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High-latitude tree growth and satellite vegetation indices: Correlations and trends in Russia and Canada (1982–2008)

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[1] Vegetation in northern high latitudes affects regional and global climate through energy partitioning and carbon storage. Spaceborne observations of vegetation, largely based on the normalized difference vegetation index (NDVI), suggest decreased productivity during recent decades in many regions of the Eurasian and North American boreal forests. To improve interpretation of NDVI trends over forest regions, we examined the relationship between NDVI from the advanced very high resolution radiometers and tree ring width measurements, a proxy of tree productivity. We collected tree core samples from spruce, pine, and larch at 22 sites in northeast Russia and northwest Canada. Annual growth rings were measured and used to generate site-level ring width index (RWI) chronologies. Correlation analysis was used to assess the association between RWI and summer NDVI from 1982 to 2008, while linear regression was used to examine trends in both measurements. The correlation between NDVI and RWI was highly variable across sites, though consistently positive ($r = 0.43$, $SD = 0.19$, $n = 27$). We observed significant temporal autocorrelation in both NDVI and RWI measurements at sites with evergreen conifers (spruce and pine), though weak autocorrelation at sites with deciduous conifers (larch). No sites exhibited a positive trend in both NDVI and RWI, although five sites showed negative trends in both measurements. While there are technological and physiological limitations to this approach, these findings demonstrate a positive association between NDVI and tree ring measurements, as well as the importance of considering lagged effects when modeling vegetation productivity using satellite data.

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1. Introduction

[2] The Arctic and boreal biomes cover 22% of the terrestrial surface, account for ~12% of annual vegetation productivity, and play an important role in regulating climate through energy partitioning and carbon storage [Chapin *et al.*, 2000, 2005; Kimball *et al.*, 2006]. While the global mean atmospheric temperature rose approximately $0.74^{\circ}\text{C} \pm 0.18^{\circ}\text{C}$ over the past century [Intergovernmental Panel on Climate Change, 2007], much of the Arctic warmed 2–4°C over the same period [Arctic Climate Impact Assessment, 2004]. Changes in temperature and hydrologic regimes within arctic ecosystems have had effects on the composition [Ostercamp *et al.*, 2000; Devi *et al.*, 2008; Hudson and Henry, 2009], distribution [Ostercamp *et al.*, 2000; Tape *et al.*, 2006; Devi *et*

al., 2008] and productivity [Zhang *et al.*, 2007; Hudson and Henry, 2009] of arctic vegetation communities. Such changes affect biogeochemical and biophysical processes inducing feedbacks to climate [Chapin *et al.*, 2005; Vygodskaya *et al.*, 2007; McGuire *et al.*, 2009]. Across the literature, satellite-derived indices of key ecosystem processes (e.g., productivity) have been increasingly used to augment site-based studies and provide more spatially complete records of ecosystem change [McGuire *et al.*, 2009].

[3] Since the 1980s, satellites have been used to monitor global vegetation activity [Tucker *et al.*, 1986] and the normalized difference vegetation index (NDVI) has emerged as one of the most widely used vegetation-related metrics. The index measures chlorophyll abundance [Myneni *et al.*, 1995], absorption of photosynthetically active radiation, and canopy photosynthetic capacity, although saturates in regions with high leaf area [Sellers, 1985, 1987]. The ability of plants to harvest light scales with resource availability and serves as an ecological integrator of carbon uptake potential [Goetz and Prince, 1999]. Time-integrated NDVI can therefore be used to estimate gross primary production (GPP). While plants exhibit evolutionary convergence in the efficiency with which

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absorbed light is used to assimilate carbon (e.g., GPP), variability in plant growth, respiration and stomatal activity complicates the use of NDVI as a measure of carbon accumulation (net primary production, NPP [Goetz and Prince, 1999]).

[4] Nemani *et al.* [2003] found that global satellite-modeled terrestrial NPP increased by 6% between 1982 and 1999, with 25% of the vegetated areas exhibiting positive trends in NPP (greening) and 7% exhibiting negative trends (browning). Summer greening was pervasive through the northern high latitudes from 1982 to 1991, while between 1994 and 2002 greening continued through much of the tundra and was replaced by browning in many forested regions [Angert *et al.*, 2005]. Concurrent with summer greening at high latitudes during the 1980s, the amplitude of CO₂ drawdown during spring and late summer increased; however, while the amplitude of spring CO₂ drawdown continued to increase between 1994 and 2002, the late summer CO₂ minimum showed no trend [Angert *et al.*, 2005]. This implies that enhanced biological C uptake during spring was canceled out by reduced C uptake during late summer, a period during which browning appears most evident in the satellite record [Angert *et al.*, 2005; Bunn and Goetz, 2006]. Browning was evident in 6% (37.6×10^6 ha) of pan-arctic needle-leaved forests [Bunn *et al.*, 2007] and was observed across 21.7% of boreal forests in North America [Goetz *et al.*, 2005]. Late summer browning appears primarily concentrated in inland areas of high tree density [Bunn and Goetz, 2006] and may be related to increased drought stress [Angert *et al.*, 2005; Bunn *et al.*, 2007; Verbyla, 2008; Zhang *et al.*, 2008].

[5] While greening of the tundra is thought to be mostly a result of increased shrub growth and range expansion [Bunn and Goetz, 2006; Tape *et al.*, 2006; Forbes *et al.*, 2010], browning within forested regions may represent increased temperature and drought stress, changes in mortality rates, and shifts in plant allocation to roots and shoots [Lapenis *et al.*, 2005; Zhang *et al.*, 2007, 2008; Verbyla, 2008; Allen *et al.*, 2010]. Inverse relationships between tree growth and temperature appear widespread and increasingly prevalent, occurring more frequently in the warmer and drier parts of species ranges [Lloyd and Fastie, 2002; D'Arrigo *et al.*, 2004; Lloyd and Bunn, 2007]. Evidence from tree rings, satellites and stable isotopes suggest that warmer and drier conditions are inducing temperature and drought-related stress, thereby causing reductions in forest growth within some regions [Barber *et al.*, 2000; Wilmking *et al.*, 2004; Goetz *et al.*, 2005; Bunn *et al.*, 2007; Lloyd and Bunn, 2007; D'Arrigo *et al.*, 2004; Zhang *et al.*, 2008]. While satellite-observed browning may reflect reduced rates of NPP in some forested regions, it is important to verify these results through ground-based sampling.

[6] Past efforts have linked satellite-based NPP estimates with biomass harvests and eddy covariance flux tower measurements, though both techniques are severely limited in terms of the potential spatial extent of validation [Running *et al.*, 2004]. Malmstrom *et al.* [1997] demonstrated a significant relationship between a NDVI-based model of NPP and measurements of annual growth rings at a mixed white spruce (*Picea glauca*) and paper birch (*Betula papyrifera*) forest stand in Alaska, thus suggesting the potential to use tree ring measurements to validate modeled productivity. The width of annual tree rings relates to NPP, while the distinct growth

rings permit retrospective analysis of forest productivity [Graumlich *et al.*, 1989; Gower *et al.*, 2001; Bascietto *et al.*, 2004]. Additional studies have demonstrated positive relationships between growing season NDVI and ring width measurements for sites in North America and Eurasia [Kaufmann *et al.*, 2004; Lopatin *et al.*, 2006].

[7] The purpose of this research was to examine the relationship between tree rings and NDVI, as derived from the NOAA advanced very high resolution radiometers (AVHRR), at selected high-latitude (60°–70°N) forest stands in Russia and Canada so as to improve interpretation of satellite-observed browning trends. Interannual variation in tree growth (i.e., C uptake), estimated from ring widths, were related to the NASA Global Inventory Modeling and Mapping Studies (GIMMS) NDVI data set [Tucker *et al.*, 2005]. The GIMMS data set extends from July 1981 through present and was chosen because it has one of the longest, best documented and continuous records and has been widely used for monitoring boreal and arctic vegetation dynamics [e.g., Myneni *et al.*, 1997; Goetz *et al.*, 2005; Bunn and Goetz, 2006]. While previous studies have related NDVI and tree rings [e.g., D'Arrigo *et al.*, 2000; Kaufmann *et al.*, 2004; Lopatin *et al.*, 2006], the spatial coverage of these studies has been limited and few studies have included tree ring data covering the period after 2000, a decade thought to be the warmest in the past two millennium [Kaufman *et al.*, 2009]. Additionally, because the timing of spring onset and fall senescence at high latitudes can vary widely across the landscape [Beck *et al.*, 2007], we sought to make use of a new algorithm to determine the mean annual growing season NDVI both spatially and temporally. The algorithm permitted the timing of the growing season to change between years, as well as across the landscape. Given the important role that high-latitude forests play in C cycling and energy partitioning, it is important to validate, through ground-based measurements, spaceborne observations of browning.

2. DATA and Methods

2.1. Tree Ring

[8] During the summers of 2008 and 2009, tree cores were collected from 22 sites in the high-latitude (60–70°N) forests of Russia ($n = 12$) and Canada ($n = 10$; Figure 1). The northeastern Russian forests are almost exclusively composed of Dahurian larch (*Larix gmelinii*). We follow the convention of most of the English language literature and refer to all of the larch we sampled as *Larix gmelinii* although a separate species, *L. cajanderi*, is recognized by Russian scientists. In southern Siberia, Scots pine (*Pinus sylvestris*) and Siberian spruce (*Picea abies* subsp. *obovata*) are also present. In northwestern Canada the forests are composed largely of black spruce (*Picea mariana*), white spruce (*P. glauca*) and jack pine (*Pinus banksiana*), though tamarack (*Larix laricina*), birch (*Betula* spp) and aspen (*Poplar* spp) also occur. Within each stand we selected 20–40 straight, mature, canopy-dominant conifers that were free from visible signs of damage. Two perpendicular cores were extracted from each tree using 5 mm increment borers. A total of 499 trees, with 18–60 trees per site, were included in the analysis.

[9] Cores were mounted, sanded, and measured to the nearest micrometer using standard procedures [Pilcher, 1990]. The dating accuracy was verified statistically in R [R Development

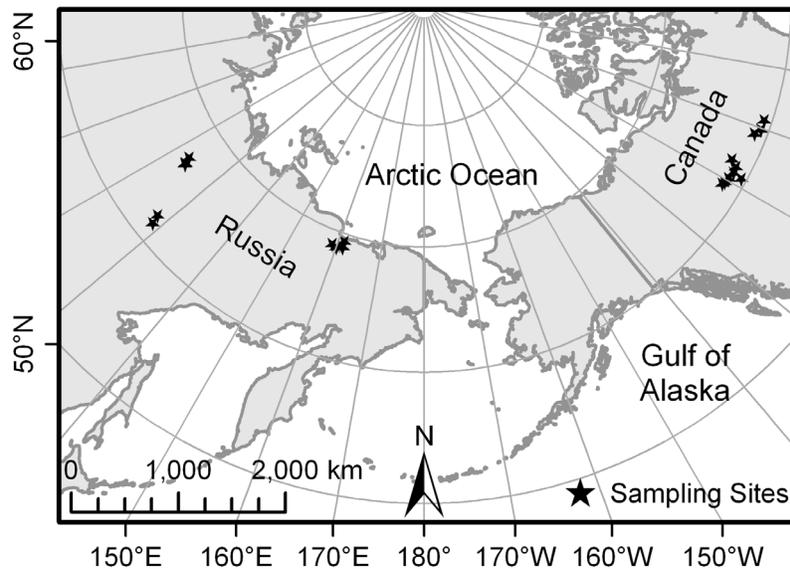


Figure 1. Tree-core samples were collected from sites along the Lena ($n = 6$) and Kolyma Rivers ($n = 6$) in Siberia, as well as in the Canadian Northwest Territories ($n = 10$).

Core Team, 2009] using the Dendrochronology Program Library in R package [dplR [Bunn, 2008, 2010]]. The series were subset after cross-dating to include only measurements from 1981 through the last complete growing season (2007 or 2008). Time series of tree ring widths are commonly standardized (producing dimensionless ring width indices) for two reasons: to remove age-related trends in growth (e.g., a geometric decline in ring width as trees age) and to eliminate individual differences in growth rate that might cause fast-growing individuals to be disproportionately reflected in the calculation of mean annual growth within a population. Age-related trends in growth are generally removed by fitting a negative exponential curve or spline, but such approaches can introduce artifacts into chronologies (e.g., end effects [D'Arrigo *et al.*, 2008]). Because we were analyzing ring widths for recent years only, we determined (by examining each time series) that there were not significant age-related declines in growth. We chose therefore to standardize more conservatively, dividing each ring width value by the series' mean. Normalized ring width index values were then used to construct an average ring width chronology for each population.

[10] We compared the mean standardized chronologies with basal area increment (BAI) chronologies and found that the median correlation at the Canadian sites was $r = 0.988$ (interquartile range: 0.940–0.996), while in Russia the median correlation was $r = 0.997$ (interquartile range: 0.989–0.999). As the two methods captured the same trends in growth over time, we chose to use ring width rather than BAI as the index of tree productivity in order to maximize the applicability of the results. There are many ring width data sets, such as those available through the National Oceanic and Atmospheric Administration's International Tree Ring Data Bank (ITRDB), where it might not be possible to calculate BAI due to missing bark or tree diameter measurements.

[11] While 17 of the 22 stands were single-species dominant, five stands exhibited codominance of tree species. This occurred once in Siberia with a mixed *L. gmelinii* and

P. abies stand and at four of the Canadian sites with mixed *P. banksiana* and *P. mariana* stands. In these cases, separate chronologies were created for each species, for a total of 27 chronologies. In mixed-species stands, the tree ring data were also pooled to create mixed-species chronologies. The mean interseries correlation of mixed-species chronologies ($r = 0.558 \pm 0.002$) did not differ significantly from that of single-species chronologies ($r = 0.600 \pm 0.004$) at the same sites (t test, $t = -1.306$, $df = 13$, $p = 0.214$). The tree ring chronologies used in this study are publically available online through the ITRDB (<http://www.ncdc.noaa.gov/paleo>).

2.2. Normalized Difference Vegetation Index

[12] The GIMMS NDVI data set (version G) from 1982 to 2008 was used in this study [Tucker *et al.*, 2005]. The 1982–2006 data are available online (<http://glcf.umd.edu/data/gimms>), while the 2007 and 2008 data were acquired from the GIMMS group at NASA. The data were derived from measurements by the AVHRR sensors carried by the afternoon-viewing NOAA satellite series (NOAA 7, 9, 11, 14, 16, and 17). Data processing includes corrections for atmospheric aerosols, solar zenith angle effects, and sensor differences and degradation [Tucker *et al.*, 2005]. GIMMS provides 24 global, maximum value composite NDVI images per year at a spatial resolution of 8 km and a spatial accuracy of ± 1 pixel. GIMMS NDVI values range from 0.0 to 1.0 and these were rescaled from 0 to 100 for the analysis.

[13] To account for spatial and temporal differences in the timing of vegetation green-up and senescence, we calculated the growing season NDVI on a pixel-by-pixel basis using a two-step process. First, the MODIS Land Cover Dynamics product (MOD12 [Zhang *et al.*, 2003]) was used to determine the latest green-up and earliest dormancy dates between 2001 and 2004. We defined the growing season length as the interval between these phenological events. These 30 arcsecond (~ 1 km) data were averaged over a 64 km^2 area to determine the mean growing season length for each GIMMS-NDVI pixel. Second, growing season

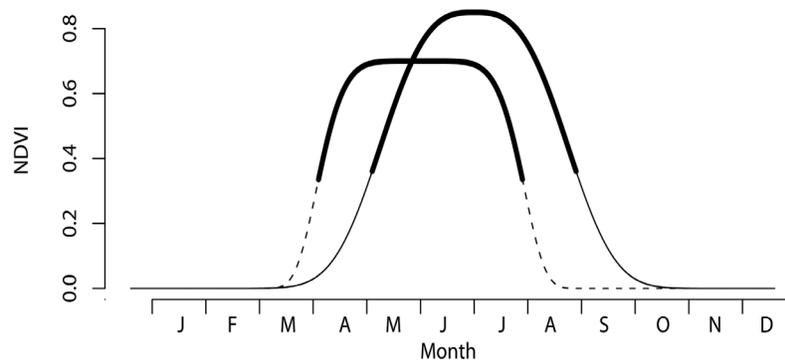


Figure 2. Hypothetical NDVI series for a pixel in two different years. Mean growing season NDVI was calculated in each year from the N continuous NDVI observations (bold line) that generated the highest mean. N reflects the length of the growing season estimated from the Land Cover Dynamics product derived from Moderate Resolution Imaging Spectroradiometer data.

NDVI was determined by selecting the highest value output from a time series moving average with window length equivalent to the mean growing season length (Figure 2). NDVI scales near-linearly with potential canopy photosynthetic capacity and time-integrated NDVI provides an estimate of GPP [Tucker and Sellers, 1986; Sellers, 1987]. We used mean NDVI over a fixed growing season length as a proxy for GPP.

[14] The NDVI data and sampling site coordinates were coregistered to a common datum (WGS 1984). A 3×3 pixel window ($\sim 576 \text{ km}^2$) was centered on each sampling site and the mean NDVI within each window was determined for each

annual growing season. The 3×3 windows were also used to derive estimates of tree cover at each site from the 500 m resolution MODIS Vegetation Continuous Fields (VCF) Tree Cover product (MOD44 [Hansen *et al.*, 2003]). The Global Land Cover 2000 database (GLC2000, European Commission, Joint Research Center, 2003, <http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php>), based on SPOT 4 VEGETATION imagery, was also used to derive estimates of forest cover and to quantify the number of land cover types occurring around each site. We then used Pearson's correlation to assess the relationship between the strength of the NDVI-RWI correlation ($r_{\text{ndvi-rwi}}$) and land cover characteristics.

Table 1. Sampling Site Characteristics and Correlations Between Ring Width Index and Normalized Difference Vegetation Index^a

Genus	Species	Site	Latitude	Longitude	Percent Tree Cover	N Trees	Pearson's Correlation		
							N_{eff}	p Value	r
Larix	gmelinii	CHE	68.748	161.424	12	57	26	0.10	0.33
		DVN	68.669	159.075	10	9	26	0.03	0.43
		GRS	68.748	161.377	12	13	26	0.01	0.57
		IND ^b	66.275	123.916	25	25	26	0.11	0.32
		PAR	68.532	160.198	12	13	26	0.69	0.08
		ROD	68.727	161.551	11	14	26	0.04	0.40
		SYL	66.210	124.004	26	24	26	0.11	0.32
		TRL	69.200	161.440	9	7	26	0.02	0.45
		YUT	62.029	128.593	41	30	26	0.19	0.27
		ZHG	66.750	123.416	25	60	26	0.01	0.67
Picea	abies	IND ^b	66.275	123.916	25	8	26	0.45	0.16
		ZHF	66.761	123.349	24	10	26	0.16	0.28
	glauca	BIS	61.691	-116.944	43	10	8	0.20	0.51
		FAL ^b	61.193	-119.992	50	8	12	0.27	0.34
	mariana	NML	60.320	-119.049	49	21	15	0.15	0.39
		DAR ^b	60.909	-111.593	29	10	26	0.12	0.31
		ELF ^a	61.353	-120.801	48	5	10	0.20	0.44
		FAH	61.433	-121.267	53	19	6	0.08	0.75
		SQT	61.094	-118.782	32	22	11	0.02	0.68
TAL ^b	60.554	-110.607	39	8	13	0.02	0.62		
Pinus	banksiana	DAR ^b	60.909	-111.593	29	14	26	0.45	0.15
		ELF ^b	61.353	-120.801	48	16	12	0.25	0.36
	sylvestris	FAL ^b	61.193	-119.992	50	10	9	0.10	-0.58
		MAR	60.556	-109.037	34	23	11	0.06	0.59
		MKZ	61.133	-117.809	45	18	9	0.01	0.82
		TAL ^b	60.554	-110.607	39	14	15	0.01	0.62
		BAL	61.340	129.084	42	31	26	0.07	0.36

^aHere $n = 22$ sites; 1982–2007/2008.

^bDenotes sites with codominant tree cover at which two species were sampled.

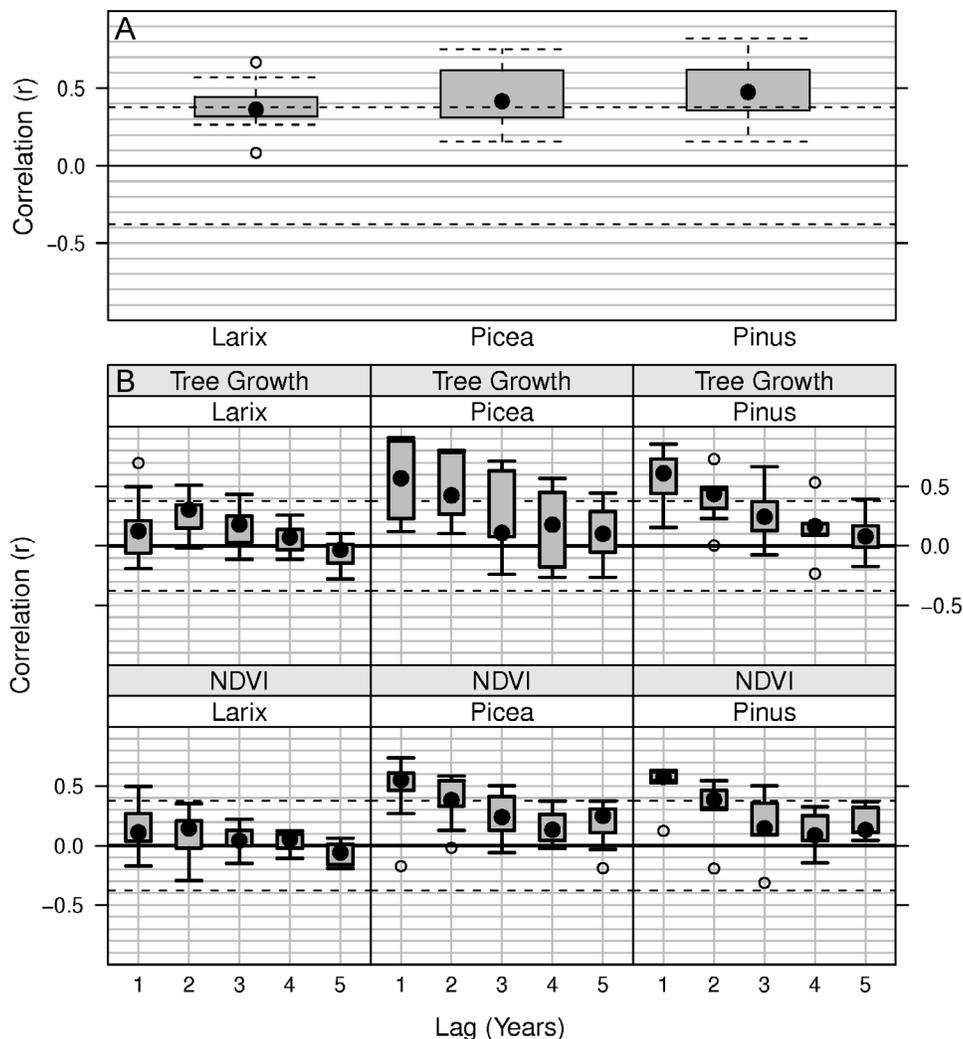


Figure 3. (a) Box and whisker plots showing ring width and NDVI correlations for larch ($n = 10$), pine ($n = 6$) and spruce ($n = 10$). Intrabox dots denote medians, while box edges denote 25th and 50th quartiles. Whiskers denote 5th and 95th percentiles, and open dots represent outliers. One pine site (FAL) showing a negative correlation was excluded. Dashed lines indicate thresholds for correlation significance at $p = 0.05$ and $n = 27$. (b) Box and whisker plots showing ring width and NDVI autocorrelation by genus.

2.3. Statistical Analyses

[15] We used the statistical program R to conduct Pearson's correlation analyses between RWI and NDVI for each chronology ($n = 27$) between 1982 and 2008. Correlation analyses assume statistical independence between samples (i.e., years), which was evaluated by calculating the autocorrelation within each RWI and NDVI series. In instances where significant autocorrelation ($p < 0.05$) was detected, the significance value of the RWI-NDVI correlation for that site was penalized by reducing the effective sample size (N_{eff}) in proportion to the strength of the autocorrelation [Dawdy and Matalas, 1964].

[16] We also assessed the annual, linear trends in both NDVI and RWI for each of the 22 sites using ordinary least squared (OLS) regression. Trends were deemed significant at a critical value (α) of 0.05 and were categorized as positive, negative, or nontrending. Regression residuals were plotted and inspected for randomness, while normality was assessed using Shapiro-Wilks tests. Forest stands showing

species codominance, such as the four *Picea mariana* and *Pinus banksiana* stands sampled in Canada, presented a complication when attempting to ascribe NDVI signals to particular taxa. We report the correlation results in terms of tree genera, but recognize that in mixed-species stands the NDVI signal is not exclusive to a particular taxon.

[17] To examine whether NDVI and RWI were related in terms of statistical predictability, we used Granger causality tests [Granger, 1969]. Granger causality (G-causality) is a linear autoregression model that tests whether past values from one time series (X) can be used to improve the forecast of a second time series (Y) to a greater extent than using past values from Y alone. The test is widely used in macroeconomic analysis, though has previously been used to examine the relationship between NDVI and tree rings [Kaufmann et al., 2004]. We used the 'lmtest' package in R [Zeileis and Hothorn, 2002] to investigate the relationship between NDVI and RWI for each site. The lmtest imple-

Table 2. Linear Regression Trends in Ring Width Index and Normalized Difference Vegetation Index^a

Genus	Site	RWI			NDVI		
		p Value	Slope	r ²	p Value	Slope	r ²
Larix	CHE	0.10	-0.011	0.07	0.02	0.223	0.16
	DVN	0.66	-0.004	-0.03	<0.01	0.428	0.34
	GRS	0.96	0	-0.04	0.03	0.152	0.14
	PAR	0.01	-0.024	0.23	<0.01	0.508	0.45
	ROD	0.21	-0.01	0.03	0.02	0.265	0.17
	SYL	0.29	-0.007	0.01	0.26	0.067	0.01
	TRL	0.19	-0.01	0.03	0.02	0.133	0.18
	YUT	<0.01	-0.024	0.52	0.66	0.05	-0.03
	ZHG	0.18	-0.009	0.04	0.83	-0.013	-0.04
	Picea	BIS	<0.01	-0.077	0.66	<0.01	-0.459
FAH		<0.01	-0.037	0.88	<0.01	-0.438	0.58
NML		0.23	-0.006	0.02	0.01	-0.327	0.25
SQT		<0.01	-0.035	0.66	<0.01	-0.31	0.30
ZHF		0.05	0.011	0.11	0.83	-0.013	-0.04
Pinus	BAL	<0.01	-0.016	0.28	0.85	-0.014	-0.04
	MAR	0.64	0.003	-0.03	0.02	0.359	0.17
	MKZ	<0.01	-0.05	0.78	<0.01	-0.415	0.47
Mixed	DAR	0.38	-0.003	-0.01	0.31	0.128	0.00
	ELF	<0.01	-0.02	0.56	<0.01	-0.429	0.54
	FAL	0.06	0.006	0.10	<0.01	-0.501	0.60
	IND	0.21	0.009	0.02	0.84	-0.012	-0.04
	TAL	0.94	0	-0.04	0.18	0.198	0.03

^aHere n = 22 sites; 1982–2007/2008; RWI, ring width index; NDVI, normalized difference vegetation index; mixed species stands were spruce and pine, except for IND which was pine and larch. Positive trends in NDVI occurred almost exclusively in larch stands, while negative trends in both NDVI and RWI were most frequent in spruce and pine stands. The NDVI slope is given in NDVI units yr⁻¹, while RWI is unitless and the slope is yr⁻¹.

mentation uses a Wald test to compare the predictive ability of the unrestricted model, in which Y is modeled as a function of both Y and X using n lagged values, and the restricted model, in which Y is modeled based on n lagged values of Y alone. To investigate whether NDVI G-caused RWI, or whether RWI G-caused NDVI, we tested two models at a one year lag:

$$\text{NDVI}_{it} = \beta_1 \text{RWI}_{it-1} + \beta_2 \text{NDVI}_{it-1} + \varepsilon_{it} \quad (1)$$

$$\text{RWI}_{it} = \beta_1 \text{NDVI}_{it-1} + \beta_2 \text{RWI}_{it-1} + \varepsilon_{it} \quad (2)$$

in which values of NDVI and RWI at site i and year t are predicted based on values of those variables at year t-1; β_1 and β_2 are fitted regression coefficients; and ε is a regression error term. The null hypothesis is that inclusion of a second time series does not improve the ability to forecasting the time series of interest (i.e., $\beta_1 = 0$). Rejection of H_0 does not imply a physically causal relationship between

the two variables; rather, it implies that one variable contains information about future states of the second variable.

3. Results

3.1. Ring Width and NDVI Correlations

[18] Ring width indices and NDVI showed consistent positive associations over the 1982 to 2008 period, except for one pine site from Canada which displayed a moderately strong negative correlation (Table 1 and Figure 3a). At a critical value (α) of 0.05, nine of the 27 were chronologies were significantly correlated with NDVI, while at $\alpha = 0.10$, 14 sites showed significant correlations between RWI and NDVI. Penalization of effective sample sizes due to significant autocorrelation in either RWI or NDVI measurements affected seven of ten spruce chronologies and five of seven pine chronologies, thereby reducing the probability of detecting significant effects at those sites. Excluding the one negative association, the mean correlation increased from 0.33 ± 0.46 to 0.43 ± 0.19 (mean \pm standard deviation). Mean correlations were 0.38 ± 0.16 for larch (n = 10), 0.45 ± 0.19 for spruce (n = 10), and 0.48 ± 0.24 for pine (n = 6). The strongest correlations observed between NDVI and RWI were 0.67 for larch, 0.75 for spruce and 0.82 for pine stands. Across sites, $r_{\text{ndvi-rwi}}$ was not related to GLC2000 forest cover ($r = 0.07$, $p = 0.75$, $df = 25$), nor to mean tree cover derived from the MODIS VCF product ($r = 0.33$, $p = 0.09$, $df = 25$). For spruce and pine sites, $r_{\text{ndvi-rwi}}$ was not related to the extent of needleleaf evergreen forest ($r = -0.23$, $p = 0.37$, $df = 15$) and at larch sites $r_{\text{ndvi-rwi}}$ showed no relationship with the extent of deciduous needleleaf forest ($r = -0.29$, $p = 0.41$, $df = 8$). Pooling sites, $r_{\text{ndvi-rwi}}$ did exhibit a weak negative relationship with the number of land cover types ($r = -0.39$, $p = 0.04$, $df = 25$).

3.2. Ring Width and NDVI Autocorrelation

[19] Persistence in ring width measurements and NDVI for each of the three genera was investigated by examining the autocorrelation within each data set. Over the 27 year period, ring width indices for pine and spruce both exhibited significant autocorrelation at lags of one and two years (Figure 3b). Mean correlations at a lag of one year were 0.61 ± 0.26 for pine and 0.56 ± 0.29 for spruce. The NDVI measurements for these two genera showed similar autocorrelation, with correlation coefficients at a one year lag of 0.52 ± 0.18 and 0.48 ± 0.22 for pine and spruce, respectively. Neither larch RWI nor NDVI measurements exhibited significant autocorrelation over the 27 year period, with a mean autocorrelation at a lag of one year of 0.13 ± 0.21 for RWI and 0.16 ± 0.21 for NDVI. Across sites and

Table 3. Categorical Summary of Trends in Ring Width Index and Normalized Difference Vegetation Index^a

Genus	Number of Sites	RWI			NDVI		
		Negative	No Trend	Positive	Negative	No Trend	Positive
Larch	9	2	7	0	0	3	6
Picea	5	3	1	1	4	1	0
Pinus	3	2	1	0	1	1	1
Mixed	5	1	4	0	2	3	0
All sites	22	8 (36%)	13 (59%)	1 (5%)	7 (32%)	8 (36%)	7 (32%)

^aRWI, ring width index; NDVI, normalized difference vegetation index.

Table 4. Contingency Table Comparing Categorical Trends in Ring Width Index and Normalized Difference Vegetation Index^a

	RWI Trend			Agreement
	Negative	No Trend	Positive	
NDVI trend				
Negative	5	2	0	5/7 (71%)
No trend	2	5	1	5/8 (63%)
Positive	1	6	0	0/8 (0%)
Agreement	5/8 (63%)	5/13 (38%)	0/1 (0%)	10/22 (45%)

^aRWI, ring width index; NDVI, normalized difference vegetation index; a chi-square test indicated no significant association between NDVI and RWI trends ($\chi^2 = 7.298$, $df = 4$, $p = 0.12$), although 71% of sites with negative trends in NDVI also showed negative trends in RWI. No sites experienced positive trends in both NDVI and RWI, though 63% of sites with no trend in NDVI also experienced no trend in RWI.

taxa, the strength of the NDVI autocorrelation at a one year lag was significantly and positively associated with the strength of the RWI autocorrelation at the same lag ($r = 0.58$, $df = 25$, $p < 0.01$).

3.3. Ring Width and NDVI Trends

[20] Trends in ring width, as determined using linear regression, varied across the 22 sites. Most sites (13/22) experienced no significant ($p < 0.05$) trend in RWI, while negative trends were somewhat common (8/22) and positive trends uncommon (1/22; Tables 2 and 3). Nontrending ring width chronologies were most prevalent in larch (7/9) and mixed-species sites (4/5). Negative trends in ring width occurred in all taxa, though were most common in pine (2/3) and spruce (3/5), while less common in larch (2/9) and at mixed-species sites (1/5). *Picea abies* at one site (ZHF), located on a floodplain in central Russia, exhibited the only positive RWI trend of the sites sampled. In terms of NDVI, the number of sites with positive (7/22), negative (7/22), and no trend (8/22) occurred with roughly equal frequency (Table 3). Positive trends in NDVI ('greening') were proportionally highest at larch sites (6/9), although one pine site (MAR) in western Canada also greened. Negative trends in NDVI ('browning') were observed primarily in spruce (4/5), followed by mixed-species (2/6) and pine stands (1/3). No larch sites browned over this period. For each taxa, 20–60% of sites showed no trend in NDVI.

[21] Compared across all sites, NDVI and RWI trends showed no consistent association ($\chi^2 = 7.298$, $df = 4$, $p = 0.12$); however, a number of patterns were evident (Table 4). Overall, 10 of 22 sites showed agreement between the sign of the NDVI trend and the sign of the RWI trend. Five sites experienced no trend in either NDVI or RWI. Five of seven sites that browned also experienced negative trends in RWI; however, of the seven sites that greened, none were associated with positive trends in RWI. Greening sites were, however, primarily associated with RWI that showed no significant trend. One larch site (PAR), which was among the most northerly stands sampled, experienced a negative trend in RWI while simultaneously greening.

[22] Plotting the NDVI trend for each site as a function of tree cover showed that both negative NDVI trends and negative RWI trends appeared most concentrated in areas of moderately high tree cover (>40%), while greening was more prevalent in areas with low tree cover (Figure 4). Across sites,

the slope of the NDVI trend was negatively related to tree cover ($r^2 = 0.59$, $p < 0.001$, $df = 20$). From 1982 to 2008, the mean changes in NDVI at greening, browning, and nontrending sites were, respectively, $+0.083 \pm 0.004$ ($n = 7$), -0.115 ± 0.019 ($n = 7$) and $+0.014 \pm 0.022$ ($n = 8$) NDVI units. Proportional to 1982 growing season NDVI values, these translate into mean changes of $+14.6\% \pm 4.4\%$, $-16.4\% \pm 3.3\%$ and $+2.2\% \pm 4.0\%$, respectively.

3.4. Granger Causality

[23] The Granger causality analysis showed minimal evidence of G-causal relationships between NDVI and RWI at a one year lag (Table 5). At $p < 0.05$, NDVI improved the RWI forecast at four of 22 sites (two spruce, one pine and one larch), thus suggesting that NDVI does not G-cause RWI in most circumstances. Similarly, RWI improved the NDVI forecast at three larch sites, implying that RWI does not normally G-cause NDVI. One larch site exhibited G-causality in both directions, implying a feedback relationship between NDVI and RWI. Overall, the Granger causality analysis showed little difference between the predictive abilities of the restricted ($Y_t = \beta_1 Y_{t-1} + \varepsilon_t$) and the unrestricted ($Y_t = \beta_1 X_{t-1} + \beta_2 Y_{t-1} + \varepsilon_t$) models, suggesting that knowledge of one vari-

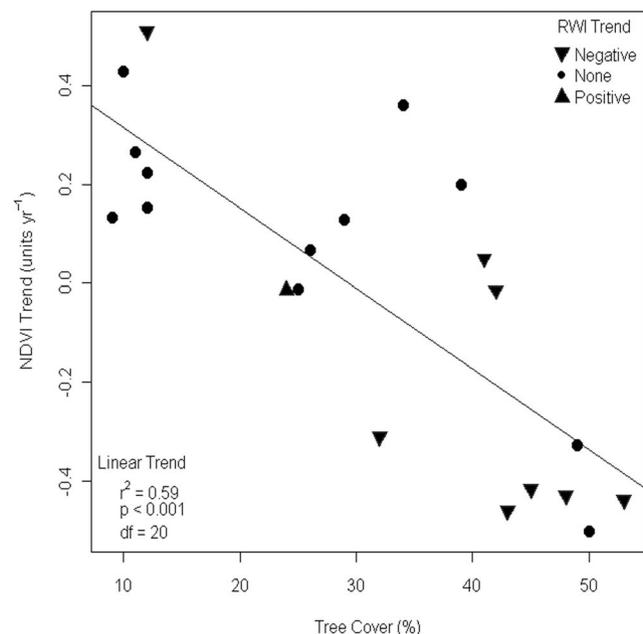


Figure 4. Normalized difference vegetation index linear trends (1982–2008) plotted as a function of tree cover for each of the 22 sampling sites. Each point represents a site, with plotting characters representing the ring width index trends over the same period. Note that a significant negative relationship existed between tree cover extent and NDVI slope ($r^2 = 0.59$, $p < 0.001$, $df = 20$), with heavily forested areas tending to exhibit negative trends in both NDVI and RWI, while sparsely forested areas showed positive trends in NDVI and minimal trends in RWI. Tree cover data from Hansen et al. [2003] and available through the Global Land Cover Facility.

Table 5. Granger Causality Tests Assessing G-Causality Between Ring Width Index and Normalized Difference Vegetation Index^a

Genus	Site	RWI G-Causes NDVI		NDVI G-Causes RWI		df ₁	df ₂
		F ^b	p Value	F	p Value		
Larix	CHE	4.920	0.04	0.870	0.36	22	23
	DVN	0.898	0.35	0.332	0.57	22	23
	GRS	2.078	0.16	0.776	0.39	22	23
	PAR	5.650	0.03	4.136	0.05	22	23
	ROD	2.521	0.13	0.278	0.60	22	23
	SYL	0.184	0.67	1.526	0.23	22	23
	TRL	5.722	0.03	0.063	0.80	22	23
	YUT	0.811	0.38	0.262	0.61	22	23
	ZHG	0.941	0.34	3.246	0.09	22	23
Picea	BIS	2.101	0.16	6.931	0.01	23	24
	FAH	0.250	0.62	3.254	0.08	23	24
	NML	0.601	0.45	0.006	0.94	23	24
	SQT	0.546	0.47	5.859	0.02	23	24
Pinus	ZHF	0.896	0.35	0.656	0.43	22	23
	BAL	0.013	0.91	1.528	0.23	22	23
	MAR	0.005	0.94	0.148	0.70	23	24
Mixed	MKZ	0.067	0.80	8.770	0.01	23	24
	DAR	2.001	0.17	1.085	0.31	23	24
	ELF	0.468	0.50	3.673	0.07	23	24
	FAL	3.597	0.07	2.614	0.12	23	24
	IND	0.671	0.42	1.714	0.20	22	23
	TAL	0.027	0.87	1.344	0.26	23	24

^aHere n = 22 sites; 1982–2007/2008; RWI, ring width index; NDVI, normalized difference vegetation index.

^bThe F value is the Wald test statistic and compares the restricted and the unrestricted models.

able does not generally improve the ability to forecast the other variable.

4. Discussion

4.1. Ring Width and NDVI Correlations

[24] Recent efforts to link NDVI with ground-based measurements of vegetation productivity have met with mixed success. In Scandinavia, mean monthly MODIS NDVI and flux tower GPP showed moderate correlations ($r = 0.7$ – 0.79) at seven forested sites; however, NDVI saturation during periods of high productivity ($NDVI > 0.9$) was a noticeable issue [Olofsson *et al.*, 2007]. At three flux tower sites located in Southeast Asian tropical forests, Huete *et al.* [2008] found that the relationship between NDVI and gross ecosystem production varied considerably with forest type ($r^2 = 0.00$ – 0.53). Satellite vegetation indices, both NDVI and the enhanced vegetation index (EVI), show stronger associations with tower measurements in forests with seasonal, rather than evergreen, canopy cover [Olofsson *et al.*, 2007; Huete *et al.*, 2008]. NDVI and EVI are related to productivity via light absorption, though differences in canopy phenology will affect the degree to which light absorption is biochemically decoupled from utilization for carbon assimilation [Goetz and Prince, 1996]. Additionally, decoupling of light absorption and utilization occurs as a result of differences in response time to short-term weather events, with GPP fluctuating rapidly and NDVI responding much more slowly [La Puma *et al.*, 2007]. Ephemeral cloud cover not adequately removed during image processing can also depress the relationship between satellite and ground-based vegetation measurements [Nagai

et al., 2010]. Recently, considerable strides have been made in validating satellite productivity measurements using flux tower data; however, validation requires a multifaceted approach to overcome the limitations of each technique [Running *et al.*, 2004].

[25] Past research has demonstrated that for areas above 40°N, ring width and mean monthly NDVI are positively related from May through July [Kaufmann *et al.*, 2008]; however, the strongest correlations occur during June and July when NDVI is at its highest [Kaufmann *et al.*, 2004]. Our use of a pixel-based, growing season NDVI capitalized on these previous findings and yielded stronger correlations between NDVI and RWI than did an analysis using NDVI during June or July, or when NDVI was summed over the June through August period (data not shown). This suggests that our definition of the NDVI growing season helped alleviate the issue of latitudinal and topographical differences among sites in the timing of maximum summer canopy development, which can be quite high in boreal regions [Beck *et al.*, 2007]. However, as the growing season length was derived from post-2000 MODIS data and held invariant between years, relationships with NDVI driven by annual changes in growing season length will not be captured.

[26] While NDVI and ring width are positively related during the growing season, the Granger causality analysis provided little evidence of G-causal relationships between the two variables at a one year lag. The lack of G-causality implies that neither metric of tree productivity can be used to forecast the other. This finding is consistent with that of Kaufmann *et al.* [2004], who used Granger causality tests to investigate the relationship between NDVI and tree rings for 48 sites located at middle to high latitudes in North America and Eurasia. The researchers found no G-causal relationship between NDVI (June and July) and ring width over the 1981 to 1999 period, concluding that the two variables instead share a common causal source, potentially NPP. The lack of G-causality suggests that there is a mediating factor between the various elements of the organism that fix and store C.

[27] The magnitude of the RWI-NDVI correlations we present are similar to those reported by Lopatin *et al.* [2006], who examined the growth of *Picea abies* subsp. *obovata* and *Pinus sylvestris* at five mixed-species sites in northwestern Russia. Both studies, however, report much lower correlations than those reported by Wang *et al.* [2004], who found very strong relationships between NDVI and ring width, seed production, litter fall and foliar biomass in three oak forests (*Quercus* spp.) in Kansas, U.S.A. Differences in land cover, landscape topography, and canopy architecture may partially account for this discrepancy. Conifers, larch in particular, tend to have lower crown width:height ratios than broadleaf deciduous trees [Gower and Richards, 1990], thus reducing their radiometric influence on satellite imagery acquired from an overhead perspective. Additionally, Wang *et al.* [2004] used the 1.1 km AVHRR Local Area Coverage data whereas both our work and that of Lopatin *et al.* [2006] used 8 km GIMMS data which were derived from the ~4 km Global Area Coverage data. One *P. banksiana* chronology from a mixed-species site displayed a negative correlation with NDVI, which may have been due to interspecific competition within the stands, or an exogenous factor (e.g., insects). These studies suggest that time-integrated NDVI

can reflect interannual variability in forest productivity, although they highlight that there are technical and physiological limitations to such an approach.

[28] Many of the technical limitations of relating tree growth and satellite-derived productivity estimates are related to differences in the scale at which each technique senses growth. Tree growth can vary significantly among individuals within a small area as a result of microhabitat variability and species-specific differences. Tree ring data are highly sensitive to this among-tree variability and it is possible that the extent of sampling at each site did not adequately capture the range in tree growth variability that occurred within the NDVI window. Imagery with coarse spatial resolution will thus represent a blend of potentially contrasting tree growth patterns. In mixed-species stands, this might obscure relations that would otherwise be apparent in single species stands [Lopatin *et al.*, 2006].

[29] Coarsely resolved satellite imagery necessarily blends different plant functional types into a single productivity value, potentially obscuring the effects of any one functional type (e.g., trees). This is likely to be particularly important in sparsely forested areas, where the radiometric influence of understory plants is more pronounced [Goetz and Prince, 1996; Rees *et al.*, 2002]. Interestingly, we found no relationship between the extent of forest cover represented by the tree ring measurements (or forest cover in general) and the strength of the NDVI and ring width correlation. This finding might reflect difficulties in satellite mapping of tree cover near the tundra-taiga transition, where shrubs and trees can be difficult to distinguish [Montesano *et al.*, 2009]. Alternatively, D'Arrigo *et al.* [2000] suggested that the relationship between NDVI and tree rings might hold when the sampled species covers only a small proportion of the landscape if tree growth and regional productivity are limited by the same environmental influences. The heterogeneous landscape, a complex mosaic of lakes, bogs, forest fire remnants, shrubs and mixed-species forests of varying tree density and age structure, hinders the ability of NDVI at a coarse spatial resolution to precisely reflect growth patterns of individual trees or even the spatially averaged growth of individuals within a stand. The influence of land cover on efforts to link satellite and ground-based measurements of productivity warrants further attention.

[30] In addition to technical complications, there are a number of physiological factors that contribute to the uncertainty in relating C accumulation, as measured by tree ring widths, to satellite-derived estimates of productivity, which generally measure C uptake (GPP). Trees experience interannual variability in C allocation among organs and in production of secondary plant compounds. The proportion of GPP allocated to above ground wood production varies depending on climatic conditions, nutrient availability, and stand age [Gower *et al.*, 1994; Litton *et al.*, 2007], and the relative allocation to foliage and wood has been shown to vary over time as a function of climatic variability [Lapenis *et al.*, 2005]. Trees throughout the northern high latitudes also experience trade-offs between reproduction and biomass accumulation, with years of high seed production generally characterized by reduced ring widths [Koenig and Knops, 1998; Selas *et al.*, 2002]. Interannual variability in C allocation thus complicates the use of tree rings in assessing past C uptake.

[31] While C allocation pathways change over time, in boreal forest ecosystems annual wood growth is closely related to NPP [Gower *et al.*, 2001] and there is considerable evidence that across forest ecosystems annual wood growth strongly reflects GPP [Litton *et al.*, 2007]. Nonetheless, the relationship between ring width and ecosystem C exchange is both complex and poorly understood. Rocha *et al.* [2006] found that, over a ten year period in Manitoba, Canada, the ring widths of *P. mariana* were uncorrelated with estimates of ecosystem C uptake (gross ecosystem productivity or net ecosystem exchange) derived from flux towers. However, Rocha *et al.* [2006] found that ring widths were positively correlated with net ecosystem productivity (NEP; $r = 0.854$) and negatively correlated with two estimates of respiration ($r = -0.733$ and -0.779). The researchers proposed two possible explanations for the lack of correlation between C uptake and ring width. First, they propose that ring width may be controlled by a factor other than C uptake. Second, they suggest that tree ring growth may rely heavily upon carbohydrates stored during previous years, and that these may effectively buffer ring width against interannual variability in C uptake. The very strong relationship between annual wood production and GPP shown by Litton *et al.* [2007] argues against ring width being controlled by a factor other than carbon uptake. Our results, including the low to moderate NDVI-RWI correlations, as well as the similarity in autocorrelation patterns between NDVI and ring width, support the idea that ring width is controlled by a variety of factors, potentially spanning many years, and not just by rates of photosynthesis or canopy development during a single season.

4.2. Ring Width and NDVI Autocorrelation

[32] Tree growth during a growing season is affected by sugars, buds, leaves, hormones and other plant compounds synthesized during previous years [Fritts, 2001]. This year to year carryover imparts a degree of persistence in tree growth patterns, with potential manifestation being statistical autocorrelation in ring width and canopy measurements [Fritts, 2001]. While autocorrelation in ring width measurements has been relatively well studied [Fritts, 2001; Monserud and Marshall, 2001; Kagawa *et al.*, 2006a, 2006b], autocorrelation in NDVI measurements from forested regions has not been widely examined. Over the 27 year study period, we observed distinct differences in both NDVI and ring width autocorrelation patterns among larch, on one hand, and spruce and pine on the other. Larch, a deciduous needleleaf conifer, displayed little autocorrelation in either measurement at a lag of one year, while spruce and pine, both evergreen conifers, exhibited significant autocorrelation at lags of one and two years. The differences among these species in both NDVI and ring width autocorrelation may relate to needle retention length. Monserud and Marshall [2001] observed differences in ring width autocorrelation associated with needle retention length and hypothesized that evergreens would exhibit higher autocorrelation than deciduous species, while evergreen species with longer needle retention would exhibit the highest autocorrelation.

[33] In spruce and pine, phenotypic plasticity permits intraspecific needle longevity to vary widely across latitudinal and elevational gradients, though retention lengths are generally three to ten years [Reich *et al.*, 1996]. Larch, on

the other hand, tend to replace foliage yearly [Gower *et al.*, 1993]. Studies using stable C isotopes show that both functional groups store photoassimilates and use them in following years for xylem and needle production [Jäggi *et al.*, 2002; Monserud and Marshall, 2001; Kagawa *et al.*, 2006a, 2006b]. Annual replacements of larch foliage draws upon C stored during previous years and reduces the amount that can be allocated to structural growth [Kagawa *et al.*, 2006a]. Evergreen conifers, on the other hand, have a lower foliage replacement demand and can use stored C to buffer xylem production to a greater extent during difficult growing conditions. In spruce and pine, lower interannual variability in xylem production may lead to higher ring width autocorrelation in comparison to larch, which exhibit higher interannual variability in ring growth and correspondingly lower autocorrelation strength.

[34] We propose that interannual persistence in canopy extent, leaf structure and chemical quality leads to autocorrelation in NDVI measured over spruce and pine stands, while for larch, annual foliage replacements leads to higher interannual variability canopy and leaf characteristics, thus limiting the NDVI autocorrelation strength. Across sites, we observed a significant, positive association between the strength of NDVI and ring width autocorrelation at a one year lag and believe that this reflects the important role of needle retention in buffering year to year xylem growth. Due to relatively high shrub cover at many of the larch sites, a large unknown is the degree to which the NDVI measurements from those stands reflected the growth dynamics of nonlarch plants. This is an area that should be investigated further.

4.3. Ring Width and NDVI Trends

[35] Although the annual correlations between NDVI and RWI were relatively weak, we believe this largely reflects strong autocorrelation, land cover heterogeneity, interannual variability in carbon allocation, and that NDVI and RWI measure different aspects of carbon exchange (uptake and accumulation). We view comparison of time series trends as a means of examining the relationship over a decadal period and not just on an annual basis. Negative trends in both RWI and NDVI were primarily concentrated in Canada at sites with tree cover >30%, while positive trends in NDVI occurred almost exclusively in sparse larch forests of northeast Siberia. The spatiality of NDVI trends is similar to those reported by Bunn and Goetz [2006], who found that across the northern high latitudes browning was most prevalent in areas of dense tree cover, while greening was common in sparsely forested areas near the tundra. There was a high consistency between NDVI and RWI trends for sites with either no trend or a negative trend in NDVI: 5 of 8 (62.5%) of sites with no trend in NDVI also showed no trend in RWI, while 5 of 7 (71%) of sites with a negative trend in NDVI also exhibited a negative trend in ring width. The biggest discrepancy between NDVI and RWI data occurred in those sites with a positive trend in NDVI ($n = 7$). None of those sites exhibited a positive trend in RWI: 6 of 7 had no significant trend in RWI, while one experienced a positive trend. The positively trending NDVI sites were predominantly in areas with sparse tree cover, where we would expect correlations with RWI to be weakest. Greening observed in these stands may not reflect enhanced tree growth so much as it reflects

enhanced understory shrub growth, as has been observed throughout the pan-Arctic [Bunn and Goetz, 2006; Tape *et al.*, 2006; Verbyla, 2008; Forbes *et al.*, 2010].

[36] Most sites ($n = 13$, 59%) showed no trend in ring width over the study period. Nontrending tree ring chronologies were most abundant in larch ($n = 7$) and mixed-species stands ($n = 4$). Spruce exhibited the highest frequency of negative trends in both NDVI and ring width, though negative trends in both measurements were also common in pine. In a circumpolar analysis of tree ring data, inverse relationships between ring width and temperature were most prevalent in these two taxa [Lloyd and Bunn, 2007]. Negative trends in NDVI at some sites may reflect inverse relationships between temperature and tree growth. Ring width at one spruce (*P. abies*) stand exhibited a positive trend since 1981 and was located along the Lena River in central Russia ($\sim 68^\circ\text{N}$). Growth at this site was positively correlated with growing season temperature and negatively correlated with precipitation over the 1902 and 2002 period [Lloyd *et al.*, 2010]. Examining within population responses of tree ring growth to climatic conditions at seven sites along the Lena River (includes sites presented in this study), Lloyd *et al.* [2010] found a relationship between NDVI trend and the response of trees to temperature: trees that were positively correlated with temperature were surrounded by pixels with more positive NDVI trends than others. This suggests that landscape-level NDVI trends may reflect within-population responses of trees to climate forcing.

4.4. NDVI Threshold of Detectability and Saturation

[37] The GIMMS NDVI data set has undergone extensive processing to remove exogenous sources of error and, when evaluated over time, shows consistent nontrending values in desert regions, which implies that the remaining influences of atmospheric conditions, bidirectional reflectance, calibration, and orbital drift are very small [Zhou *et al.*, 2001; Tucker *et al.*, 2005]. Given that atmospheric conditions and sun-surface-sensor geometry in low to midlatitude deserts might not be representative of conditions in northern high-latitude forests, Zhou *et al.* [2001] assessed the relationship between land surface temperatures and GIMMS NDVI and found a strong relationship, suggesting that interannual variation in GIMMS NDVI is measuring vegetation responses to temperature. Calibration error in the 1 km AVHRR NDVI data has been reported as 0.02–0.04 NDVI units [Vermote and Kaufman, 1995]. Chilar *et al.* [1998] found that beyond calibration error, interannual variability exceeding 0.02–0.04 NDVI units could be detected in these data. However, the detection threshold in the GIMMS NDVI data set is considerably lower than the 0.04–0.08 thresholds suggested by the two prior studies [Tucker *et al.*, 2005], owing to the superior calibration and solar zenith angle corrections in the GIMMS data processing. The site-level changes in GIMMS NDVI reported here, (about 0.08 NDVI units at greening sites and -0.12 NDVI units at browning sites) exceed the aforementioned detection thresholds and are therefore not attributable to measurement error in the data.

[38] When used as a proxy for leaf area, NDVI saturates once the leaf area index (LAI) exceeds ~ 4 ; however, saturation is generally less outspoken when NDVI is used as a proxy for maximum photosynthetic rate [Sellers, 1985, 1987], although still hinders the use of NDVI to model productivity

in areas of high biomass [e.g., see *Olofsson et al.*, 2007]. Given the variability in tree cover across the coarse spatial resolution of GIMMS-NDVI data, in situ leaf area measurements were not taken at our study sites. In Saskatchewan and Manitoba, however, roughly 5°S of our study sites in the Northwest Territories, *Chen et al.* [1997] reported the LAI ranging from one to four (mean ~2) in *P. banksiana* stands and from one to six (mean ~3) in *P. mariana* stands. It should be noted, that in the present study, vegetation cover at the Russian sites (66°–69°N) tended to be sparser than at the Canadian sites. In theory, a reduced sensitivity of NDVI to productivity changes with increasing LAI could thus reduce our ability to detect temporal trends in NDVI in the most densely forested (highest LAI) areas of our study domain, as it would reduce the signal-to-noise ratio. However, our results, as well as earlier findings by *Bunn and Goetz* [2006], show that, contrary to this expectation, negative trends in NDVI are most prominent in areas of high tree cover implying that NDVI saturation effects have minimal bearing on our analysis.

4.5. Summary

[39] Our findings demonstrate a loose coupling between space-based measurements of canopy greenness and xylem production for three common tree taxa in northern Canada and Russia. The correlation magnitude is not entirely surprising given the complexity of trying to monitor tree ring growth from space, particularly since NDVI and ring width represent different metrics of carbon exchange. While neither is a perfect proxy, we know that NDVI is related to carbon uptake (GPP) via light harvesting, while ring width is more closely related to carbon assimilation (NPP). Starting from this point of divergence, there are many places where the relationship can further break down (sensor to canopy, canopy to needle, needle to plant, and plant to cambium). Landscape heterogeneity, decoupling of light absorption and utilization for carbon fixation, interannual variability in carbon allocation, and technical limitations (e.g., spatial and temporal resolution) all complicate relating NDVI and ring width on an annual basis. In spite of these limitations, we still observe a weak, though consistently positive and frequently statistically significant, association between the two measurements of carbon exchange.

[40] Across the 22 sampling sites, greening, browning and nontrending sites occurred with roughly equal frequency, though browning was concentrated in spruce and pine stands, while greening was most prevalent in sparse larch stands near tree line. Though the majority of sites that browned also experienced negative trends in ring width, greening was not accompanied by positive trends in ring width and may have largely resulted from increased shrub growth. Satellite-observed browning at some sites thus appears to relate to reduced forest C uptake and sequestration.

[41] We observed distinct autocorrelation patterns between evergreen (spruce and pine) and deciduous (larch) conifers in both NDVI and ring width measurements. This suggests that needle retention length influences interannual C storage and utilization for canopy and structural growth. This work illustrates that multiyear, lagged effects need to be considered when modeling forest productivity. Global carbon models are partially driven by spectral vegetation indices using space-based records that cover wide geographic

areas but are only a few decades long. Tree ring records are spatially limited but span centennial to millennial timescales and show high decadal to centennial variability. It may be possible to incorporate some of the long-term (low frequency) variability into carbon models to develop scenarios for future changes to carbon fluxes that more realistically follow long-term tree growth dynamics.

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References

- Allen, C. D., et al. (2010), A global overview of drought and heat-induced mortality reveals emerging climate change risks for forests, *For. Ecol. Manage.*, 259, 660–684, doi:10.1016/j.foreco.2009.09.001.
- Angert, A., S. Biraud, C. Bonfils, C. C. Henning, W. Buermann, J. Pinzon, C. J. Tucker, and I. Fung (2005), Drier summers cancel out the CO₂ uptake enhancement induced by warmer springs, *Proc. Natl. Acad. Sci. U. S. A.*, 102, 10823–10827, doi:10.1073/pnas.0501647102.
- Arctic Climate Impact Assessment (2004), *Impacts of a Warming Arctic—Arctic Climate Impact Assessment*, 146 pp., Cambridge Univ. Press, Cambridge, U. K.
- Barber, V., G. P. Juday, and B. Finney (2000), Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress, *Nature*, 405, 668–673, doi:10.1038/35015049.
- Bascietto, M., P. Cherubini, and G. Scarascia-Mugnozza (2004), Tree rings from a European beech forest chronosequence are useful for detecting growth trends and carbon sequestration, *Can. J. For. Res.*, 34, 481–492, doi:10.1139/x03-214.
- Beck, P. S. A., P. Jönsson, K. A. Høgda, S. R. Karlén, L. Eklundh, and A. K. Skidmore (2007), A ground-validated NDVI dataset for monitoring vegetation dynamics and mapping phenology in Fennoscandia and the Kola peninsula, *Int. J. Remote Sens.*, 28, 4311–4330, doi:10.1080/01431160701241936.
- Bunn, A. G. (2008), A dendrochronology program library in R (dplR), *Dendrochronologia*, 26, 115–124, doi:10.1016/j.dendro.2008.01.002.
- Bunn, A. G. (2010), Statistical and visual crossdating in R using the dplR library, *Dendrochronologia*, 28, 251–258, doi:10.1016/j.dendro.2009.12.001.
- Bunn, A. G., and S. J. Goetz (2006), Trends in circumpolar satellite observed gross photosynthesis from 1982–2003: The role of cover type and vegetation density, *Earth Interact.*, 10, 1–19, doi:10.1175/EI190.1.
- Bunn, A. G., S. J. Goetz, J. S. Kimball, and K. Zhang (2007), Northern high-latitude ecosystem response to climate change, *Eos Trans. AGU*, 88, 333–340, doi:10.1029/2007EO340001.
- Chapin, F. S., III, et al. (2000), Arctic and boreal ecosystems of western North America as components of the climate system, *Global Change Biol.*, 6, 211–223, doi:10.1046/j.1365-2486.2000.06022.x.
- Chapin, F. S., III, et al. (2005), Role of land-surface changes in arctic summer warming, *Science*, 310, 657–660, doi:10.1126/science.1117368.
- Chen, J. M., P. M. Rich, S. T. Gower, J. M. Norman, and S. Plummer (1997), Leaf area index of boreal forests: Theory, techniques, and measurements, *J. Geophys. Res.*, 102, 29,429–29,443, doi:10.1029/97JD01107.
- Chilar, J., J. M. Chen, Z. Li, F. Huang, R. Latifovic, and R. Dixon (1998), Can interannual land surface signal be discerned in composite AVHRR data?, *J. Geophys. Res.*, 103, 23,163–23,172, doi:10.1029/98JD00050.
- D'Arrigo, R. D., C. M. Malmstrom, G. C. Jacoby, S. O. Los, and D. E. Bunker (2000), Correlation between maximum latewood density of annual tree rings and NDVI based estimates of forest productivity, *Int. J. Remote Sens.*, 21, 2329–2336, doi:10.1080/01431160050029611.
- D'Arrigo, R. D., R. K. Kaufmann, N. Davi, G. C. Jacoby, C. Laskowski, R. B. Myneni, and P. Cherubini (2004), Thresholds for warming-induced growth decline at elevational tree line in the Yukon Territory, Canada, *Global Biogeochem. Cycles*, 18, GB3021, doi:10.1029/2004GB002249.
- D'Arrigo, R., R. Wilson, B. Liepert, and P. Cherubini (2008), On the 'divergence problem' in northern forests: A review of the tree-ring evi-

- dence and possible causes, *Global Planet. Change*, *60*, 289–305, doi:10.1016/j.gloplacha.2007.03.004.
- Dawdy, D. R., and N. C. Matalas (1964), Statistical and probability analysis of hydrological data, part III: Analysis of variance, covariance and time series, in *Handbook of Applied Hydrology, a Compendium of Water-Resources Technology*, edited by V. T. Chow, pp. 8.68–8.90, McGraw-Hill, New York.
- Devi, N., F. Hagedorn, P. Moiseev, H. Bugmann, S. Shiyatov, V. Mazepa, and A. Rigling (2008), Expanding forests and changing growth forms of Siberian larch at the Polar Urals treeline during the 20th century, *Global Change Biol.*, *14*, 1581–1591, doi:10.1111/j.1365-2486.2008.01583.x.
- Forbes, B. C., M. M. Fauria, and P. Zetterberg (2010), Russian Arctic warming and ‘greening’ are closely tracked by tundra shrub willows, *Global Change Biol.*, *16*, 1542–1554, doi:10.1111/j.1365-2486.2009.02047.x.
- Fritts, H. C. (2001), *Tree Rings and Climate*, Blackburn, Caldwell, N. J.
- Goetz, S. J., and S. D. Prince (1996), Remote sensing of net primary production in boreal forest stands, *J. Agric. For. Meteorol.*, *78*, 149–179, doi:10.1016/0168-1923(95)02268-6.
- Goetz, S. J., and S. D. Prince (1999), Modeling terrestrial carbon exchange and storage: Evidence and implications of functional convergence in light use efficiency, *Adv. Ecol. Res.*, *28*, 57–92, doi:10.1016/S0065-2504(08)60029-X.
- Goetz, S. J., A. Bunn, G. Fiske, and R. A. Houghton (2005), Satellite observed photosynthetic trends across boreal North America associated with climate and fire disturbance, *Proc. Natl. Acad. Sci. U. S. A.*, *102*, 13,521–13,525, doi:10.1073/pnas.0506179102.
- Gower, S. T., and J. H. Richards (1990), Larches: Deciduous conifers in an evergreen world, *BioScience*, *40*, 818–826, doi:10.2307/1311484.
- Gower, S. T., P. B. Reich, and Y. Son (1993), Canopy dynamics and aboveground production of 5 tree species with different leaf longevities, *Tree Physiol.*, *12*, 327–345.
- Gower, S. T., H. L. Gholz, K. Nakane, and V. C. Baldwin (1994), Production and carbon allocation patterns of pine forests, *Ecol. Bull.*, *43*, 115–135.
- Gower, S. T., O. Krankina, R. J. Olson, M. Apps, S. Linder, and C. Wang (2001), Net primary production and carbon allocation patterns of boreal forest ecosystems, *Ecol. Appl.*, *11*, 1395–1411, doi:10.1890/1051-0761(2001)011[1395:NPPACA]2.0.CO;2.
- Granger, C. J. (1969), Investigating causal relationship by econometric models and cross-spectral methods, *Econometrica*, *37*, 424–438, doi:10.2307/1912791.
- Graumlich, L. J., L. B. Brubaker, and C. C. Grier (1989), Long-term trends in forest net primary productivity: Cascade Mountains, Washington, *Ecology*, *70*, 405–410, doi:10.2307/1937545.
- Hansen, M., R. S. DeFries, J. R. G. Townshend, M. Carroll, C. Dimiceli, and R. A. Sohlberg (2003), Global percent tree cover at a spatial resolution of 500 meters: First results of the MODIS vegetation continuous fields algorithm, *Earth Interact.*, *7*, 1–15, doi:10.1175/1087-3562(2003)007<0001:GPTCAA>2.0.CO;2.
- Hudson, J. M. G., and G. H. R. Henry (2009), Increased plant biomass in a high arctic heath community from 1981 to 2008, *Ecology*, *90*, 2657–2663, doi:10.1890/09-0102.1.
- Huete, A. R., N. Restrepo-Coupe, P. Ratana, K. Didan, S. R. Saleska, K. Ichii, S. Panuthai, and M. Gamo (2008), Multiple site tower flux and remote sensing comparisons of tropical forest dynamics in Monsoon Asia, *Agric. For. Meteorol.*, *148*, 748–760, doi:10.1016/j.agrformet.2008.01.012.
- Intergovernmental Panel on Climate Change (2007), *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., Cambridge Univ. Press, Cambridge, U. K.
- Jäggi, M., M. Saurer, J. Fuhrer, and R. Siegwolf (2002), The relationship between stable carbon isotope composition of needle bulk material, starch, and tree rings in *Picea abies*, *Oecologia*, *131*, 325–332, doi:10.1007/s00442-002-0881-0.
- Kagawa, A., A. Sugimoto, and T. C. Maximov (2006a), Seasonal course and translocation, storage and remobilization of ¹³C pulse-labeled photoassimilate in naturally growing *Larix gmelinii* saplings, *New Phytol.*, *171*, 793–804, doi:10.1111/j.1469-8137.2006.01780.x.
- Kagawa, A., A. Sugimoto, and T. C. Maximov (2006b), ¹³CO₂ pulse-labelling of photoassimilates reveals carbon allocation within and between tree rings, *Plant Cell Environ.*, *29*, 1571–1584, doi:10.1111/j.1365-3040.2006.01533.x.
- Kaufman, D. S., et al. (2009), Recent warming reverses long-term Arctic cooling, *Science*, *325*, 1236–1239, doi:10.1126/science.1173983.
- Kaufmann, R. K., R. D. D’Arrigo, C. Laskowski, R. B. Myneni, L. Zhou, and N. K. Davi (2004), The effect of growing season and summer greenness on northern forests, *Geophys. Res. Lett.*, *31*, L09205, doi:10.1029/2004GL019608.
- Kaufmann, R. K., R. D. D’Arrigo, L. F. Paletta, H. Q. Tian, W. M. Jolly, and R. B. Myneni (2008), Identifying climatic controls on ring width: The timing of correlations between tree rings and NDVI, *Earth Interact.*, *12*, doi:10.1175/2008EI263.1.
- Kimball, J. S., M. Zhao, K. C. McDonald, and S. W. Running (2006), Satellite remote sensing of terrestrial net primary production for the pan-Arctic basin and Alaska, *Mitig. Adapt. Strategies Glob. Change*, *11*, 783–804, doi:10.1007/s11027-005-9014-5.
- Koenig, W. D., and J. M. H. Knops (1998), Scale of mast-seeding and tree-ring growth, *Nature*, *396*, 225–226, doi:10.1038/24293.
- Lapenis, A., A. Shvidenko, D. Shepaschenko, S. Nilsson, and A. Aiyer (2005), Acclimation of Russian forests to recent changes in climate, *Global Change Biol.*, *11*, 2090–2102, doi:10.1111/j.1365-2486.2005.001069.x.
- La Puma, I. P., T. E. Philippi, and S. F. Oberbauer (2007), Relating NDVI to ecosystem CO₂ exchange patterns in response to season length and soil warming manipulations in arctic Alaska, *Remote Sens. Environ.*, *109*, 225–236, doi:10.1016/j.rse.2007.01.001.
- Litton, C. M., J. W. Raich, and M. G. Ryan (2007), Carbon allocation in forest ecosystems, *Global Change Biol.*, *13*, 2089–2109, doi:10.1111/j.1365-2486.2007.01420.x.
- Lloyd, A. H., and A. G. Bunn (2007), Responses of the circumpolar boreal forest to 20th century climate variability, *Environ. Res. Lett.*, *2*, 045013, doi:10.1088/1748-9326/2/4/045013.
- Lloyd, A. H., and C. L. Fastie (2002), Spatial and temporal variability in the growth and climate response of treeline trees in Alaska, *Clim. Change*, *52*, 481–509, doi:10.1023/A:1014278819094.
- Lloyd, A. H., A. G. Bunn, and L. Berner (2010), A latitudinal gradient in tree response to climate warming in the Siberian taiga, *Global Change Biol.*, doi:10.1111/j.1365-2486.2010.02360.x.
- Lopatin, E., T. Kolstrom, and H. Spiecker (2006), Determination of forest growth trends in Komi Republic (northwestern Russia): Combination of tree-ring analysis and remote sensing data, *Boreal Environ. Res.*, *11*, 341–353.
- Malmstrom, C. E., M. V. Thompson, G. P. Juday, S. O. Los, J. T. Randerson, and C. B. Field (1997), Interannual variation in global-scale net primary production: Testing model estimates, *Global Biogeochem. Cycles*, *11*, 367–392, doi:10.1029/97GB01419.
- McGuire, A. D., A. G. Anderson, T. R. Christensen, S. Dallimore, L. D. Guo, M. Heimann, T. D. Lorenson, R. W. Macdonald, and N. Roulet (2009), Sensitivity of the carbon cycle in the Arctic to climate change, *Ecol. Monogr.*, *79*, 523–555.
- Monserud, R. A., and J. D. Marshall (2001), Time-series analysis of $\delta^{13}\text{C}$ from tree rings. I. Time trends and autocorrelation, *Tree Physiol.*, *21*, 1087–1102.
- Montesano, P. M., R. Nelson, G. Sun, H. Margolis, A. Kerber, and K. J. Ranson (2009), MODIS tree cover validation for the circumpolar taiga-tundra transition zone, *Remote Sens. Environ.*, *113*, 2130–2141, doi:10.1016/j.rse.2009.05.021.
- Myneni, R. B., F. G. Hall, P. J. Sellers, and A. L. Marshak (1995), The interpretation of spectral vegetation indices, *IEEE Trans. Geosci. Remote Sens.*, *33*, 481–486, doi:10.1109/36.377948.
- Myneni, R. B., C. D. Keeling, C. J. Tucker, G. Asrar, and R. R. Nemani (1997), Increased plant growth in the northern high latitudes from 1981 to 1991, *Nature*, *386*, 698–702, doi:10.1038/386698a0.
- Nagai, S., N. Saigusa, H. Muraoka, and K. N. Nasahara (2010), What makes the satellite-based EVI-GPP relationship unclear in a deciduous broad-leaf forest, *Ecol. Res.*, *25*, 359–365, doi:10.1007/s11284-009-0663-9.
- Nemani, R. R., C. D. Keeling, H. Hashimoto, W. M. Jolly, S. C. Piper, C. J. Tucker, R. B. Myneni, and S. W. Running (2003), Climate-driven increases in global terrestrial net primary production from 1982 to 1999, *Science*, *300*, 1560–1563, doi:10.1126/science.1082750.
- Olofsson, P., F. Lagergren, A. Lindroth, J. Lindström, L. Klemetsson, and L. Eklundh (2007), Towards operational remote sensing of forest carbon balance across northern Europe, *Biogeosciences Discuss.*, *4*, 3143–3193, doi:10.5194/bgd-4-3143-2007.
- Ostercamp, T. E., L. Viereck, Y. Shur, M. T. Jorgenson, C. Racine, A. Doyle, and R. D. Boone (2000), Observations of thermokarst and its impacts on boreal forests in Alaska, U.S.A., *Arct. Antarct. Alp. Res.*, *32*, 303–315, doi:10.2307/1552529.
- Pilcher, J. R. (1990), Sample preparation, cross-dating, and measurement, in *Methods of Dendrochronology*, edited by E. R. Cook and L. A. Kairiukstis, pp. 40–50, Kluwer Acad., Boston, Mass.
- R Development Core Team (2009), *R: A language and environment for statistical computing*, R Found. for Stat. Comput., Vienna, Austria.

- Rees, G., I. Brown, K. Mikkola, T. Virtanen, and B. Werkman (2002), How can the dynamics of the tundra-taiga boundary be remotely monitored?, *Ambio*, *12*, 56–62.
- Reich, P. B., J. Oleksyn, J. Modrzyński, and M. G. Tjoelker (1996), Evidence that longer needle retention of spruce and pine populations at high elevations and high latitudes is largely a phenotypic response, *Tree Physiol.*, *16*, 643–647.
- Rocha, A. V., M. L. Goulden, A. L. Dunn, and S. C. Wofsy (2006), On linking interannual tree ring variability with observation of whole-forest CO₂ flux, *Global Change Biol.*, *12*, 1378–1389, doi:10.1111/j.1365-2486.2006.01179.x.
- Running, S., R. Nemani, F. Heinsch, M. Zhao, M. Reeves, and H. Hashimoto (2004), A continuous satellite-derived measure of global terrestrial primary production, *BioScience*, *54*, 547–560, doi:10.1641/0006-3568(2004)054[0547:ACSMOG]2.0.CO;2.
- Selas, V., G. Piovesan, J. M. Adams, and M. Bernabei (2002), Climate factors controlling reproduction and growth of Norway spruce in southern Norway, *Can. J. For. Res.*, *32*, 217–225, doi:10.1139/x01-192.
- Sellers, P. J. (1985), Canopy reflectance, photosynthesis, and transpiration, *Int. J. Remote Sens.*, *6*, 1335–1372, doi:10.1080/01431168508948283.
- Sellers, P. J. (1987), Canopy reflectance, photosynthesis, and transpiration. II. The role of biophysics in the linearity of their interdependence, *Remote Sens. Environ.*, *21*, 143–183, doi:10.1016/0034-4257(87)90051-4.
- Tape, K., M. Strum, and C. Racine (2006), The evidence for shrub expansion in northern Alaska and the Pan-Arctic, *Global Change Biol.*, *12*, 686–702, doi:10.1111/j.1365-2486.2006.01128.x.
- Tucker, C. J., and P. J. Sellers (1986), Satellite remote sensing of primary production, *Int. J. Remote Sens.*, *7*, 1395–1416, doi:10.1080/01431168608948944.
- Tucker, C. J., I. Y. Fung, C. D. Keeling, and R. H. Gammon (1986), Relationship between atmospheric CO₂ variations and a satellite-derived vegetation index, *Nature*, *319*, 195–199, doi:10.1038/319195a0.
- Tucker, C. J., J. E. Pinzon, M. E. Brown, D. A. Slayback, E. W. Pak, R. Mahoney, E. F. Vermote, and N. Saleous (2005), An extended AVHRR 8-km NDVI data set compatible with MODIS and SPOT vegetation NDVI data, *Int. J. Remote Sens.*, *26*, 4485–4498, doi:10.1080/01431160500168686.
- Verbyla, D. (2008), The greening and browning of Alaska based on 1982–2003 satellite data, *Glob. Ecol. Biogeogr.*, *17*, 547–555, doi:10.1111/j.1466-8238.2008.00396.x.
- Vermote, E. F., and Y. J. Kaufman (1995), Absolute calibration of AVHRR visible and near-infrared channels using ocean and cloud views, *Int. J. Remote Sens.*, *16*, 3519–3545, doi:10.1080/01431169508954561.
- Vygodskaya, N. N., P. Y. Groisman, N. M. Tchepakova, J. A. Kurbatova, O. P. Panfyorov, E. I. Parfenova, and A. F. Sogachev (2007), Ecosystems and climate interactions in the boreal zone of northern Eurasia, *Environ. Res. Lett.*, *2*, 045033, doi:10.1088/1748-9326/2/4/045033.
- Wang, J., P. M. Rich, K. P. Price, and W. D. Kettle (2004), Relations between NDVI and tree productivity in the central Great Plains, *Int. J. Remote Sens.*, *25*, 3127–3138, doi:10.1080/0143116032000160499.
- Wilmking, M., G. Juday, B. Barber, and H. Zald (2004), Recent climate warming forces contrasting growth responses of white spruce at treeline in Alaska through temperature thresholds, *Global Change Biol.*, *10*, 1724–1736, doi:10.1111/j.1365-2486.2004.00826.x.
- Zeileis, A., and T. Hothorn (2002), Diagnostic checking in regression relationships, *R News*, *2*, 7–10.
- Zhang, K., J. S. Kimball, K. C. McDonald, J. J. Cassano, and S. W. Running (2007), Impacts of large-scale oscillations on pan-Arctic terrestrial net primary production, *Geophys. Res. Lett.*, *34*, L21403, doi:10.1029/2007GL031605.
- Zhang, K., J. S. Kimball, E. H. Hogg, M. Zhao, W. C. Oechel, J. J. Cassano, and S. W. Running (2008), Satellite-based model detection of recent climate-driven changes in northern high-latitude vegetation production, *J. Geophys. Res.*, *113*, G03033, doi:10.1029/2007JG000621.
- Zhang, X., M. A. Friedl, C. B. Schaaf, A. H. Strahler, J. C. F. Hodges, F. Gao, B. C. Reed, and A. Huete (2003), Monitoring vegetation phenology using MODIS, *Remote Sens. Environ.*, *84*, 471–475, doi:10.1016/S0034-4257(02)00135-9.
- Zhou, L., C. J. Tucker, R. K. Kaufmann, D. Slayback, N. V. Shabanov, and R. B. Myneni (2001), Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999, *J. Geophys. Res.*, *106*, 20,069–20,083, doi:10.1029/2000JD000115.

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