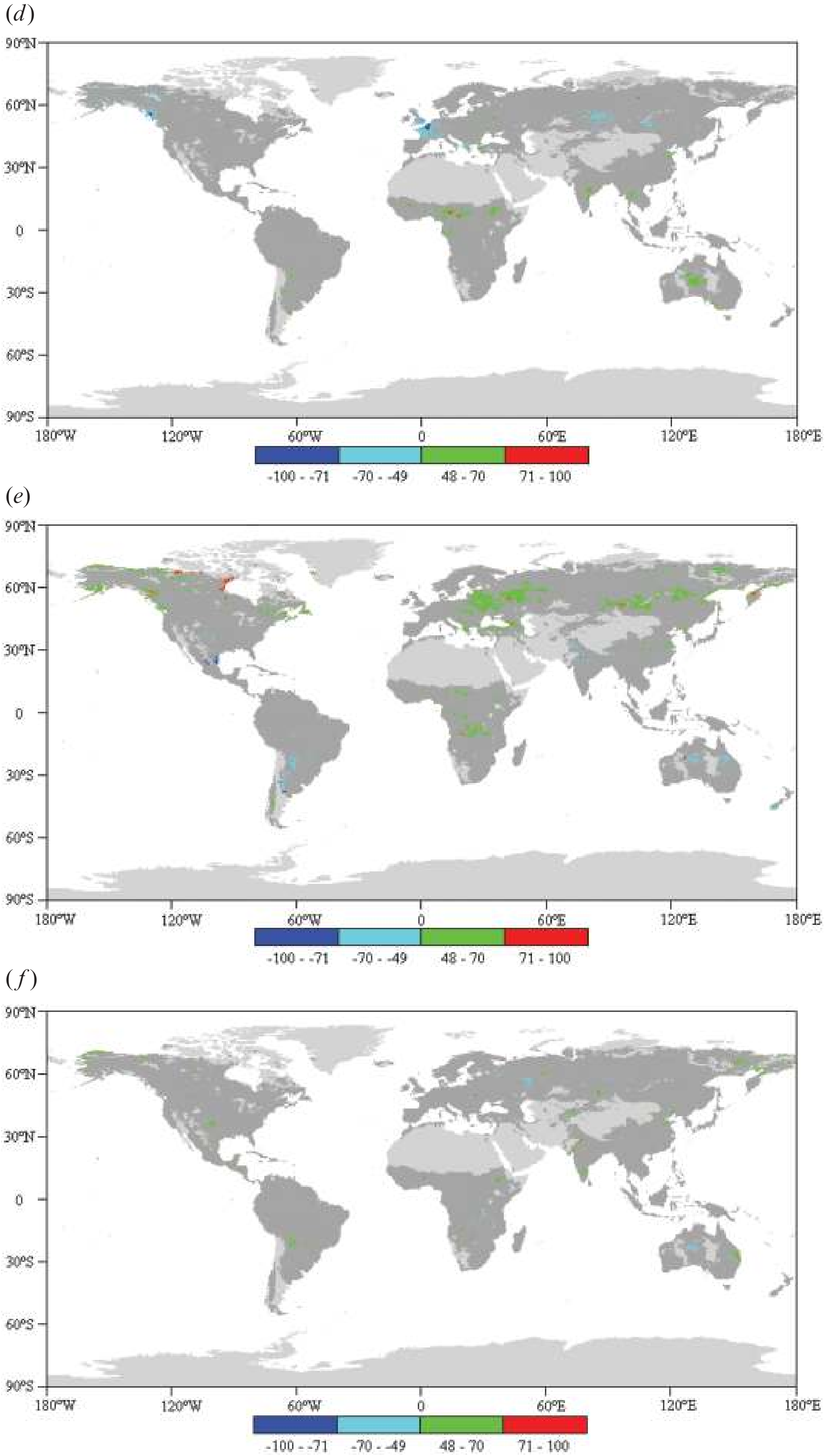


Figure 3. (*Continued*)

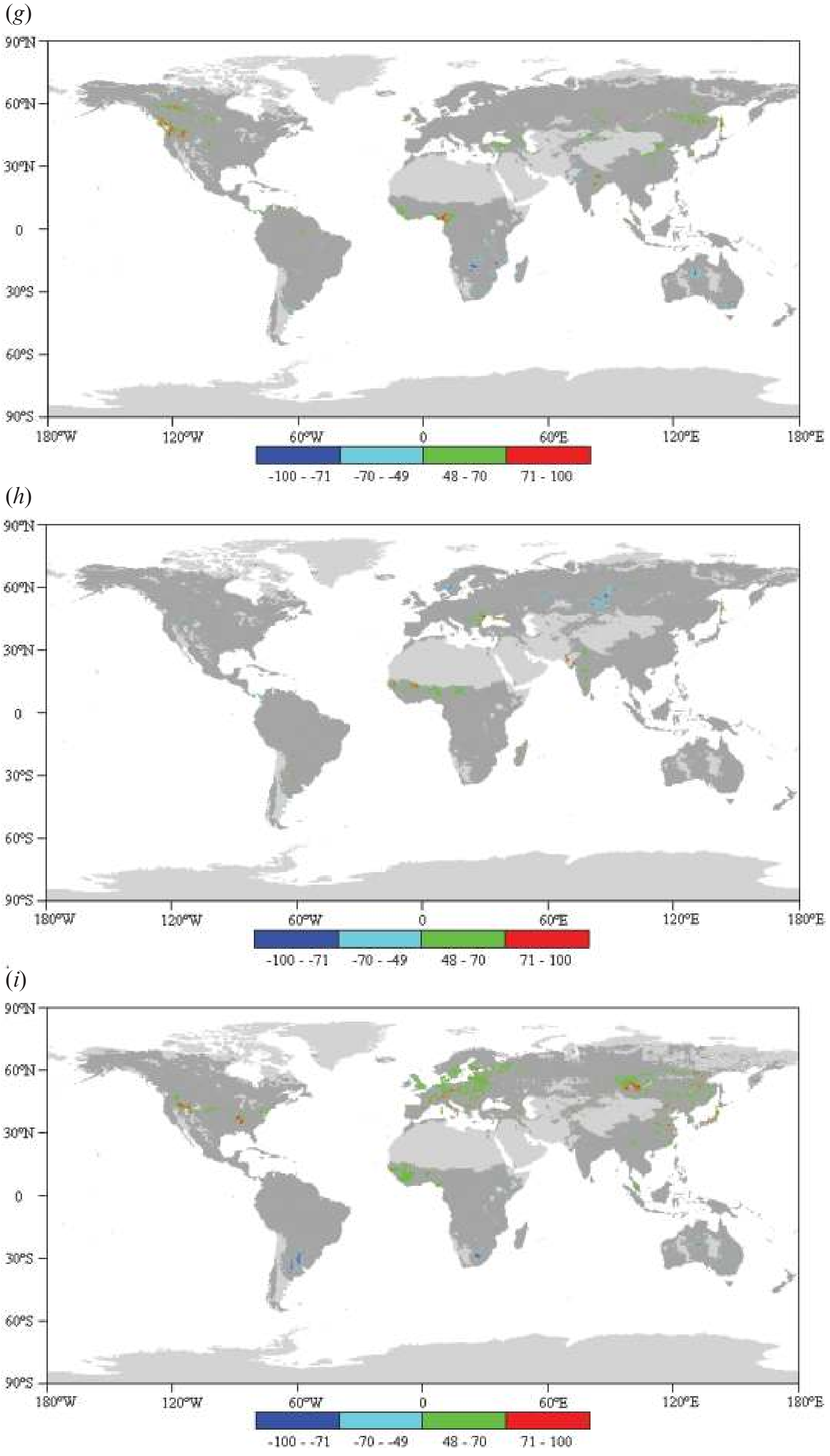


Figure 3. (*Continued overleaf*)

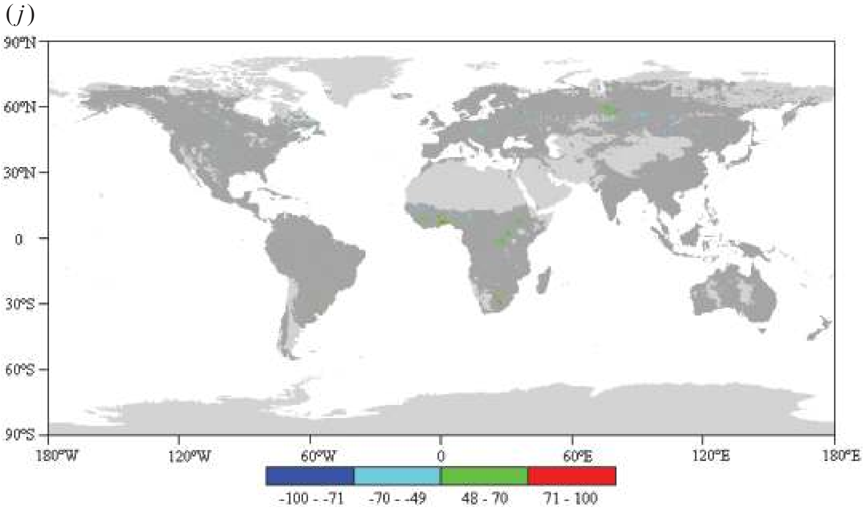


Figure 3. Correlations between NDVI averages and temperature and correlations between NDVI averages and precipitation that are statistically significant ($p<0.05$) from 1982 to 1998: (*a*) annual NDVI averages versus annual mean temperature; (*b*) annual NDVI averages versus annual precipitation; (*c*) NDVI averages versus temperature over March–May; (*d*) NDVI averages versus precipitation over spring (March–May); (*e*) NDVI averages versus temperature over summer (June–August); (*f*) NDVI averages versus precipitation over summer (June–August); (*g*) NDVI averages versus temperature over autumn (September–November); (*h*) NDVI averages versus precipitation over autumn (September–November); (*i*) NDVI averages versus temperature over winter (December–February); and (*j*) NDVI averages versus precipitation over winter (December–February). The coloured pixels represent those pixels that have significant NDVI trends as well as significant NDVI–climate correlations; the greyed pixels represent non-vegetated areas; the dark-greyed pixels represent those vegetated pixels either with significant NDVI trends but no significant NDVI–climate correlations or with significant NDVI–climate correlations but no significant NDVI trends. The correlation coefficients are given in percentages (%).

5. Discussion

5.1 *Northern high latitudes*

Our results showed an overall greening trend from 1982 to 1998 for the northern high latitudes. The greening trend was distributed over a broad contiguous swath of land from Alaska and western Canada through central Europe to Russia and

Table 4. Percentages of pixels with statistically significant ($p<0.05$) correlations between NDVI and temperature among vegetated pixels with significant ($p<0.05$) linear trends in NDVI for different geographical regions.

Region	Annual	March–May	June–August	September–November	December–February
Northern high latitudes	41.60	64.78	33.90	19.42	26.26
Northern middle latitudes	27.28	20.45	17.70	19.12	24.80
Tropic regions	31.06	7.94	17.76	21.83	11.68
Conterminous US	21.57	34.82	16.13	21.10	30.42
China	54.58	40.02	15.64	26.96	46.99

Table 5. Percentages of pixels with statistically significant ($p<0.05$) correlations between NDVI and precipitation among vegetated pixels with significant ($p<0.05$) linear trends in NDVI for different geographical regions.

Region	Annual	March–May	June–August	September–November	December–February
Northern high latitudes	6.44	11.62	6.17	10.47	4.69
Northern middle latitudes	7.30	4.04	9.29	9.25	3.79
Tropic regions	14.12	15.67	9.30	15.84	8.48
Conterminous US	6.37	6.89	10.34	7.09	3.82
China	8.71	3.65	10.99	3.44	4.40

north-eastern China. This greening pattern is roughly consistent with patterns reported elsewhere (Tucker *et al.* 2001, Zhou *et al.* 2001, Slayback *et al.* 2003).

Our results suggest that, compared with precipitation, temperature is a more important climatic correlate of the greening trend in the northern high latitudes and western Europe between 1982 and 1998. In other studies that focused solely on high latitude greening trends, Zhou *et al.* (2001), Tucker *et al.* (2001) and Lucht *et al.* (2002) also argued that temperature is the leading climatic factor. Precipitation was assumed to play a minor role in increasing vegetation activity and was not fully considered by Zhou *et al.* (2001). Lucht *et al.* (2002) suggested that precipitation contributes only marginally to the greening trend. Our results support the assumption of Zhou *et al.* (2001) and the conclusion of Lucht *et al.* (2002).

Myneni *et al.* (1997) and Zhou *et al.* (2001) attributed the overall high-latitude greening trend to an advance of spring budburst and a delay of autumn leaf-fall. Our results suggest that, compared with autumn temperature, spring warming makes a greater contribution to the high-latitude greening trend than autumn temperature does, especially in Alaska.

5.2 *Northern middle latitudes*

Our results suggest that the northern middle latitudes (23.5° N–40° N) also exhibited an overall greening trend from 1982 to 1998. The greening trend was mainly observed in north-eastern and south-eastern North America, northern India, and China. The observed greening pattern is stronger and more contiguous than that shown by Kawabata *et al.* (2001) over a much shorter period (1982–1990). Our results suggest that the greening trend in the northern middle latitudes is partly due to temperature rises, as also suggested by Ichii *et al.* (2002).

Interestingly, the greening trends in eastern US and much of India were not related to changes in either temperature or precipitation. The greening trend in these regions may be due to continuing forest regrowth following the abandonment of agricultural lands or plantations.

The greening pattern observed in the conterminous US may suggest increasing carbon accumulation in US forests. Nemani *et al.* (2002) suggested that precipitation is the leading climatic factor enhancing the terrestrial carbon sink in the conterminous US. By contrast, Caspersen *et al.* (2000) indicated that land-use change is the dominant factor controlling the rate of carbon accumulation in US forests, with growth enhancement due to climate change, CO_2 fertilization, and N deposition making only minor contributions. Our results suggest that temperature makes a greater contribution to the increased vegetation activity in the conterminous US than precipitation does (tables 4 and 5). Our results further suggest that climatic factors only explain a fraction of the greening trend in the conterminous US. Thus, the increased rate of carbon accumulation in US forests may be due to the combined effect of forest regrowth and growth enhancement due to elevated temperature.

The greening trend in China is consistent with increasing vegetation activity suggested by Xiao and Moody (2004a) based on a satellite-derived leaf area index (LAI) dataset and a gridded climate dataset. The prevalent greening pattern in China may suggest an increasing terrestrial carbon stock in vegetation biomass during the past two decades. This is consistent with the reported increase of carbon stock in forest biomass in China over this period (Goodale *et al.* 2002). Temperature makes a greater contribution to the increased vegetation activity than precipitation does. Moreover, the overall greening trend in China is mainly attributed to the greening in spring. These results suggest that the overall greening trend in China, as with the northern high latitudes, is partly brought about by earlier budburst due to spring warming.

However, the greening trend in China cannot be fully explained by elevated temperature or other climatic factors. The total forest coverage in China has increased from 5.2% in 1950 to 13.9% in 1995 primarily due to tree-planting projects (Liu 1996), although natural forest has declined to 30% of the total forest area due to extensive cutting of forests (Zhang *et al.* 1999). Thus, the greening pattern in China may result from land-use changes, such as afforestation and reforestation, and tree-growth enhancement due to temperature rises, especially in spring. Xiao and Moody (2004a) suggested that trends in agricultural practices, such as increased use of high-yield crops and application of chemical fertilizers, along with land-use changes such as afforestation and reforestation, may have made a greater contribution to the greening trend than temperature.

5.3 *Tropics*

No greening trend was observed for the tropics as a whole from 1982 to 1998. This is not surprising, since the tropics provide a large carbon source due to extensive clearing of natural forests (Houghton *et al.* 2000). However, greening patterns were observed for parts of tropical Africa, India, the northern portion of South America, southern Mexico, and Indonesia. Nemani *et al.* (2003) suggested that the largest increase in NPP was in tropical ecosystems, Amazon rainforests in particular. They also showed increase in NPP in tropical Africa and other tropical areas. The greening pattern in tropical Africa shown by our analysis is generally consistent with the increase in NPP in this region suggested by Nemani *et al.* (2003).

Kawabata *et al.* (2001) suggested contiguous greening patterns in south-east Asia for a short period (1982–1990). By contrast, our results suggest a spatially-fragmented greening pattern in these regions from 1982–1998. The patchiness of the greening pattern may be associated with deforestation and forest regrowth after fires since forests account for a large fraction of the greenness in these regions (Fuller 1994). Ichii *et al.* (2002) suggested that tropical regions with NDVI increases such as central Africa did not exhibit significant NDVI–climate correlations, and attributed increased vegetation activity to CO_2 fertilization and N deposition. However, our results suggest positive correlations between NDVI and precipitation in the southern edge of the Sahel, and positive correlations between NDVI and temperature for tropical Africa to the south of the Sahel. Thus, climate changes may also contribute to the increases in vegetation activity in tropical Africa.

The vegetation greening trend in parts of tropical Africa may suggest a regional terrestrial carbon sink, although tropical Africa as a whole is a large carbon source primarily due to deforestation (Watson *et al.* 2000). Greening trends may be attributed to the combined effect of increased precipitation and elevated temperature. Precipitation may shift vegetation from grasses to shrubs and thus result in a larger fraction of woody component in this region (Fuller and Prince 1996). In addition to climatic effects, overgrazing by cattle may also shift vegetation from grasses to shrubs in the Sahelian region (Kerr 1998). CO_2 fertilization (Cao and Woodward 1998, Smith *et al.* 2000) and N deposition (Nadelhoffer *et al.* 1999) may also contribute to the increased vegetation activity in parts of tropical Africa.

Decreased vegetation activity was observed in some regions in southern South America, southern Africa, and Australia from 1982 to 1998. Ichii *et al.* (2002) suggested that NDVI decreases in these regions resulted from decreases in precipitation. However, our results suggest that the declined vegetation activity in these arid and semi-arid regions may be due to the combined effect of elevated temperature and decreased precipitation.

6. Conclusions

The results of this study document the geographical distribution of trends in vegetation greenness using a high-quality long-term database. In areas that exhibited strongly significant trends, the correlation of these trends with changes in temperature and precipitation were evaluated. Our results suggest the following.

1) Greening trends exhibit substantial latitudinal and longitudinal variability, with the strongest greening taking place in the northern high latitudes, parts of the tropics, south-eastern North America and eastern China.
2) Over large areas, these greening trends are strongly correlated with trends in temperature, especially in Europe, eastern Eurasia, and tropical Africa.
3) Precipitation does not appear to be a strong driver of increases in greenness, except for isolated and spatially fragmented regions.
4) Decreases in greenness occurred mainly in the Southern Hemisphere, in southern Africa, southern South America, and central Australia. These trends are strongly associated with both increases in temperature and decreases in precipitation.
5) Vast regions of the globe, even in the northern high latitudes, exhibit no trend in greenness.
6) Large areas that are undergoing strong greening trends show no associations with trends in temperature or precipitation.

Based on these results we conclude that, while greening trends are strong in many areas, these trends are only partially explained by climatic drivers. In large regions, other factors, such as CO_2 fertilization, reforestation, forest regrowth, woody plant proliferation and trends in agricultural practices, may be at play. Precipitation is generally not a significant driver of increasing greenness. Southern Hemisphere decreases in greenness appear to be driven by changes in both temperature and precipitation, reflecting their joint control over soil water budgets.

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