Recent primary production increases in arctic lakes

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[1] A new application of reflectance spectroscopy enables inferences of lake sediment chlorophyll *a* concentrations and hence of historical trends in lacustrine primary production. In a survey of six arctic lakes on Baffin Island (Nunavut, Canada), pronounced increases of spectrally-inferred chlorophyll *a* concentrations are consistently expressed in sediments deposited during the 20th century. Climate warming appears to be increasing both aquatic chlorophyll *a* production and its sequestration to sediments, as these lakes enter new biological regimes that are largely unique in the context of the late Holocene. **Citation:** Michelutti, N., A. P. Wolfe, R. D. Vinebrooke, B. Rivard, and J. P. Briner (2005), Recent primary production increases in arctic lakes, *Geophys. Res. Lett.*, *32*, L19715, doi:10.1029/2005GL023693.

1. Introduction

[2] Recent trends in ocean primary production show increases attributable to a warming Earth, most notably in coastal [*Gregg et al.*, 2005] and cold-water [*Richardson and Schoeman*, 2004] regions. However, it remains to be determined whether similar trends are manifested in freshwater ecosystems. Remote arctic regions are ideal for examining climate-driven changes in aquatic production, because they are not directly influenced by eutrophying human activities. Recent paleoecological studies have revealed widespread changes in circumpolar algal and invertebrate communities that are consistent with recent climate warming [*Smol et al.*, 2005]. Although the suggestion has been made that these biological reorganizations include increased primary production owing to longer summer growing seasons, this interpretation has not yet been tested explicitly. Here, we assess trends of arctic lake primary production, over the last several millennia, using an application of reflectance spectroscopy that enables quantitative inferences of sediment chlorophyll *a* concentrations.

2. Field Area

[3] The six study lakes are located near the hamlet of Clyde River on east-central Baffin Island, Arctic Canada, Nunavut (~70°N, 70°W). The region has mean annual and mean July temperatures of −12.3°C and +4.5°C, respectively, and mean annual precipitation of ~230 mm. Underlying geology is primarily Precambrian granites and gneisses overlain with various Quaternary deposits. Detailed limnological variables and UTM coordinates for the study lakes are provided in Table 1. In general, water chemistry is acidic (pH = 5.3–6.1), chemically dilute (specific conductance = 90–180 μS cm^{-1}), and oligotrophic (total dissolved phosphorus = 3–40 μg L^{-1}).

3. Methods

3.1. Spectral Inferences of Sediment Chlorophyll *a*

[4] The chlorophyll *a* inference model is based on a compilation of forty-six sediment samples that have been analyzed for both spectral reflectance and pigment concentrations, as described in detail elsewhere [*Das et al.*, 2005; A. P. Wolfe et al., Experimental calibration of lake-sediment spectral reflectance to chlorophyll *a* concentrations: Methodology and paleolimnological validation, submitted to *Journal of Paleolimnology*, 2005]. Sediment reflectance spectra between 350 and 2500 nm were obtained on freeze-dried and sieved (<125 μm) samples with a FieldSpec® Pro spectroradiometer and are expressed as % reflectance relative to a spectralon reference panel. Each sample's spectrum is the average of 5–10 scans. Sedimentary chlorophyll *a* and related compounds including degradation products were quantified by reverse-phase high-performance liquid chromatography (HPLC). Resulting concentrations of primary chlorophyll *a*, chlorophyll *a* isomers, and associated pheopigments (pheophytin *a* + pheophorbide *a*) were regressed linearly against several spectral indices that capture the pronounced trough in reflectance near 675 nm (Figure 1a). Of these indices, the dimensionless trough area between 650 nm and 700 nm produces the strongest correlation ($r^2 = 0.86$, $p < 0.001$) with summed concentrations of sediment chlorophyll *a* and its major derivatives (Figure 1b). The strength of this correlation, coupled to the similarity of the trough in red reflectance with known regions of chlorophyll *a* absorption in vivo [e.g., *Schalles et al.*, 1998], provide compelling evidence supporting the use of visible reflectance as an estimate of chlorophyll preserved in lake sediment. From this linear relationship, we are able to reconstruct sedimentary chlorophyll concentrations with the equation:

$$[\text{Chlorophyll } a + \text{derivatives}] = 0.002 * \text{trough area}_{(650\text{-}700\text{ nm})} - 0.0122$$

[5] Diagenetic processes appear to exert little influence on our reconstructions because the primary products of chlorophyll *a* degradation, pheophytin *a* and pheophorbide *a*, have similar spectral signatures to that of chlorophyll *a* itself, as suggested by the robust correlation ($r^2 = 0.75$, $p <$

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Table 1. Water Chemistry Data and Locations of the Baffin Island Study Lakes[a]

	Lostpack L.	Moss L.	Farkel L.	Goose L.	Perfection L. 2
TDP (μg L^{-1})	2.50	2.80	2.50	3.10	39.60
TN (μg L^{-1})	636.18	329.54	331.83	269.04	380.37
DOC (mg L^{-1})	1.72	3.20	3.39	2.54	2.42
DIC (mg L^{-1})	0.51	0.75	0.30	0.55	0.56
Chlorophyll *a* (μg L^{-1})	0.34	0.46	0.26	1.10	0.28
pH	5.5	6.1	5.2	5.1	4.3
Spec. Cond. (μS cm^{-1})	160	90	180	160	160
UTM	19W 0501852, 7748821	19W 0495323, 7831822	19W 0500502, 7833160	19W 0527194, 7786176	19W 0496080, 7746580

[a]No data is available for Perfection Lake 3 (19W 0494462, 7745073). TDP = total dissolved phosphorus; TN = total nitrogen; DOC, DIC = dissolved organic/inorganic carbon; Spec. Cond. = specific conductance.

0.001) between pheopigment concentrations and reflectance trough area (Figure 1c). Thus, our spectral inference model reliably tracks concentrations of both primary and degraded chlorophyll *a* in lake sediments. It is because of the additive influences of these compounds on reflectance spectra in the region of interest that we reconstruct the summed 'family' of chlorophyll *a* and its derivatives, both for modern (Figure 1b) and fossil (Figure 2) samples. Similar techniques employing spectral data have been previously used to estimate chlorophyll *a* concentrations from other materials, but not from lake sediments [e.g., *Kim et al.*, 1994; *Carrère et al.*, 2004].

3.2. Sediment Cores

[6] Sediment cores preserving intact mud-water interfaces were recovered in May 2003 and 2004 by gravity coring, and extruded in the field in continuous 0.5 cm or 1.0 cm increments [*Glew et al.*, 2001]. Sediment samples were kept cool and dark prior to freeze-drying upon return to the laboratory. The chronology of one core (Lost Pack Lake) was determined using excess ^{210}Pb activities for near-surface sediments, and two accelerator mass spectrometry (AMS) ^{14}C dates (10.5 cm and 21.5 cm). Reflectance spectra were determined for core samples using identical protocols as in the calibration, and concentrations of total chlorophyll *a* (and major derivatives) were inferred by applying the regression of Figure 1b to computed trough areas between 650 and 700 nm. To facilitate comparisons among lakes, inferred concentrations of sediment chlorophyll are expressed as departures from the mean value for each lake. This approach also obviates problems associated with high mineral reflectance observed in certain core samples of low organic content, where the trough in red reflectance becomes muted or even obscured. We estimate the lower limit of detection of this method to be ~0.01 mg g^{-1}. In addition, total organic carbon (TOC), biogenic silica ($BSiO_2$), and C/N molar ratios were determined by standard protocols [*Meyers and Teranes*, 2001; *Conley and Schelske*, 2001] on the core from Lost Pack Lake, as independent indicators of lake paleo-production.

4. Results and Discussion

4.1. Long-Term Trends in Sediment Chlorophyll *a* Concentrations

[7] All six lakes reveal dramatic increases of inferred chlorophyll *a* concentrations within the upper-most 4 cm of sediment, following prolonged intervals of comparatively low values (Figure 2). The inferred quantities of chlorophyll *a* enrichment are variable from lake to lake, ranging from ~0.025 mg g^{-1} (Perfection Lake 3) to more than 0.075 mg g^{-1} (Farkel Lake). In each case these trends represent large positive excursions with respect to mean values for the recovered intervals of deposition

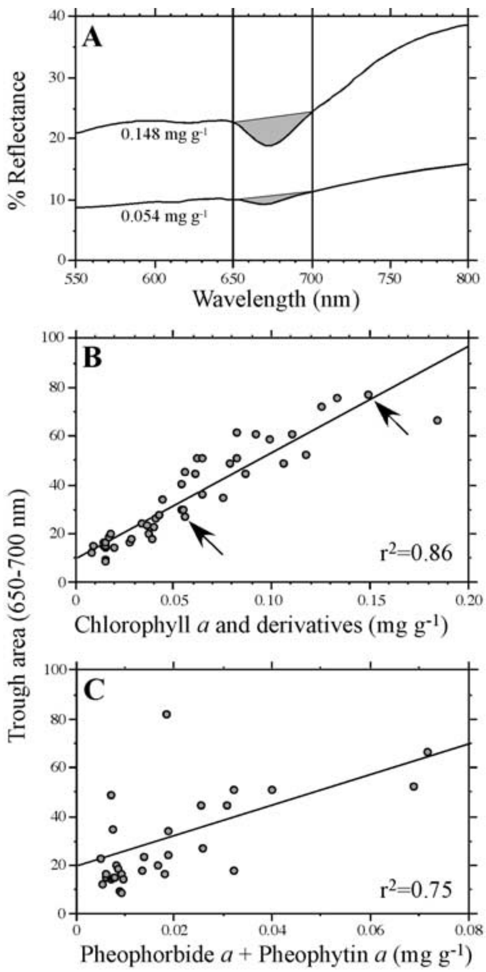

Figure 1. (a) Portions of typical sediment reflectance spectra (550–800 nm), and corresponding chlorophyll *a* concentrations, for two of the samples used in the calibration set. Shaded area is the trough in reflectance between 650 and 700 nm. Relationships are shown between this trough's area and corresponding concentrations of (b) summed chlorophyll *a* and derivatives, and (c) pheopigments (pheophytin *a* + pheophorbide *a*). Arrows in Figure 1b indicate the two samples used in Figure 1a.

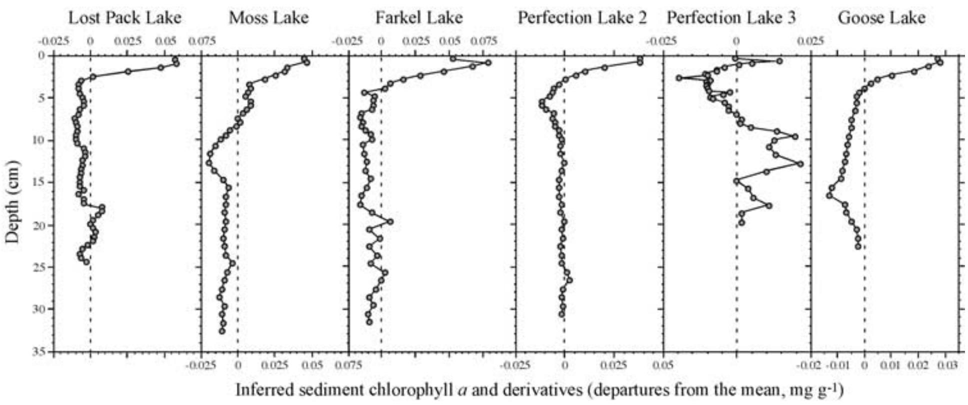

Figure 2. Inferred concentrations of sediment chlorophyll *a* and derivatives, plotted as departures from the mean value for each series, for the six study lakes.

(Figure 3). In only one core (Perfection Lake 3), is this recent increase not unprecedented.

[8] The available chronological data for Lost Pack Lake indicates that the excess ^{210}Pb inventory is confined to the upper 2.5 cm of the core, indicating an age of A.D. ~1850. AMS ^{14}C ages of 3415 ± 15 cal. BP (10.5 cm) and 4740 ± 20 cal. BP (21.5 cm) indicate that the 25 cm core represents over 5000 years of deposition. Similarly low rates of sediment accumulation are recorded regionally [*Wolfe et al.*, 2004], implying that each of the cores reported here represents several millennia of deposition. Moreover, the ^{210}Pb data from Lost Pack Lake suggest that the recent excursions of inferred chlorophyll *a* concentrations contained in the uppermost 2.5–4.0 cm are features of the 19th to 21st centuries. We surmise that recent increases of whole-lake production have arisen regionally in response to climate warming since the Little Ice Age, with subsequent acceleration throughout the Anthropocene [*Smol et al.*, 2005].

4.2. Additional Evidence of Enhanced Lake Production

[9] Several independent proxies of aquatic production from the Lost Pack Lake core support our spectral inferences (Figures 3b and 3c). TOC reflects the balance between organic matter production and decomposition, whereas $BSiO_2$ is a direct measure of diatom and chrysophyte production. Both of these parameters show dramatic increases coeval with the inferred sediment chlorophyll *a* profile. The parallel behaviour of TOC and $BSiO_2$ suggests that siliceous algae are important vectors for organic matter delivery to sediments. At the same time, sediment C/N molar ratios decline to their lowest values in the upper 2.5 cm of this core, indicating enhanced contributions of organic matter derived from aquatic sources. These proxies are entirely consistent with increased primary production in Lost Pack Lake since A.D. ~1850, thus corroborating spectral inferences of sediment chlorophyll *a*. In the 20th century, all four proxies attain values that are unique in the context of the last five millennia. We note that the onset of these changes corresponds well with the chronology of recent warming in the Arctic, which began A.D. ~1840 [*Overpeck et al.*, 1997] (Figure 3f). Although the initial warming of the Arctic that terminated the Little Ice Age was likely naturally-mediated, it is increasingly probable that human activities have contributed to the exceptional warmth of the 20th century. We therefore

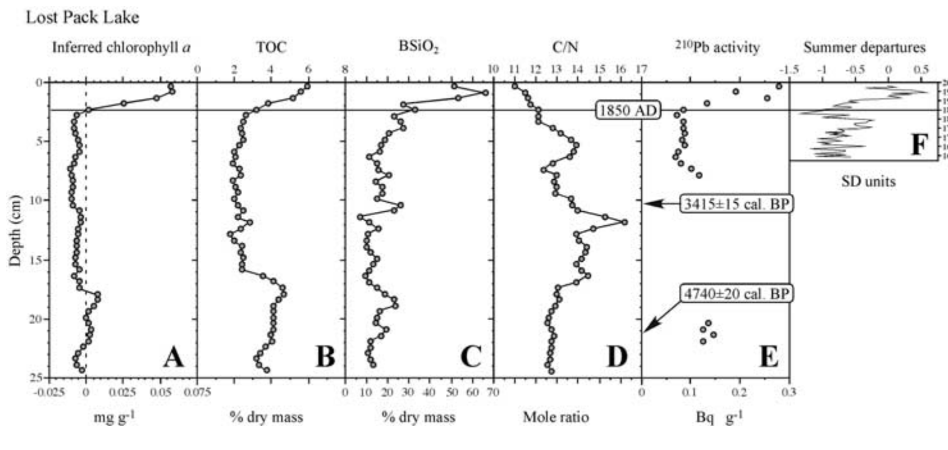

Figure 3. Comparison of (a) inferred sediment chlorophyll *a* concentrations to independent proxies of lake production in Lost Pack Lake, including (b) total organic carbon, (c) biogenic silica, and (d) C/N ratios. The demarcation of A.D. 1850 at 2.5 cm depth is based on a constant rate of supply model applied to the (e) ^{210}Pb activities. (f) Summer temperature trends, expressed as mean departures, from various proxy records obtained throughout the circumpolar arctic (data from *Overpeck et al.* [1997]).

view the remarkable production increases in arctic lakes documented here as, in part, the limnological legacy of anthropogenic warming in these remote areas.

5. Conclusions

[10] Spectral inferences of sediment chlorophyll *a* concentrations, verified by independent proxies, reveal recent whole-lake production increases in six lakes on Baffin Island. In five of these lakes, 20th century production levels appear unique in the context of the late Holocene. Where sediment chronology is available, these events appear synchronized with the record of recent climate change [*Overpeck et al.*, 1997], implying that warming is inducing directional shifts towards more productive ecological and biogeochemical states. The most likely mechanisms linking climate warming to arctic lake primary production involve lengthening of the growing season, increased algal habitat availability, and enhanced catchment nutrient fluxes [*Douglas and Smol*, 1999]. These observations constitute yet another dimension of the widespread regime shifts observed in circumpolar lake ecosystems [*Smol et al.*, 2005]. Reflectance-based sedimentary chlorophyll inferences provide a rapid, non-destructive, and relatively inexpensive approach to documenting these changes, thereby offering considerable potential for augmenting the density of sampling sites for paleoenvironmental reconstruction.

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