Climatic Control of the High-Latitude Vegetation Greening Trend and Pinatubo Effect

**Wolfgang Lucht,[1*] I. Colin Prentice,[2] Ranga B. Myneni,[3]
Stephen Sitch,[1] Pierre Friedlingstein,[4] Wolfgang Cramer,[1]
Philippe Bousquet,[4] Wolfgang Buermann,[3] Benjamin Smith[5]**

A biogeochemical model of vegetation using observed climate data predicts the high northern latitude greening trend over the past two decades observed by satellites and a marked setback in this trend after the Mount Pinatubo volcano eruption in 1991. The observed trend toward earlier spring budburst and increased maximum leaf area is produced by the model as a consequence of biogeochemical vegetation responses mainly to changes in temperature. The post-Pinatubo decline in vegetation in 1992–1993 is apparent as the effect of temporary cooling caused by the eruption. High-latitude CO_2 uptake during these years is predicted as a consequence of the differential response of heterotrophic respiration and net primary production.

Satellite observations over the past two decades indicate a trend toward longer growing seasons and greater annual net primary production (NPP) in high latitudes (*1–3*). Using a dynamic vegetation model that predicts leaf area index (LAI), primary production, and net ecosystem carbon exchange from first principles (*4–7*), we show that the trend and variability in the satellite observations are consistent quantitatively with independent climate data and qualitatively with net ecosystem carbon exchange, which was independently calculated from atmospheric CO_2 concentration measurements (*8*).

We analyzed data for a 1982–1998 interval for which we had access to both climate and satellite data. A previous analysis of 10 years of data from the Advanced Very High Resolution Radiometer (AVHRR) indicated a progressive greening of the boreal zone. A steady increase in annual maximum LAI during 1981–1991 was associated with a slight advance of spring budburst and delay of autumn abscission (*1*). Subsequent work spanning 1981–1999 has confirmed these findings (*2*, *9*), but doubts about the validity of the trend have persisted because of the need for data corrections for instrumental and navigational drift, intercalibration of successive instruments, and consideration of aerosol effects (*10*). Such doubts could be dispelled if the interannual variations in greenness and growing season length were shown to be quantitatively consistent with independent expectations on the basis of climate variability and/or with independent reconstructions of changes in regional CO_2 balance. This analysis uses a climate-driven terrestrial carbon cycle model capable of simulating the interannual variability of LAI and the components of the terrestrial carbon balance.

We compare monthly LAI anomalies for the boreal zone, derived from a recent version of the AVHRR data, with monthly LAI anomalies independently predicted by the LPJ Dynamic Global Vegetation Model (LPJ-DGVM), a biogeochemical process model driven by monthly climate observations and by the global mean CO_2 concentration increase (see Materials and Methods in supporting online material). Both simulated and observed LAI anomalies show an overall increasing trend, but periods lasting several years with positive or negative deviations from the trend can be discerned in the observations and are correctly simulated (Fig. 1). The pattern of LAI anomalies within each year is, in general, correctly simulated, although discrepancies are seen in 1988 and 1996. The similarity between the model results and the observations is seen not only for the whole boreal zone but also for each separate continent, even though the patterns differ substantially among the continents.

Further analysis of the data and model results (Fig. 2) reveals an increasing trend in the annual maximum LAI during 1982–1991 (+0.23, observed), an abrupt decline from 1991–1992, and a resumed increase during 1992–1998 (+0.19). The model reproduces 65% of the amplitude of the increasing trend before 1992, 85% of the trend after 1992, and 63% of the overall trend (table S1). According to the AVHRR data, the overall greening trend is associated with an advance of spring budburst by several days and a similar delay of autumn leaf-fall (Fig. 2). The model agrees closely with the trend in spring onset and its interannual variability (r = 0.91), and it also shows a delay in autumn onset. The amplitude of this delay is underestimated, but this quantitative comparison is less appropriate than for spring onset because the model estimates the timing of cessation of carbon assimilation rather than the timing of leaf abscission, which is what is visible from space.

During the analysis period, global average CO_2 concentration rose by 25 parts per million (ppm), annual mean temperature in the boreal zone increased by 0.8 K, and annual precipitation increased by 9.7 mm. Individually, each of these changes would be expected to increase NPP. The model showed boreal zone NPP increasing by 34.6 gC/m^2/year (where gC is grams of carbon) and heterotrophic respiration by 31.7 gC/m^2/year (linear trends), which is an imbalance of −2.9 gC/m^2/year (the minus sign denotes uptake from the atmosphere, i.e., a terrestrial carbon sink). When taking into account the modeled burning of biomass, the magnitude of the sink is increased to −3.6 gC/m^2/year (−0.1 PgC/year for the region). The average overall modeled sink for the period is −7.8 gC/m^2/year (−0.2 PgC/year).

To determine the climatic factors leading to the observed trends and variability, we ran the vegetation model while keeping selected climatic inputs constant at 1966–1995 average values. We find that variations in temper-

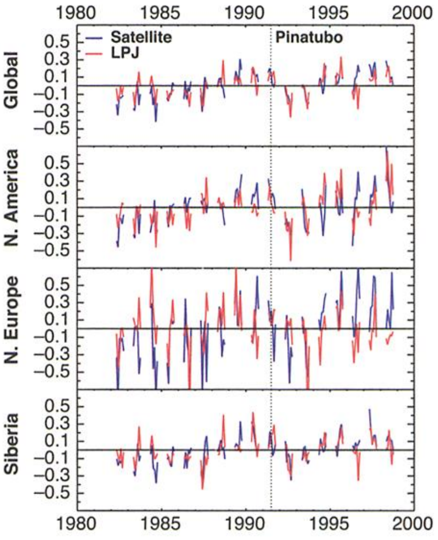

Fig. 1. Monthly boreal zone anomalies of LAI from the AVHRR satellite time series and simulated with the LPJ-DGVM. Due to the low solar angle and snow cover during the winter, only growing season anomalies (May to October) were evaluated. Dotted vertical line indicates time of Pinatubo event.

---

[1] Potsdam Institute for Climate Impact Research, Post Office Box 601203, D–14412 Potsdam, Germany. [2] Max Planck Institute for Biogeochemistry, Post Office Box 100164, D–07745 Jena, Germany. [3] Department of Geography, Boston University, Boston, MA 02215, USA. [4] Laboratoire des Sciences du Climat et de'l Environment, F–91198 Gif-sur-Yvette Cedex, France. [5] Department of Physical Geography and Ecosystems Analysis, Lund University, S-22362 Lund, Sweden.

*To whom correspondence should be addressed. E-mail: Wolfgang.Lucht@pik-potsdam.de

ature alone account for nearly all of the modeled behavior. Changes in precipitation and physiological effects of atmospheric CO_2 concentration contribute only marginally (Figs. 2 and 3).

Stratospheric aerosol generated by the Pinatubo eruption in 1991 depressed incoming short-wave radiation. The global effect was still ≈ -1 W/m^2 even a year after the event (*11*, *12*). As a result, an anomalous cooling of ≈ -0.5 K was observed (*13*) in the northern high-latitude growing seasons of 1992–1993. The AVHRR data indicate a large negative anomaly of LAI in the boreal zone during these years. The reliability of this finding, taken in isolation, is uncertain because volcanic aerosols increase atmospheric scattering and could have spuriously lowered the apparent LAI. However, the LAI values estimated from the satellite data agree closely with those we simulate from climate data during this period (Fig. 2). Both data and model results indicate that the northern biosphere suffered an abrupt setback (*9*) after 1991, followed by a resumption of the greening trend in 1993. The decline in LAI from 1991 to 1992 was 0.27 in the satellite data and 0.22 in the model results. Spring onset was delayed by four days according to the satellite data and three days in the model. Autumn onset was brought forward by nine days according to the satellite data and four days in the model. These reactions to the Pinatubo eruption occurred more or less uniformly on all three northern continents (Fig. 1).

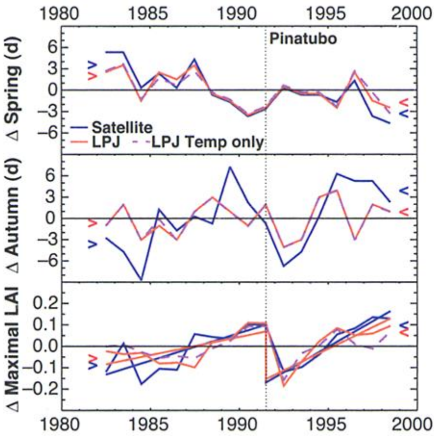

Fig. 2. Relative changes in boreal zone timing of spring green-up and autumn senescence, and anomalies of maximal LAI, from the AVHRR satellite time series (blue) and simulated with the LPJ-DGVM (red). Markings on either side of the curves indicate the starting and ending points of linear fits to the whole time period. The LAI is shown to display a break of linear trends in 1991, the year in which the volcano Mount Pinatubo erupted. Results for LPJ-DGVM simulations with constant atmospheric carbon dioxide concentration, precipitation, and cloudiness (1966–1995 averages) but variable observed temperatures are given for comparison (purple dashed line).

The agreement of satellite data and model results suggests that the LAI setback seen in the satellite data during 1992–1993 represents the response of the biosphere to the Pinatubo cooling event. Furthermore, simulated net primary production was reduced by 21.5 gC/m^2 and simulated heterotrophic (soil microbial) respiration was reduced by 32.2 gC/m^2. When variability in natural biomass burning (a small but significant contribution to the overall carbon balance of boreal ecosystems) is also accounted for, the modeled effect of the Pinatubo anomaly is to increase the boreal zone carbon sink (excluding agricultural lands) by -0.17 PgC/year compared with the 17-year average. The modeled occurrence of an enhanced sink in the years immediately after the Pinatubo event agrees qualitatively with numerical inversion results (*8*) based on spatial patterns of measured atmospheric CO_2 concentrations in the remote troposphere (Fig. 3). The climate-driven model results and the inversion results agree that boreal zone carbon exchange anomalies before 1992 were neutral or positive, whereas an anomalous sink developed in 1992–1993. A difference in the magnitude of net ecosystem exchange (NEE) and its anomalies between the model and the inversion is possibly caused in the former by remaining uncertainty in the temperature dependence of respiration; the latter, however, is not fully robust for the boreal region due to the sparsity of the CO_2 observation network at high northern latitudes, potentially leading to influence from adjacent temperate regions. The unbalanced effect of cooling on NPP and microbial respiration provides a more simple explanation for additional high-latitude CO_2 uptake than a proposed mechanism of increased NPP due to an increase in diffuse sky light (*14*). Our findings support the suggestion (*15*) that the effects of cooling in the boreal zone contributed to the reduction in the growth rate of the global atmospheric CO_2 concentration during 1992–1993 (*16*).

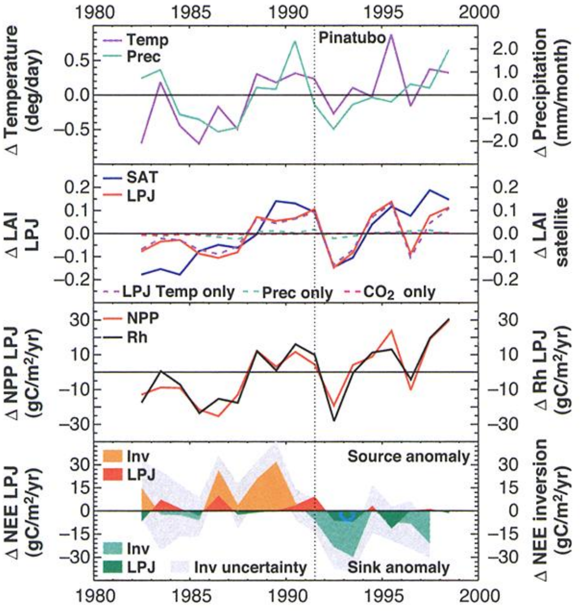

Fig. 3. Global boreal zone anomalies of climate (University of East Anglia monthly climatology), LAI (AVHRR satellite time series and LPJ-DGVM simulations), NPP and soil respiration (LPJ-DGVM simulations), and NEE of carbon (LPJ-DGVM simulations and inversions of observations of atmospheric CO_2 concentration). For comparison, results are given of LPJ-DGVM simulations allowing only temperature (purple dashed line), precipitation (green dashed line), or atmospheric CO_2 concentration (red dashed line) to vary while other climatic inputs were kept constant at 1966–1995 average values.

We conclude that there has been a greening trend in the high northern latitudes, associated with a gradual lengthening of the growing season [which has also been shown by additional evidence such as tree phenology trends (*17*) and reduced snow cover extent (*18*)], caused by a slight warming of boreal climate during the past two decades. The trend cannot easily be explained away as an artifact of the methods used to calibrate long satellite time series. The trend was dramatically interrupted by the Pinatubo eruption, which reduced LAI while producing an increased carbon sink that contributed to the observed (and temporary) slowdown in the global rate of atmospheric CO_2 concentration growth (*19*). Understanding the causes of such variability is an important step in distinguishing natural from human-induced perturbations of Earth's ecosystems.

References and Notes

1. R. B. Myneni, C. D. Keeling, C. J. Tucker, G. Asrar, R. R. Nemani, *Nature* **386**, 698 (1997).
2. R. B. Myneni *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **98**, 14784 (2001).
3. L. Zhou *et al.*, *J. Geophys. Res.* **106**, 20069 (2001).
4. S. Sitch, thesis, Lund University, Sweden (2000).
5. W. Cramer *et al.*, *Global Change Biol.* **7**, 357 (2001).
6. D. McGuire *et al.*, *Global Biogeochem. Cycles* **15**, 183 (2001).
7. S. Sitch *et al.*, in preparation.
8. P. Bousquet *et al.*, *Science* **290**, 1342 (2000).
9. C. J. Tucker *et al.*, *Int. J. Biometeorol.* **45**, 184 (2001).

10. J. Cihlar *et al.*, *J. Geophys. Res.* **103**, 23163 (1998).
11. G. L. Stenchikov *et al.*, *J. Geophys. Res.* **103**, 13837 (1998).
12. C. Timmreck, H.-F. Graf, I. Kirchner, *J. Geophys. Res.* **104**, 9337 (1999).
13. F. Yang, M. E. Schlesinger, *J. Geophys. Res.* **106**, 14757 (2001).
14. M. L. Roderick, G. D. Farquhar, S. L. Berry, I. R. Noble, *Oecologia* **129**, 21 (2001).
15. J. Conway *et al.*, *J. Geophys. Res.* **99**, 22831 (1994).
16. The cooling effect of the El Chichón volcano eruption in March to April 1982 (≈−0.2 K) was smaller than that of Pinatubo. Only half the amount of SO_2 was injected into the stratosphere [S. Self, P. J. Mouginis-Mark, *Rev. Geophys.* **33** suppl. 1, 257 (1995)].
17. A. Menzel, P. Fabian, *Nature* **397**, 659 (1999).
18. P. Y. Groisman, T. R. Karl, R. W. Knight, *Science* **263**, 198 (1994).
19. C. D. Keeling, J. F. S. Chin, T. P. Whorf, *Nature* **382**, 146 (1996).
20. W. Knorr, C. Timmreck, and A. Bondeau have contributed to the interpretation of results; J. Dong and C. J. Tucker were essential to the preparation of the AVHRR data time series; and P. Peylin and P. Ciais contributed to the inversion of atmospheric CO_2 observations. The climatology used was produced by the University of East Anglia's Climatic Research Unit. Funding of W.L. by the German Ministry for Education and Research (BMBF) in the DEKLIM program, project CVECA, is gratefully acknowledged. The work of R.B.M. and W.B. was funded by NASA's Earth Science Enterprise.

Supporting Online Material
www.sciencemag.org/cgi/content/full/296/5573/1687/DC1
Materials and Methods
Table S1

13 March 2002; accepted 1 May 2002

Rapid Changes in Flowering Time in British Plants

A. H. Fitter[1]* and R. S. R. Fitter[2]

The average first flowering date of 385 British plant species has advanced by 4.5 days during the past decade compared with the previous four decades: 16% of species flowered significantly earlier in the 1990s than previously, with an average advancement of 15 days in a decade. Ten species (3%) flowered significantly later in the 1990s than previously. These data reveal the strongest biological signal yet of climatic change. Flowering is especially sensitive to the temperature in the previous month, and spring-flowering species are most responsive. However, large interspecific differences in this response will affect both the structure of plant communities and gene flow between species as climate warms. Annuals are more likely to flower early than congeneric perennials, and insect-pollinated species more than wind-pollinated ones.

Climatic warming has been shown to alter the timing of important developmental or behavioral events in birds (*1*, *2*), plants (*3*, *4*), amphibians (*5*), and insects (*6*, *7*); most studies have involved single or small sets of species. The timing of flowering is a key event for plants. It affects their chances of pollination, especially when the pollinator (for example, an insect) is itself seasonal, and determines the timing of seed ripening and dispersal: Fruit set may be pollen limited at both the start and end of the flowering period (*8*). Flowering time also influences animals for which pollen, nectar, and seeds are important resources (*9*), and earlier flowering also implies earlier activity in other processes (leaf expansion, root growth, nutrient uptake) that are important for niche differentiation among coexisting species (*10*, *11*) and so will alter competitive interactions between species. Large changes in flowering date will therefore disrupt ecosystem structure.

We have analyzed the first flowering date for a set of 557 plant species, recorded by a single observer (R.S.R.F.) over a period of 47 years in the vicinity of a single locality in south-central England (*12*). We previously analyzed data for 267 of these species for the period 1954–1989 (*13*), and the criteria used here were the same, except that species used were those for which data were available for more than half the years (i.e., >23) with at least four records in the period 1991–2000, giving a total of 385 species (*14*) [table S1 (*15*)].

The first flowering date (FFD) of these 385 species for the decade 1991–2000 was on average 4.5 ± 0.40 (mean ± SE; modal value = −4.0) days earlier than that for the period 1954–1990 (Fig. 1); 60 (16%) were significantly earlier ($P < 0.05$; Student's t test), with a mean deviation of −15 days. Ninety-four species (24%) had a deviation in mean FFD >0; in other words, these species showed later flowering in the 1990s than previously, but the deviation was only significant for 10 species (3%). A few species showed extreme and significant deviations in the 1990s from the long-term mean, including *Lamium album* (Lamiaceae; −55 days: 18 March in 1954–1990 versus 23 January in 1991–2000) and *Cymbalaria muralis* (Scrophulariaceae; −35 days: 15 April versus 11 March). *L. album* is a species that used occasionally to flower through the winter and now routinely does so; earlier floras give the FFD as March (*16*), April (*17*), or May (*18*, *19*). One species, the introduced shrub *Buddleja davidii* (Buddlejaceae), was strongly delayed in the 1990s, by 36 days compared with the 1954–1990 mean. These data are similar to, but more marked than, those seen in a study of 100 species over 30 years (1970–1999) in Washington, DC (*20*): 89% were advanced and 11% retarded, with an overall mean advancement of 2.4 days in 30 years, and extreme shifts of −46 to +10 days.

FFD showed little variation in flowering time during the first four decades of the period studied (Fig. 1, inset), but there has been a major shift in FFD since the 1980s. We have explored the impact of climatic variables on these changes by using the data from the Central England Temperature (CET) Record (*21*) and the North Atlantic Oscillation (NAO) (*22*, *23*). Correlations with CET data were stronger than with NAO data in all cases. We grouped species by the month of their mean FFD and determined

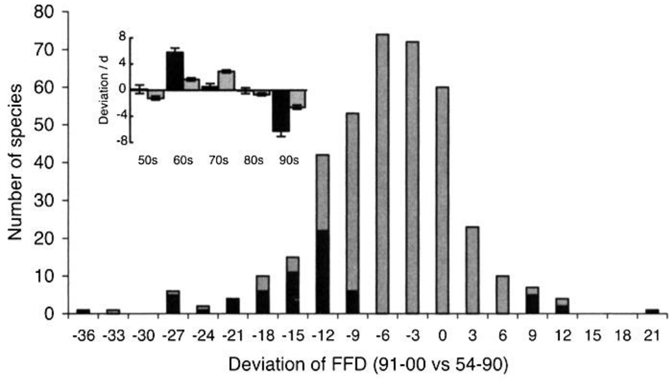

Fig. 1. Frequency distribution of deviations in FFD in the decade 1991–2000 from the mean over the period 1954–1990. Categories are 3-day periods; numbers represent the lower bound of each category. Solid values of the column represent species for which the deviation was significantly different from zero. Negative values indicate earlier flowering than the 1954–1990 mean, positive values later flowering. Two species with extreme deviations [*L. album* (–55 days) and *B. davidii* (+36 days)] have been omitted for clarity. (**Inset**) Mean deviation of the FFD for each decade from the long-term mean (1954–2000); solid bars represent species flowering in spring (January to April); open bars denote summer-flowering species (May to August). Error bars represent standard errors.

---

[1] Department of Biology, University of York, York YO10 5DD, UK. [2] Danewood, 9 Coppice Avenue, Great Shelford, Cambridge CB2 5AQ, UK.

*To whom correspondence should be addressed. E-mail: ahf1@york.ac.uk