Reply to Comment on "Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981–1999" by J. R. Ahlbeck

R. K. Kaufmann,[1] L. Zhou,[1] C. J. Tucker,[2] D. Slayback,[3] N. V. Shabanov,[1] and R. B. Myneni[1]

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[1] *Ahlbeck* [2002] raises an important issue: Is the increase in the atmospheric concentration of CO_2 [*Keeling and Whorf*, 2001] partially responsible for the increase in the normalized difference vegetation index (NDVI), which we report in the work of *Zhou et al.* [2001]? To demonstrate its effect, *Ahlbeck* [2002] adds the atmospheric concentration of CO_2 (hereinafter referred to as CO_2) to equation (11) in the *Zhou et al.* [2001] article. *Ahlbeck* [2002] finds that CO_2 is correlated with NDVI and concludes that "fertilizing due to increased atmospheric carbon dioxide concentration also may increase greenness." As described below, this conclusion, and the results on which it is based, is a statistical artifact. When the regression equation is specified correctly, we find that there is no relation between the NDVI and the atmospheric concentration of CO_2.

[2] To confirm Ahlbeck's results, we estimate the following equation:

$$\mathrm{NDVI} = \beta_0 + \beta_1 \ \mathrm{temp} + \beta_2 \ CO_2 + \varepsilon, \quad (1)$$

with data from North America and Eurasia. Here temp denotes temperature. To determine whether CO_2 or temperature has a statistically measurable effect on NDVI, we use a *t* statistic to test the null hypothesis that the regression coefficient is equal to zero. Rejecting this null indicates that the variable associated with the regression coefficient has a statistically measurable effect on NDVI. As indicated in Table 1, the *t* statistic for β_2 estimated from the North American data set is 7.36 ($p < 0.0001$). This result, and that estimated from the data set for Eurasia, is consistent with Ahlbeck's claim that increases in CO_2 are partially responsible for increases in NDVI.

[3] However, a careful comparison of equation (1) with equation (11) from *Zhou et al.* [2001] indicates that *Ahlbeck* [2002] does not simply add CO_2 to equation (11), he also eliminates the time trend. If we reintroduce the time trend and estimate the following equation,

$$\mathrm{NDVI} = \beta_0 + \beta_1 \ \mathrm{time} + \beta_2 \ \mathrm{temp} + \beta_3 \ CO_2 + \varepsilon, \quad (2)$$

with data from North America and Eurasia, we find that the *t* statistic associated with β_3 cannot reject the null hypothesis that $\beta_3 = 0$ (Table 1). This result indicates that CO_2 has no measurable effect on NDVI in North America or Eurasia when we include a time trend. Notice that the regression coefficient (β_2) associated with temperature retains its statistical significance (Table 1).

[4] Why does the presence of a time trend eliminate the statistical significance of CO_2? The answer can be seen in the work of *Ahlbeck* [2002, Figure 1]. The atmospheric concentration of CO_2 rises steadily over the sample period, 1982–1999. As such, CO_2 "looks like" a time trend. As such, the two variables in equation (2) are highly correlated. The resulting colinearity causes ordinary least squares to overstate the size of the standard errors associated with β_1 and β_3. Under these conditions, the regression coefficients appear to be statistically insignificant.

[5] The confusion about statistical significance associated with the colinearity begs a critical question: Does CO_2 (absent a time trend) affect NDVI because it "looks like" a time trend or does the time trend (absent CO_2) affect NDVI because it "looks like" CO_2? We can answer this question by removing the time trend from CO_2 and testing whether movements in CO_2 beyond a linear time trend explain movements in NDVI. To do so, we use data from the sample period, 1982–1999, to estimate the following equation:

$$CO_2 = \alpha_0 + \alpha_1 \ \mathrm{time} + \mu, \quad (3)$$

in which α_0 and α_1 are regression coefficients and μ is the regression error. This regression error corresponds to movements in CO_2 beyond a linear time trend.

[6] If CO_2 affects NDVI (and not some other variable that "looks like" a time trend), movements in CO_2 which are faster or slower than the linear time trend will have explanatory power about NDVI beyond the explanatory power of the linear time trend; that is, if CO_2 does affect

[1]Department of Geography, Boston University, Boston, Massachusetts, USA.

[2]Biospheric Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

[3]Science Systems & Applications Inc., Biospheric Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

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Table 1. Regression Results for Equations (1), (2), (4), and (5)

	Regression Slopes		
	North America Ordinary Least Squares	Eurasia Ordinary Least Squares	Combined (Fixed Effects Estimator)
Equation (1)			
temp β_1	0.019[a]	0.015[a]	0.017[a]
	(5.58)	(4.13)	(6.63)
CO_2 β_2	0.001[a]	0.001[a]	0.001[a]
	(7.36)	(3.93)	(7.71)
Equation (2)			
time β_1	−0.002	0.0002	−0.001
	(0.38)	(0.05)	(0.25)
temp β 2	0.014[a]	0.019[a]	0.016[a]
	(3.30)	(5.11)	(5.84)
CO_2 β_3	0.002	0.001	0.002
	(0.63)	(0.52)	(0.80)
Equation (4)			
time β_1	0.001[a]	0.002[a]	0.002[a]
	(3.83)	(7.06)	(7.59)
temp β_2	0.014[a]	0.019[a]	0.016[a]
	(3.30)	(5.12)	(5.83)
μ β_3	0.002	0.001	0.002
	(0.63)	(0.52)	(0.80)
Equation (5)			
Δ temp β_1	0.014[a]	0.020[a]	0.016[a]
	(4.21)	(6.73)	(7.31)
Δ CO_2	−0.004	−0.003	−0.004
β_2	(1.00)	(0.88)	(1.41)

t statistics in parentheses.
[a]Values exceed the $p < 0.01$ threshold.

NDVI, NDVI should rise faster than predicted by the linear time trend in years when CO_2 increases faster than the time trend. Similarly, NDVI should increase slower than predicted by the linear time trend in years when CO_2 increases slower than the time trend.

[7] We evaluate the explanatory power of CO_2 relative to the linear time trend by estimating the following equation:

$$\mathrm{NDVI} = \beta_0 + \beta_1\,\mathrm{time} + \beta_2\,\mathrm{temp} + \beta_3\,\mu + \varepsilon, \qquad (4)$$

in which μ is the error term from equation (3). If the regression coefficient that is associated with μ (β_3) is statistically different from zero, this result will indicate that movements in CO_2, slower or faster than a linear time trend, have explanatory power about NDVI that is not contained in a time trend. Alternatively, if β_3 is not statistically significant, this result would indicate that movements in CO_2, faster or slower than a time trend, have no explanatory power about NDVI relative to a time trend.

[8] When equation (4) is estimated from data for North America and Eurasia, the estimate for β_3 is not statistically different from zero. This result indicates that movements in CO_2, faster or slower than a time trend have no explanatory power about NDVI beyond a time trend. This implies that the result found by *Ahlbeck* [2002] is caused by the similarity between CO_2 and a time trend during the sample period, and not the effect of CO_2 on NDVI.

[9] This conclusion is reinforced by estimating a version of equation (12) from *Zhou et al.* [2001] which is expanded to include CO_2 as follows:

$$\Delta\mathrm{NDVI} = \beta_0 + \beta_1\,\Delta\mathrm{temp} + \beta_2\,\Delta CO_2 + \varepsilon, \qquad (5)$$

in which Δ is the first difference operator. Again, the regression coefficient that is associated with the first difference of CO_2 (β_2) is not statistically different from zero, while the regression coefficient associated with the first difference of temperature (β_1) retains its statistical significance. This also indicates that the result found by *Ahlbeck* [2002] is due to the similarity between CO_2 and a time trend during the sample period, and not the effect of CO_2 on NDVI.

[10] We recognize that the interpretation of the statistical results described above is limited by the small sample size of the North American and Eurasian data sets. These limits can be alleviated by combining the two data sets and using *F* tests to evaluate whether the coefficients estimated from the North American data set are equal to those estimated from the Eurasian data set [*Hsiao*, 1986]. These *F* tests indicate that we cannot reject restrictions that equalize the coefficients other than the intercepts for equations (1), (2), (4), and (5). Under these conditions, the equations can be estimated from the combined data set using a fixed effects estimator. This allows us to estimate results that have more than twice the degrees of freedom than those estimated from the individual data sets. These results confirm those described above (Table 1).

[11] Together, these results indicate that there is no evidence that increases in the atmospheric concentration of CO_2 are responsible for the increases in NDVI described by *Zhou et al.* [2001]. Although CO_2 correlates with NDVI, the relation described by *Ahlbeck* [2002] is a coincidence based on the similarity between CO_2 and a linear time trend. The mechanism that lays behind the linear increase in NDVI is uncertain but could include forest regrowth following the effects of human disturbance and/or the decay of the

increase in aerosol optical depth associated with the volcanic eruption of El Chichon at the start of the sample period (L. Zhou et al., manuscript in preparation, 2001).

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R. K. Kaufmann, R. B. Myneni, N. V. Shabanov, and L. Zhou, Department of Geography, Boston University, 675 Commonwealth Avenue, Boston, MA 02215, USA. (kaufmann@bu.edu)

C. J. Tucker, Biospheric Sciences Branch, Code 923, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

D. Slayback, Science Systems & Applications Inc., Biospheric Sciences Branch, Code 923, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.