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Power laws governing hydrology and carbon dynamics in northern peatlands

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Abstract

Environmental and biological variables fluctuate over different time scales. On the basis of power spectral analysis of 14 time series at four sites from northern peatlands (fens and raised bogs), the temporal variability of physical environment (temperatures, water tables) and biological variables (CO_2 flux) shows power-law behaviour, with a scaling exponent ranging from about 0.5 to 1.5. The scaling exponents of air temperatures change from 1.5 at high frequency to 0.5 at low frequency, with a break point at diurnal period. Comparison with similar analysis of temperature data from climate stations suggests that the atmosphere above peatlands has more active heat exchange with waterlogged peatlands than with upland terrestrial ecosystems. Water tables from different peatlands show almost identical power spectra, with a scaling exponent of 1.0 over all time scales. CO_2 exchange has more complex spectral structure, with two break points at daily and monthly periods. This spectral structure suggests scale-dependent influence of climatic and hydrological fluctuations on CO_2 fluxes. CO_2 flux responds to air temperature with a distinct diurnal spectral peak. These results indicate that time scales are important in discussing hydrology and carbon dynamics in peatlands, and that scaling up of short-term experimental results may be inadvisable. Further statistical analysis on drained and harvested peatlands would provide insights into understanding shift in peatland dynamics due to human disturbance.

Keywords: northern peatlands; power laws; carbon cycle; climate change; system dynamics

1. Introduction

Environmental and ecological variables fluctuate over different time scales. To describe this variability and to understand the underlying mechanisms, we often need to separate "noise" from "signal". After removing predictable signal components from time series such as secular trends and periodicities, the residual variability "can be considered as inherently unpredictable in a strictly deterministic sense" (Steele, 1985). However, the structure of environmental fluctuation is well described by a phenomenon called "1/*f*-noise", and the understanding of this phenomenon would have important consequences for the interpretation of ecological time series and for ecological modelling (Halley, 1996).

Environmental fluctuations arise from various factors that may correlate on different time scales, so the noise cannot be assumed as "white noise" that has no temporal correlation. In a 1/*f*-noise model, the correlation of fluctuations falls off as a power law. The 1/*f*-noise was so named because of the shape of its spectral density, which is characterised by power-law spectra of the form: $S(f) \propto 1/f^{\beta}$, where $0 \leq \beta \leq 2$ ($\beta = 0$: white noise/flat

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spectra; $\beta=1$: pink noise; $\beta=2$: brown noise (Brownian motion/random walk)). The 1/*f*-spectra have been associated with some ecological and geophysical time series (e.g., Mandelbrot and Wallis, 1969; Steele, 1985; Pimm and Redfearn, 1988; Rhodes and Anderson, 1996; Pelletier and Turcotte, 1997; Pelletier, 1998; Keitt and Stanley, 1988). Temporal variation of the physical environment usually has a reddened spectrum, which means that the amplitude of low frequency in a spectral analysis is consistently greater than that of high frequency and variability appears to increase at the longer time scales. In practice, the spectrum yields an approximately straight-line relationship between log variance and log frequency. Comparison of power-spectral structure between environmental and biological time series would help in understanding the causal mechanisms of ecological changes, such as population fluctuation. If both time series show reddened spectra, changing physical processes may have driven populations (climatic school of population regulation) (Sugihara, 1995). In contrast, different biological fluctuation patterns may suggest independent behaviour or self-regulation of dynamics.

Peatlands are important land surface feature of the globe, and understanding feedback mechanisms of their components is crucial in the study of the global carbon cycle. Northern peatlands have accumulated up to 450 Gt of carbon over the last 12,000 years (e.g., Clymo et al., 1998). Their large C pool raises concerns that peatlands may become significant sources for atmospheric C under a changing climate. However, significant uncertainties exist in addressing the environmental controls of C dynamics and peatlands sensitivity to environmental change. The credible assessment of C sink–source relationships would need to consider processes operating over short and long time scales (Yu et al., 2003; Bauer, 2004).

Numerous studies have been carried out in recent years on environmental controls of carbon fluxes in peatland ecosystems. Most of these studies are trying to find correlative relations statistically or visually between CO_2/CH_4 and environmental measurements (Moore and Knowles, 1989; Moore and Roulet, 1993; Suyker et al., 1997; Lafleur et al., 1997; Lafleur, 1999; Joiner et al., 1999; Carroll and Crill, 1997; Silvola et al., 1996; among others). Here I explore the differences and similarities of temporal variability in physical environment (temperatures, water tables) and biological variables (CO_2 fluxes) from four northern peatlands. Spectral analysis was used to derive the scaling exponents of time series and to understand the underlying fundamental dynamics of these systems. The comparison of physical and biological variability would provide some insights into the environmental controls of carbon dynamics over short time scale (1 h to 1 year). I find that many of these time series have scaling exponents of between 0.5 and 1.5. These 1/*f*-power spectra suggest that variations of these variables correlate with each other through time.

2. Peatland data

The data sets (Fig. 1) are from peatlands in central Alberta (Wolf Creek fen), central Saskatchewan (BOREAS Southern Study Area (SSA) fen), northern Manitoba (BOREAS NSA fen) and southwest Scotland (Ellergower Moss raised bog). The Wolf Creek site (lat. 53°25′N, long. 116°03′W; elevation 950 m asl) is a treed fen and is one of several peatland sites for peatland drainage and forestry experiments (Hillman, 1997). It is in a subhumid continental climate. The mean annual temperature from nearby climate station is 1.1 °C and annual precipitation of 536 mm, 361 mm of which falls during May through September (1951–1980 climate record). The on-site rainfall and water-table depth (WTD; depth to the water table below the peat surface) measurements from a control site (#2) for the years of 1987, 1988, 1990 and 1991 were used in the analysis. Total data points are over 7000, summarised every 1.5–3 h from automated continuous measurements. Among these four growing seasons of measurements, there was a dry year (1988), with growing season (15 May to 3 October) precipitation of 298 mm. On the other hand, 1990 was a wet year, with 423 mm of precipitation for the same period. The WTD response to these years was different, with the WTD reaching much greater values in the dry year than in the wet year (Fig. 1K–L) and with a much more pronounced mode of WTD values in the dry year than in the wet year, which can be seen to have had a more variable WTD (Fig. 2A–B).

The BOREAS SSA site (53°57′N, 105°57′W) is a minerotrophic, patterned fen surrounded by black spruce and jack pine forests. The climate has a mean annual air temperature of 0.9 °C and annual precipitation of 424 mm (at nearby Prince Albert, Saskatchewan; Environment Canada, 2003). Air temperatures, water tables and atmospheric CO_2 exchange were measured during the growing season in 1994 (Suyker et al., 1997; Fig. 1A–C). The site from NSA (55.9°N, 98.4°W) is a minerotrophic fen. The region has a mean annual air temperature of −3.4 °C and annual precipitation of 536 mm (at nearby Thompson, Manitoba; Environment Canada, 2003). Air temperatures, water tables and CO_2 fluxes were measured during the growing seasons in 1994 (Lafleur et al., 1997; Fig. 1D–F) and in 1996 (Joiner et al., 1999; Fig. 1G–H). All continuous measurements are averaged for 1 half-hour intervals from NSA and SSA sites.

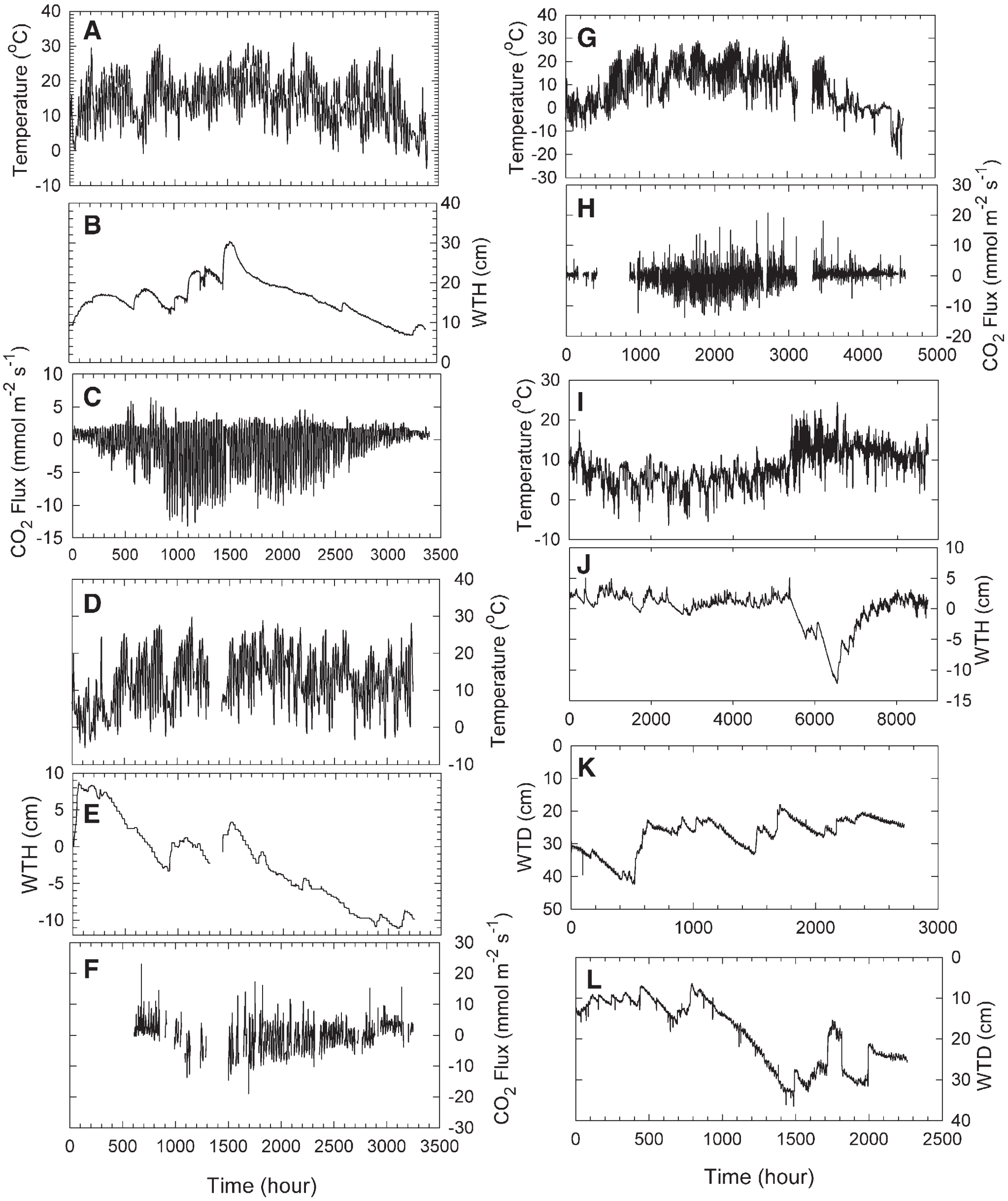

Fig. 1. Time series data used in analysis. (A) Air temperature, (B) relative water-table height (WTH) and (C) CO_2 fluxes from BOREAS SSA fen in 1994 (time as hours from 19 May to 7 October 1994; Suyker et al., 1997); (D) air temperature, (E) relative water-table height (WTH) and (F) CO_2 fluxes from BOREAS NSA fen in 1994 (time as hours from 8 April to 23 September 1994; Lafleur et al., 1997); (G) air temperature and (H) CO_2 fluxes from BOREAS NSA fen in 1996 (time as hours from 29 April to 4 November 1996; Joiner et al., 1999); (I) air temperature and (J) relative water-table height (WTH) from Ellergower Moss Bog, Scotland (time as hours since the end of September 1991; Clymo, 1992; R.S. Clymo, 1999, personal communication); (K) water-table depth (WTD) from the peat surface at Wolf Creek in a dry year (time as hours from 4 May to 20 October 1988; Hillman, 1997); (L) water-table depth (WTD) at Wolf Creek in a wet year (time as hours from 15 May to 3 October 1990; Hillman, 1997).

The Ellergower Moss site (lat. 55°05′N, long. 4°22′ W) is an elliptical raised bog of about 900 by 550 m in size (R.S. Clymo, 1999, personal communication). Measurements were made every minute and averaged over 60 min during the entire hydrological year from October 1991 through the end of September 1992 (Fig. 1I–J). The analysis was performed on the 1-h interval data for air temperature (150 cm above ground), rainfall amounts and water-table depth for a whole hydrological year from 1991 to 1992. The water-level data have been published in Clymo (1992) and its main feature is shown in Fig. 2C.

3. Power spectral analysis

There are several methods in analysing the dynamic behaviours of time series, including power spectral analysis, rescaled-range analysis and autocorrelation analysis (Schepers et al., 1992). It has been found that the power spectral analysis is better than other methods because it yields the least biased results (Schepers et al., 1992; Pelletier and Turcotte, 1997). The power spectral analysis was carried out using the periodogram method in the computer program AnalySeries (Paillard et al., 1996). The power spectrum is calculated directly from the Fourier coefficients after Fourier transformation of the data and shows the variance of the function at different frequencies. The scaling exponent β is computed from a least-square fit of log–log data plot for each time series as shown in Fig. 3—essentially the slope of the regression line through the data points for each time series. A linear regression of log-transformed data is better than non-linear fit on raw data because the residual error will be distributed as a quadratic and minimum error is guaranteed (Sole et al., 1997).

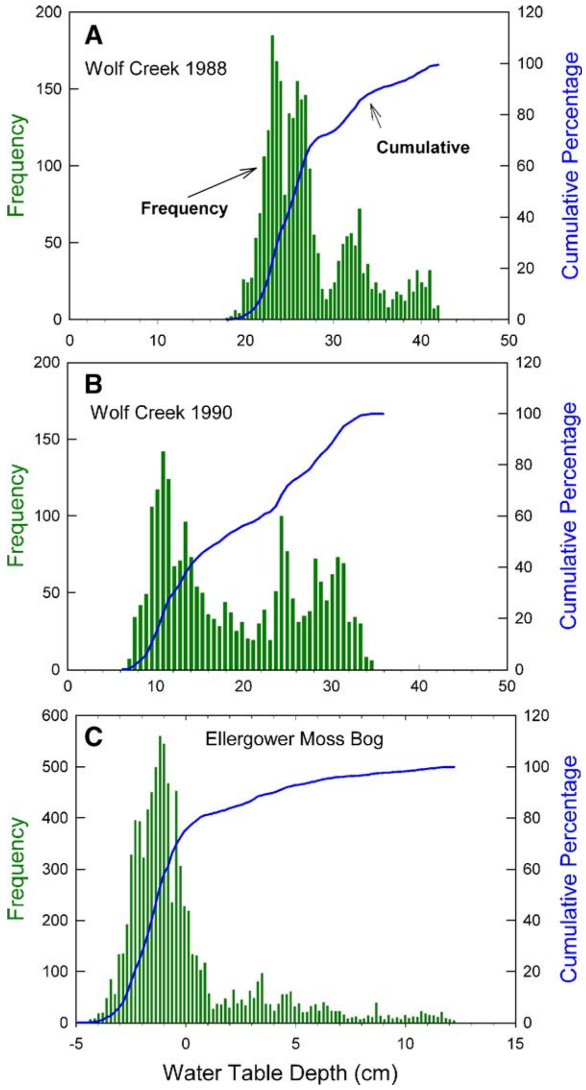

Fig. 2. Water-table depth (WTD) frequency and cumulative percentage. (A) Wolf Creek in 1988, a dry year having WTD at 22–28 cm for 60% of the time (data from Hillman, 1997); (B) Wolf Creek in 1990, a wet year having WTD at 10–15 cm for 40% of the time (data from Hillman, 1997); and (C) Ellergower Bog in 1991–1992, showing water table in a 5-cm range for 80% of the time (Clymo, 1992).

4. Power-law behaviour of peatland time series and its interpretation

The results from spectral analysis of peatland time series show power-law behaviour of peatland hydrology and carbon dynamics. They all show that log (frequency) vs. log (power spectra) plots have a non-flat spectrum with scaling exponents of between 0.5 and 1.5. The spectral structure of air temperatures from four data sets has scaling exponents of ~1.5 at high frequency but of ~0.5 at lower frequency (Fig. 3A). It has a breaking point at 24 h, which show a diurnal temperature cycle. The water tables of seven data sets have a scaling exponent of ~1.0, showing continuous change without a break point (Fig. 3B). CO_2 exchange from three BOREAS data sets has more complex spectral structure (Fig. 3C), with two breaking points at daily and monthly periods. Its scaling exponent is 1.0 at frequency higher than 24 h, lowers to 0.5 between daily and monthly periods and returns to 1.0 again at frequency lower than 1 month.

Pelletier (1998) examined the power spectral structure of atmospheric temperatures from climate stations and ice-core proxy records at various time scales ranging from 1 day to a million years. He found a distinct set of scaling exponents of 0 (a flat spectrum) from 40,000 to 1,000,000 years, of 2.0 from 2000 to 40,000 years, of 0.5 less than 2000 years, and of 1.5 for continental stations and of 0.5 for maritime stations from 1 month to 1 day. The difference between continental and maritime regions was explained by Pelletier (1998) as due to difference in heat exchange among land, ocean and atmosphere. He modelled the vertical transport of heat in the atmosphere as a stochastic diffusion process and found that the air mass above a maritime station exchanges heat with both the atmosphere above and the ocean below, while a continental station exchanges heat mostly with the atmosphere above. My analysis of air temperatures above peatlands shows an exponent of 0.5 at time scale of 1 day to 1 month, which is more similar to one from maritime station as discussed in Pelletier (1998). This similarity

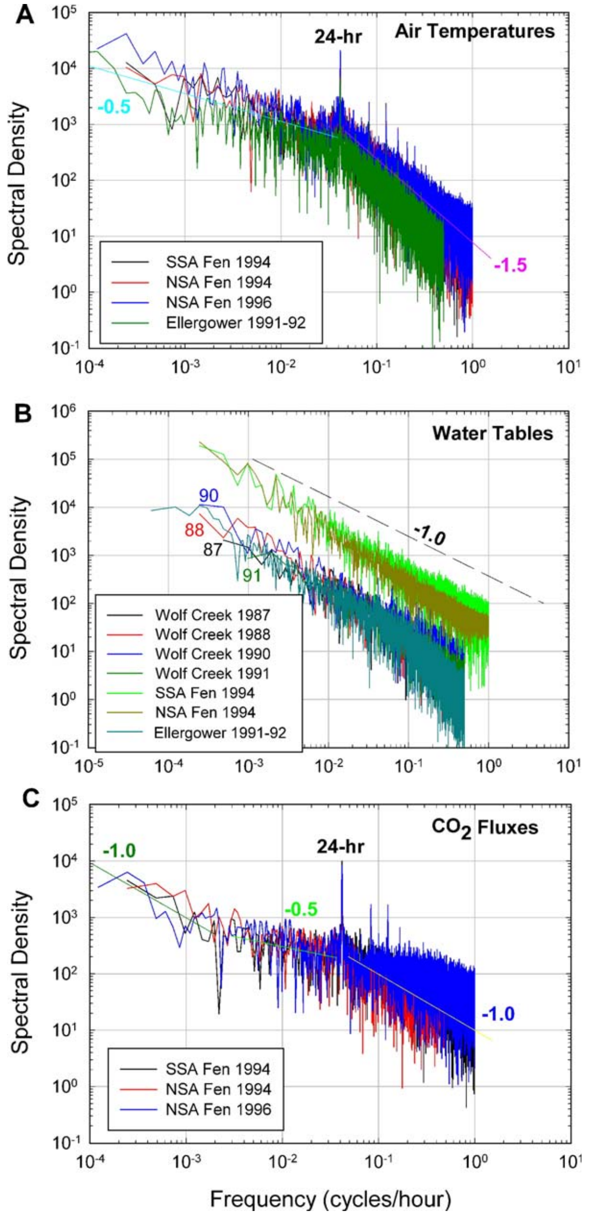

Fig. 3. Power density spectra of climatic, hydrological and biological time series. (A) Air temperatures, (B) water tables and (C) CO_2 fluxes. Data sources: SSA fen in 1994 (Suyker et al., 1997), NSA fen in 1994 (Lafleur et al., 1997), NSA fen in 1996 (Joiner et al., 1999), Wolf Creek in 1987–1991 (Hillman, 1997) and Ellergower Bog (Clymo, 1992). The power spectrum is given as a function of frequency as plotted in a log–log scale. The scaling exponents of between 0.5 and 1.5 at different time scales, suggesting a relation of $S(f) \propto 1/f^{\beta}$. The power-law behavior of peatland dynamics may suggest the self-regulating mechanisms in peatlands.

could well be explained by his model as a consequence of heat exchange with both waterlogged peatlands as well as with the atmosphere. Peatlands are distinct from the surrounding upland terrestrial ecosystems, as they have more interactions with the atmosphere through water vapour and trace gas fluxes (Sellers et al., 1995; Lafleur et al., 1997). The spectral structure of relative humidity from Ellergower Bog is almost identical with the one for air temperatures, with 1.5 and 0.5 exponents breaking by a diurnal peak (not shown here). Pelletier (1998) did not analyse temperature data down to time scale shorter than 1 day, so we do not know how the scaling exponent of 1.5 compares with typical continental and maritime climate stations.

It is remarkable that water tables from such a wide variety of peatland ecosystems show almost identical power spectra, with a scaling exponent close to 1.0. The data sets from four growing seasons at Wolf Creek include years drier and wetter than normal. SSA fen is in the middle of boreal forest, but NSA fen is close to the northern limit of boreal forests. More strikingly, Ellergower site is a raised bog in a maritime climate. Despite all these differences, their spectral structures are essentially the same. The $1/f$-noise suggests that the dynamics of a system is strongly influenced by past events. In contrast, white noise, a random signal, implies no correlation between the current dynamics and past events. These power-law patterns imply the presence of long memory or persistence in water-table time series, as discussed in Pelletier and Turcotte (1997). Persistence for a water-table time series means that high water-table years (or weeks or days or hours) are, more often than not, followed by a high water-table years. The persistence can be regarded as self-similar with variability on long time scales larger than on short time scales. The overall effect of low frequency (rare) events has a great influence than that of high frequency (common) events per unit frequency (Halley, 1996).

These findings support the idea that a nonlinear response of the peatland ecosystems to perturbations (such as rainfall events) provides the main mechanisms for the water-level fluctuations and then peatland dynamics. The power-law distribution was evidence of self-organized criticality (stability at an edge). A self-similar behaviour of peatland hydrology may come from self-organized criticality, where fluctuations over all time scales and power laws are a direct consequence of criticality (Sole et al., 1997). The question of whether power-law temporal fluctuations signal self-organized criticality in natural systems cannot be answered until more is known about the processes underlying these patterns, but interactions across scales have been found to be important in generating and stabilizing patterns at a variety of scales (Perry, 1995). These results suggest that self-similar and self-organized behaviours might exist in peatland WTD dynamics. Such a fractal-like organization of peatlands has been demonstrated in a peatland dynamics simulation model, using two coupled stochastic differential equations for peat depth and WTD, respectively (Hilbert et al., 2000). This is consistent with the generally held belief that peatlands regulate their own water levels (e.g., Ingram, 1982).

The relatively complex spectral structure of CO_2 exchanges suggests complex influence of climate and hydrological fluctuations on this biological variable. CO_2 flux responds to air temperature with a distinct 24-h spectral peak (diurnal cycle). The exponent of 1.0 at time scales short than 1 day suggests possible connection more with water-table dynamics than temperatures. The flattened spectrum between 1 day and 1 month suggests either a strong control by temperature or possible biotic self-regulation of peatland carbon exchanges. Vourlitis and Oechel (1999) found that importance of meteorology, hydrology and phenology in controlling CO_2 exchange varies at different time scales in an Alaskan tundra. Environmental controls of carbon fluxes on peatlands have recently been actively investigated (Moore and Roulet, 1993). Water tables appear to dictate CO_2 and CH_4 fluxes because they shift the peat column under aerobic or anaerobic conditions. My analysis suggests this more likely occurs at shorter and longer time scales, but not at intermediate scale of 1 day to 1 month.

5. Implication for peatland dynamics

A key feature of peatland ecosystems is their long-term accumulation of peat at slow rates over millennia, in addition to their short-term C flux dynamics. As a result, integration and interactions of these diverse processes at various time scales are an important issue in peatland C dynamics studies (e.g., Bauer, 2004). The analysis results from this paper indicate that time scales are important in discussing hydrology and carbon dynamics in northern peatlands. Possible self-regulation of peatland dynamics is also scale-dependent. Water tables are an integrated part of peatland systems and determine carbon exchange over certain time scales in peatlands. However, the importance of environmental factors (temperatures, moistures) in controlling peatland carbon dynamics varies at different time scales. This consideration is useful in scale up of a process-based simulation model, as scaling up has become an important modeling tool in global change studies.

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References

Bauer, I., 2004. Modelling effects of litter quality and environment on peat accumulation over different time-scales. Journal of Ecology 92, 661–674.

Carroll, P., Crill, P., 1997. Carbon balance of a temperate poor fen. Global Biogeochemical Cycles 11, 349–356.

Clymo, R.S., 1992. Models of peat growth. Suo 43, 127–136.

Clymo, R.S., Turunen, J., Tolonen, K., 1998. Carbon accumulation in peatland. Oikos 81, 368–388.

Environment Canada, 2003. Canadian Climate Normals. http://climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html.

Halley, J.M., 1996. Ecology, evolution and 1/*f*-noise. Trends in Ecology & Evolution 11, 33–37.

Hilbert, D.W., Roulet, N., Moore, T., 2000. Modelling and analysis of peatlands as dynamical systems. Journal of Ecology 88, 230–242.

Hillman, G.R., 1997. Effects of engineered drainage on water tables and peat subsidence in an Alberta treed fen. In: Trettin, C.C., Jurgensen, M.F., Grigal, D.F., Gale, M.R., Jeglum, J.K. (Eds.), Northern Forested Wetlands: Ecology and Management. CRC Lewis Publishers, New York, pp. 253–272.

Ingram, H.A.P., 1982. Size and shape in raised mire ecosystems: a geophysical model. Nature 297, 300–303.

Joiner, D.W., Lafleur, P.M., McCaughey, J.H., Bartlett, P.A., 1999. Interannual variability in carbon dioxide exchanges at a boreal wetland in the BOREAS northern study area. Journal of Geophysical Research 104, 27,663–27,672.

Keitt, T.H., Stanley, H.E., 1988. Dynamics of North American breeding bird populations. Nature 393, 257–260.

Lafleur, P.M., McCaughey, J.H., Joiner, D.W., Bartlett, P.A., Jelinski, D.E., 1997. Seasonal trends in energy, water, and carbon dioxide fluxes at a northern boreal wetland. Journal of Geophysical Research 102, 29,009–29,020.

Lafleur, P.M., 1999. Growing season energy and CO_2 exchange at a subarctic boreal woodland. Journal of Geophysical Research 104, 9571–9580.

Mandelbrot, B.B., Wallis, J.R., 1969. Some long-run properties of geophysical records. Water Resources Research 5, 321–340.

Moore, T.R., Knowles, R., 1989. The influence of water table levels on methane and carbon dioxide emissions from peatland soils. Canadian Journal of Soil Science 69, 33–38.

Moore, T.R., Roulet, N.T., 1993. Methane flux: water table relations in northern wetlands. Geophysical Research Letters 20, 587–590.

Paillard, D., Labeyrie, L., Yiou, P., 1996. Machintosh program performs time-series analysis. Eos 77, 379.

Pelletier, J.D., 1998. The power spectral density of atmospheric temperature from time scales of 10^{-2} to 10^6 yr. Earth and Planetary Science Letters 158, 157–164.

Pelletier, J.D., Turcotte, D.L., 1997. Long-range persistence in climatological and hydrological time series: analysis, modeling and application to drought hazard assessment. Journal of Hydrology 203, 198–208.

Perry, D.A., 1995. Self-organizing systems across scales. Trends in Ecology & Evolution 10, 241–244.

Pimm, S.L., Redfearn, A., 1988. The variability of population densities. Nature 334, 613–614.

Rhodes, C.J., Anderson, R.M., 1996. Power laws governing epidemics in isolated populations. Nature 381, 600–602.

Schepers, H.E., van Beek, J.H.G.M., Bassingthwaighte, J.B., 1992. Four methods to estimate the fractal dimension from self-affine signal. IEEE Engineering in Medicine and Biology Magazine 11, 57–64.

Sellers, P.J., et al., 1995. The Boreal Ecosystem-Atmosphere Study (BOREAS): an overview and early results from 1994 field year. Bulletin of the American Meteorological Society 76, 1549–1577.

Silvola, J., Alm, J., Ahlholm, U., Nykanen, H., Martikainen, P.J., 1996. CO_2 fluxes from peat in boreal mires under varying temperature and moisture conditions. Journal of Ecology 84, 219–228.

Sole, R.V., Manrubla, S.C., Benton, M., Bak, P., 1997. Self-similarity of extinction statistics in fossil record. Nature 388, 764–767.

Steele, J.H., 1985. A comparison of terrestrial and marine ecological systems. Nature 313, 355–358.

Sugihara, G., 1995. From out of the blue. Nature 378, 559–560.

Suyker, A.E., Verma, S.B., Arkebauer, T.J., 1997. Season-long measurement of carbon dioxide exchange in a boreal fen. Journal of Geophysical Research 102, 29,021–29,028.

Vourlitis, G.L., Oechel, W.C., 1999. Eddy covariance measurements of CO_2 and energy fluxes of an Alaskan tussock tundra ecosystem. Ecology 80, 686–701.

Yu, Z.C., Vitt, D.H., Campbell, I.D., Apps, M.J., 2003. Understanding Holocene peat accumulation pattern of continental fens in western Canada. Canadian Journal of Botany 81, 267–282.