Extended abstract No. 54

PEATLAND DYNAMICS IN PATAGONIA: ABRUPT MID-HOLOCENE FEN-TO-BOG TRANSITION AND CARBON SEQUESTRATION IMPLICATIONS

Julie Loisel, Department of Earth and Environmental Sciences, Lehigh University, 1 West Packer Avenue, Bethlehem, PA 18015-3001, United States of America, (001) 610-758-3660, jul208@lehigh.edu

Zicheng Yu, Department of Earth and Environmental Sciences, Lehigh University

Paolo D'Odorico, Department of Environmental Sciences, University of Virginia

SUMMARY

We use peatlands from southern Patagonia as model examples to investigate the role of regional-scale allogenic controls on the fen-bog transition, an important regime shift that had occurred throughout high-latitude regions of both hemispheres and that likely impacted the global carbon cycle through a major change in the rate of methane emissions and peat-carbon sequestration. In addition to documenting the mid-Holocene fen-bog transition in Patagonia, our goals are: (1) to identify and describe key fen and bog stability properties, and (2) to integrate these mechanisms into conceptual and process-based models. We argue that peatlands are 'complex adaptive systems', and that a reappraisal and better understanding of fundamental and important peatland processes such as the fen-bog transition under this view is critical to better assess the role of external forcing such as climate change on peatland structure and functioning.

KEYWORDS. fen-bog transition, non-linear ecosystem shift, conceptual and process-based models, Patagonia, paleoecology

RATIONALE

Over the past 12,000 years, peatlands have played a significant role in the global carbon (C) cycle by acting as long-term carbon dioxide (CO_2) sinks and as the most important natural sources of methane (CH_4) to the atmosphere (MacDonald *et al*., 2006; Yu, 2011). These ecosystems have had a net cooling effect on the global climate throughout the Holocene, as they have sequestered up to about 550 gigatons of C, which accounts for roughly 1/3 of all organic soil C and represents as much as to 2/3 of the present atmospheric C pool (Yu *et al*., 2010). There is a growing body of evidence suggesting that peatland dynamics are non-linear: rather than displaying gradual structural and functional changes that match the frequency of external forcing, these ecosystems show long periods of little change that are punctuated with step-like transitions to alternative states (Belyea and Baird, 2006; Belyea, 2009). From a theoretical standpoint, therefore, peatlands can be considered 'complex adaptive systems' (Levin, 1998). As abrupt changes in peatland dynamics may directly impact peat-C sequestration rates, profound effects on the global C cycle and the climate system can result from such a non-linear behavior.

Peatlands as complex adaptive systems

There is increasing recognition that ecosystems often exhibit non-linear, step-like responses to external forcing mechanisms (Andersen *et al*., 2009). Such abrupt transitions from one steady state to another are described as bifurcations (or tipping points), and they occur once the stability properties of an ecosystem are suddenly lost to the expense of a new (or alternative) stable state (Scheffer *et al*., 2001). Once in place, the alternative ecosystem state may be maintained by self-regulating physical, biological, and/or chemical positive feedbacks, making it difficult or impossible to reverse (Scheffer and Carpenter, 2003). The difficulty to foresee these non-linear responses is concerning because changes in ecosystem structure may lead to critical shifts in ecosystem function and associated services.

Most high-latitude peatlands start their development as fens. As peat accumulates over time, fen surfaces progressively get farther away from the mineral groundwater, and a shift to bog vegetation occurs (Foster and Wright, 1990). Here, the expression ‘bog’ represents *Sphagnum*-dominated peatlands and therefore includes poor fens. This transition is usually thought of being strictly governed by the plant community itself through peat accumulation: as peat thickness progressively increases, groundwater inputs diminish until precipitation becomes the sole water source to the peatland surface (Zobel, 1988). In nature, however, an ‘intermediate’ stage between the fen and bog states does not exist, suggesting that the transition from fen to bog is unstable, or transient (Fig. 1).

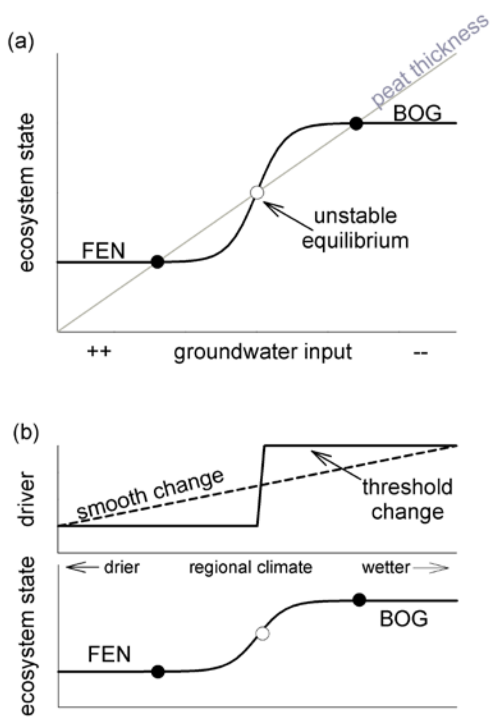

Figure 1. Conceptual models for the fen-bog transition. (a) autogenic bistable system: increasing peat depth leads to a lower nutrient level, itself leading to a weakening of the fen resilience until the ecosystem jumps to the alternative state. (b) driver-threshold: the ecosystem shift is induced after an external driver (e.g., climate) exceeds a threshold. Adapted from Andersen *et al*., 2009.

Here we hypothesize that both the bog and fen phases possess specific stability properties that promote their own self-maintenance, explaining the abruptness of the fen-bog transition. We speculate that, over time, fens lose their resilience due to increasing peat thickness and, as a result, they become more sensitive to perturbations (Fig. 1). Under this scenario, we argue that the ecosystem reaches a tipping point where the bog state becomes more attractive than the fen domain, inducing a rapid fen-bog transition via positive feedback loops. We also predict that, over time, changes in climate (moisture and temperature) and stochastic disturbance events (e.g., drought, flood, volcanic eruption, fire) get increasingly important in facilitating the fen-bog transition (i.e., the fen state becomes less stable over time). Specifically, our goals are: (1) to identify and describe key fen and bog stability properties, and (2) to integrate these mechanisms into a conceptual model (Fig. 1) as well as a process-based model. The latter is being developed as a bimodal model that is capable of simulating peat accumulation and self-maintaining mechanisms for two alternative states using simple 'fen' and 'bog' vegetation functions and feedback loops.

CASE STUDY: FEN-BOG TRANSITION IN SOUTHERN PATAGONIA

Patagonian peatlands (Fig. 2) are strikingly similar to their northern counterparts in terms of structure and functioning, but these ecosystems have developed under very different boundary conditions, including unique climatic settings, landscape features, and disturbance regimes. Therefore, these southern ecosystems provide a unique opportunity to test hypotheses about local- and regional-scale controls on peatland dynamics.

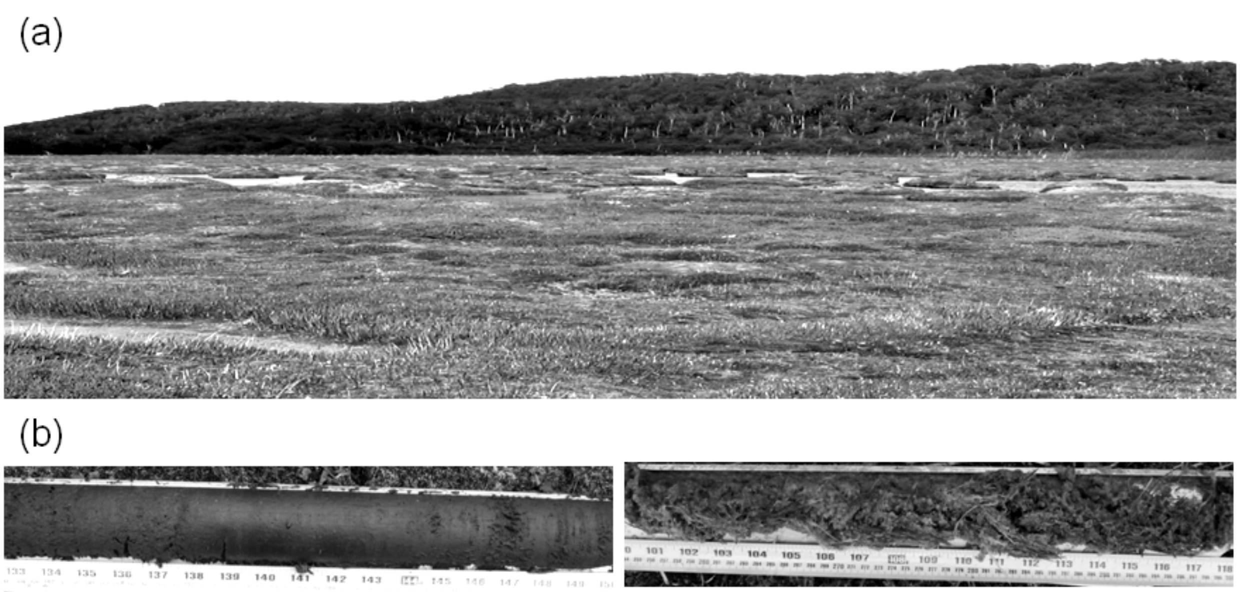

Figure 2. Cerro Negro peatland, southern Chile. (a) photo of the study site; (b) peat cores showing highly decomposed fen peat (left) and fresh-looking bog peat (right).

We present peat-core evidence for abrupt, three-fold increases in peat-carbon accumulation rates in Patagonian peatlands around 4200 years ago (Fig. 2). This sudden increase in C sequestration is coincident with a rapid transition from groundwater-fed minerotrophic fens to precipitation-fed ombrotrophic bogs, as shown by our high-resolution plant macrofossil analysis. Our data synthesis from 46 sites similarly indicates a large-scale switch from fens to bogs across southern Patagonia at the same time, pointing towards a regional-scale, 'driver threshold-type' control on the fen-bog transition and associated peat-C dynamics (Fig. 1). We use this transition as a 'natural experiment' to explicitly test and evaluate the following two important, non-exclusive hypotheses.

(1) Increasing precipitation and flushing reduced the influence of mineral-rich groundwater and allowed the pioneer bog genus *Sphagnum* to establish, which rapidly led to the fen-bog transition and to increased C sequestration around 4200 years ago (Granath *et al*., 2010). Under this scenario, climatic conditions facilitated *Sphagnum* establishment and growth. In the study region, precipitation constitutes a key control on ecosystem dynamics (Tuhkanen, 1992). Paleoecological evidence from peat and lake cores indicates major millennial- and centennial-scale changes in the regional fire regime, forest extent, and lake productivity around 5000 years ago (Moy *et al*., 2009). These ecosystem shifts have been linked to important precipitation variability that was induced by changes in the strength and latitudinal position of the southern westerly winds (Moreno *et al*., 2009).

(2) A catastrophic disturbance around 4200 years ago induced an abrupt acidification of the peatland surface that facilitated *Sphagnum* establishment, which led to the fen-bog transition. We hypothesize that volcanic fallout and sulfur dioxide (SO_2) release from Mount Burney, a stratovolcano situated in the southern Andes that erupted 4200 ± 900 years ago (Stern, 2008), has caused intense peatland acidification because of fens weak buffering capacity (Gorham *et al*., 1984), which led to nutrient seepage and an abrupt ecosystem shift. A tephra layer from this eruption was identified along several peat profiles (> 40) throughout southern Patagonia, indicating that the volcanic plume effectively affected the entire study region. In addition, major, long-lasting damage to forest, aquatic and peatland ecosystems caused by Mount Burney's eruption have previously been reported, though they were restricted to the vicinity of the volcano (Kilian *et al*., 2006). Our scenario implies a much broader, regional-scale impact for this eruption.

IMPLICATION

Since fens emit 10 to 100 times more CH_4 than bogs (Laine and Vasander, 1996), and bogs possess a greater C sequestration capacity than fens (Granath *et al*., 2010), the fen-to-bog transition has clear implications for soil-atmosphere C exchanges at a regional to global scale. For instance, the progressive decrease in atmospheric CH_4 concentration that has been occurring between 8000 and 4000 years ago might relate to the fen-to-bog transition across the boreal biome (MacDonald *et al*., 2006). The processes leading to this ecosystem shift, however, remain poorly understood (Hugues, 2000).

Overall, a reappraisal and better understanding of fundamental and important peatland processes such as the fen-bog transition is critically needed to better assess the role of allogenic factors on peatland change and carbon sequestration ability. In addition to documenting the mid-Holocene fen-bog transition in Patagonia, our conceptual and process-based models clearly represent a step forward in reducing the complexity of peatland dynamics by identifying the key variables and quantifying the interactions that control non-linear behavior in peatlands.

ACKNOWLEDGEMENTS

We thank Daniel Brosseau and Greg Sills for field, laboratory, or mapping assistance. The research was funded by a Faculty Innovation Grant from Lehigh University (2009), a US-NSF Doctoral Dissertation Improvement Grant (DEB-1110665), the Department of Earth and Environmental Sciences at Lehigh University, and an NSERC Canada Postgraduate Scholarship (BESC-D3-362645-2008).

REFERENCES

Andersen, T., Carstensen, J., Hernández-Garcia, E., Duarte, C.M. (2009). Ecological thresholds and regime shifts: approaches and identification. *Trends in Ecology and Evolution* **24**(1): 49-57.

Belyea, L.R. (2009). Non-linear dynamics of peatlands and potential feedbacks on the climate system. In Baird, A., Belyea, L., Comas, X., Reeve, A., Slater, L. (eds.) *Northern Peatlands and Carbon Cycling*. American Geophysical Union Monograph Series.

Belyea, L.R., Baird, A.J. (2006). Beyond “The limits to peat bog growth”: cross-scale feedback in peatland development. *Ecological Monographs* **76**(3): 299–322.

Foster, D., Wright, H.E. Jr. (1990). Role of ecosystem development and climate change in bog formation in central Sweden. *Ecology* **71**: 450-463.

Gorham, E., Bayley, S.E., Schindler, D.W. (1984). Ecological effects of acid rain deposition upon peatlands: a neglected field in ‘acid-rain’ research. *Canadian Journal of Fisheries and Aquatic Science* **41**: 1256-1268.

Granath, G., Strengbom, J., Rydin, H. (2010). Rapid ecosystem shifts in peatlands: linking plant physiology and succession. *Ecology* **91**(10): 3047-3056.

Hugues, P.D.M. (2000). A reappraisal of the mechanisms leading to ombrotrophy in British raised mires. *Ecology Letters* **3**: 7-9.

Kilian, R., Biester, H., Behrmann., J, Baeza., O, Fesq-Martin, M., Hohner, M., Schimpf, D., Friedmann, Mangini, A. (2006). Millennium-scale volcanic impact on a superhumid and pristine ecosystem. *Geology* **34**(8): 609-612.

Laine J., Vasander, H. (1996). Ecology and vegetation gradients of peatlands. In Vasander, H. (ed.), *Peatlands in Finland*. Finnish Peatland Society.

Levin, S.A. (1998). Ecosystems and the biosphere as complex adaptive systems. *Ecosystems* **1**: 431-436.

MacDonald, G.M., Beilman, D.W., Kremenetski, K.V., Sheng, Y., Smith, L., Valichko, A.A. (2006). Rapid early development of circumarctic peatlands and atmospheric CH_4 and CO_2 variations. *Science* **314**: 285-288.

Moreno, P.I., François, J.P., Villa-Martınez, R.P., Moy, C.M. (2009). Millennial-scale variability in Southern Hemisphere westerly wind activity over the last 5000 years in SW Patagonia. *Quaternary Science Reviews* **28**: 25-38.

Moy, C.I., Moreno, P.I., Dunbar, R.B., Kaplan, M.R., Francois, J.P., Villalba, R., Haberzettl, T. (2009). Climate change in southern South America during the last two millennia. In Vimeux, F., Sylvestre, F. and Khodri, M. (eds.), *Past climate variability in South America and surrounding regions*. Springer.

Scheffer, M. Carpenter, S.R. (2003). Catastrophic regime shifts in ecosystems : linking theory to observation. *Trends in Ecology and Evolution* **18**(12): 648-656.

Scheffer, M., Carpenter, S., Foley, J.A., Folke, C., Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature* **413**: 591-596.

Stern, C.R. (2008). Holocene tephrochronology record of large explosive eruptions in the southernmost Patagonian Andes. *Bulletin of Volcanology* **70**:435–454.

Tuhkanen, S. (1992). The climate of Tierra del Fuego from a vegetation geographical point of view and its ecoclimatic counterparts elsewhere. *Acta Botanica Fennica* **145**: 1-64.

Yu, Z. (2011). Holocene carbon flux histories of the world's peatlands: global carbon-cycle implications. *The Holocene* **21**: 761-774.

Yu, Z., Loisel, J., Brosseau, D.P., Beilman, D.W., Hunt, S.J. (2010). Global peatland dynamics since the Last Glacial Maximum. *Geophysical Research Letters* **37**: L13402 doi:10.1029/2010GL043584.

Zobel, M. (1988). Autogenic succession in boreal mires – a review. *Folia Geobotanica et Phytotaxonomica* **28**: 417-445.