Alternative stable states between subtropical forest and grassland

A palaeoecological case study in southern Brazil

Resumo em português

Na Mata Atlântica do sul e sudeste do Brasil, o ecossistema dos campos naturais ocorre em locais onde o clima atual permitiria o estabelecimento de ecossistemas florestais. Ainda que a precipitação de verão e também a proporção de florestas nesta região tenham aumentado gradualmente durante o Holoceno, a ocorrência de fogo também se tornou mais frequente. O aumento da população humana durante o Holoceno tardio pode ter alterado o regime natural do fogo.

O objetivo deste projeto é usar o sedimento da Lagoa Dourada e/ou das bacias próximas a ela para estudar a vegetação do passado e a dinâmica do fogo em detalhes para estabelecer os avanços e retrações entre a vegetação e o fogo.

Mais de 10 metros de sedimentos foram acumulados ao longo dos últimos 10.000 anos na Lagoa Dourada e o estudo polínico, geoquímico e de partículas de carvão permitirão novos conhecimentos sobre paleofogo e dinâmica da vegetação. Apesar de diversos sedimentos turfosos já terem sido coletados nos ecossistemas de interesse, ainda não há coleta de sedimento de lago. Como os sedimentos de lago normalmente são muito mais longos que os sedimentos turfosos, possibilitam uma resolução muito maior dos dados, gerando informações que não são possíveis a partir dos sedimentos mais compactos. A partir de um bote inflável, fixado no meio da Lagoa Dourada, serão coletados sedimentos utilizando-se um coletor de sedimentos de operação manual (Livingstone). Este projeto é uma cooperação entre Brasil e Alemanha. Enquanto os perfis de sedimentos serão coletados no Brasil, as análises serão realizadas na Alemanha. Todos os resultados serão tornados públicos.

Project description

Background and introduction

Human induced global change has the potential to drive individual Earth systems over “tipping points” and into qualitatively different states (e.g. Lenton et al. 2008). These nonlinear responses are potentially inherent in many systems, but they are still poorly understood. Grasslands and forests in subtropical regions may represent two different states that may exist under the same climate conditions and their extent is large enough that changes in their state may have an impact on the Earth system (Higgins & Scheiter 2012).

Forest and grassland are vastly contrasting terrestrial ecosystems, which differ in their functionality in biogeographical cycles. The transition between subtropical forests and savannah or grasslands is often abrupt, and this sharp boundary is generally assumed to be determined by fire and grazing. Tropical and subtropical forests have a closed canopy creating humid conditions at the forest floor, thus preventing frequent fires. Grassland species are fire adapted and frequent fires act as a positive feedback in these systems, eliminating forest species. Thus both systems are self-stabilizing and it has been suggested that they can occur under the same external abiotic conditions and thus represent alternative stable states (e.g. Sternberg 2001, Warman & Moles 2009). Alternative stable states between grassland, savannah and forest in the tropics and subtropics have received much attention (e.g. Hirota et al. 2011, Staver et al. 2011, Higgins & Scheiter 2012), as state shifts are likely to be abrupt, difficult to predict and potentially difficult to revert. While the carbon sequestration of savannah and grassland is high (Grace et al. 2006), most of it is released during frequent fires. Tropical and subtropical wet forests on the other hand, are among the biomes with the highest storage of carbon. Considering the large areas these biomes occupy, shifts between states are important for the global carbon cycle as well as for local and regional ecosystem services like water retention.

There is growing consensus that tropical forest and savannah exist as fire-mediated alternative stable states (e.g. Murphy & Bowman 2012). However, the evidence to support this theory is still limited and at a large scale comes from satellite-derived tree cover, showing forest and open savannah as two main attractors with few points representing intermediate cover (Hirota et al. 2011). The theory is however, in agreement with regional observations (e.g. Warman & Moles 2009) and model experiments (e.g. Sternberg 2001, Hirota et al. 2010). Uncertainty remains whether the system shifts are rapid or gradual (Ratajczak and Nippert 2012, van Nes et al. 2012). While time series are commonly used in the analysis of alternative stable states (e.g. Wang et al. 2012, Scheffer & Carpenter 2003), there has been little use of them to address this phenomenon.

Palaeoecological techniques are ideally suited to provide long time-series data that will allow critical insights into the dynamics and stability of these systems shifts. Sub-fossil pollen from lakes and bogs are well suited to reconstruct past changes in plant abundance and past fire frequencies and severity can be readily obtained from the same sediment cores.

The research proposed aims to use the Holocene vegetation dynamics of the Mata Atlântica as a model system to explore the potential forest-grassland bi-stability through time, examining feedbacks, tipping points and rates of change.

The study system

The Araucaria forest region within the Mata Atlântica in southern and south eastern Basil has been the focus of much palaeoecological research. Pollen diagrams document that this landscape was mainly covered by species rich campos grasslands during the last glacial with pollen diagrams reaching back to more than 44 ka (Behling et al. 2004, Jeske-Pieruschka et al. 2012). Towards the northeast a pollen diagram from Colônia crater (São Paulo) covering the last glacial period documents that the vegetation here shifted between a domination of forest and grassland including a forested period around 30 ka followed by a dominance of grasses until 10 ka (Ledru et al. 2009). The campos grassland in the present Araucaria region on the other hand was stable until about 14.5 ka with a proportional increase in pollen from campos vegetation between 31 ka and 14.5 ka. However, species from the wet

Atlantic forest were regionally present, possibly restricted to deep valleys and coastal slopes (Behling et al. 2007). The onset of the Holocene shows no changes in vegetation type, although changes in species composition are discernible and the early Holocene is characterized by a sharp decrease in pollen diversity (Behling et al. 2007). From the early Holocene onwards, increased charcoal levels indicate frequent fires in the grasslands generally with maximum values just before the increase in pollen from forest taxa. Pollen from tree taxa slowly increase particularly during the second half of the Holocene, culminating often in an abrupt expansion between 4 ka and 1 ka ago. All Holocene pollen diagrams available from the *Araucaria* region were constructed from peat bogs and most show a change in sediment composition and/or change in sediment accumulation rate at or around the time of forest expansion. This hampers detailed insights into the dynamics of this process.

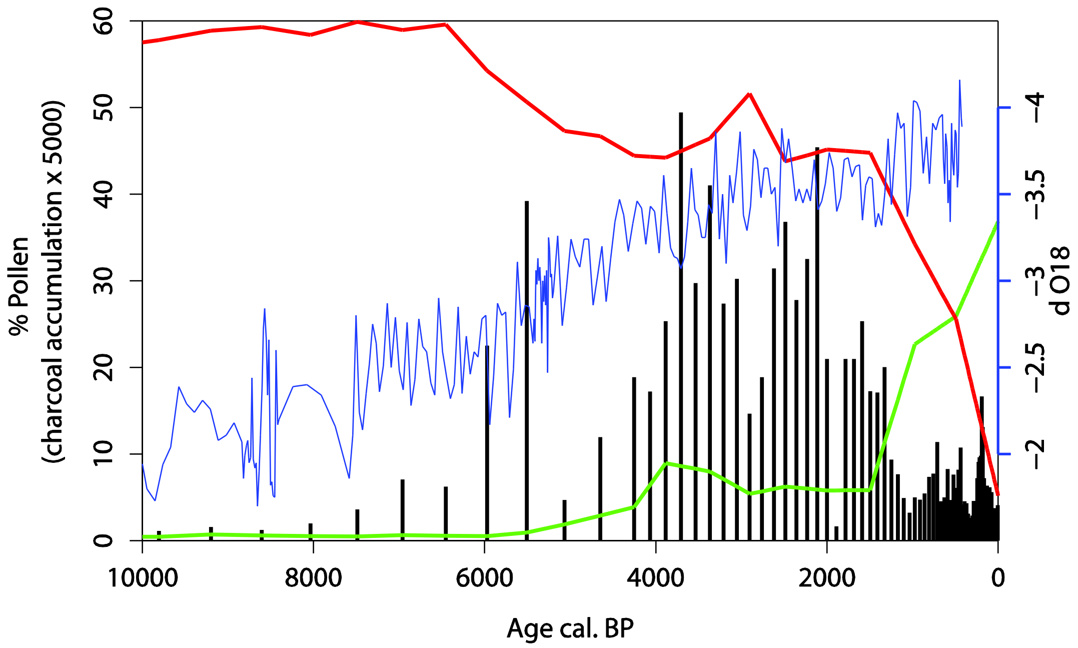

Figure 1. Proportions of pollen from *Araucaria angustifolia* (green), Poaceae (red) and accumulation rate of charcoal particles (black) for the Cambará do Sul core (Behling et al. 2004) over the last 10,000 years. Overlayed is a high resolution oxigen isotope record from Botuverá Cave (Wang et al. 2006) 200 km north of Cambará do Sul. More negative values are interpreted to reflect stronger South American monsoon, more summer precipitation.

An important prerequisite for the proposed study is the availability of vegetation independent information on past climate change, which, for this region, is available from oxygen isotope records An important prerequisite for the proposed study is the availability of vegetation independent information on past climate change, which, for this region, is available from oxygen isotope records from the Botuverá Cave (Cruz et al. 2005, Wang et al. 2006, 2007) and Santana Cave (Cruz et al. 2006) as well as various analysis of a marine sediment core GeoB 6211-2 (Razik et al. 2013). The speleothem records document that changes in precipitation over southern Brazil are generally controlled by summer insulation (Cruz et al. 2005, Wang et al. 2007). Therefore, these records may mainly provide information on the strength of South American Summer Monsoon and resulting summer precipitation, which was at a minimum during the early Holocene and has gradually increased since.

The speleothem data indicate a gradual increase in summer precipitation over the Holocene, while vegetation reconstructions often show a sudden shift in vegetation cover. The currently available data often show abrupt shifts from the grassland to the forest (e.g. Fig. 1), which may in part be due to the local signal provided by these sites. Once the forest has established locally the regional signal is drowned. Conversely, it is difficult to estimate how high the regional forest cover had been, previous to local forest establishment. In addition, as the local forest establishment reduces local fire, it is difficult to evaluate whether a change in the fire regime had caused the forest expansion. Moreover, *Araucaria* seeds were an important food source for indigenous groups and the frequency of dates for settlement sites seem to coincide with the expansion of the tree (Iriarte and Behling 2007).

In summary, the Mata Atlântica in southern and south eastern Basil contains natural grasslands where climate would allow the establishment of forest. The proportion of forest in this region has generally increased during the Holocene, while fires were more frequent and/or stronger during the second half of the Holocene. Summer precipitation has increased gradual over the Holocene, while shifts in vegetation cover often appear sudden. Increased human population during the late Holocene could have changed the natural fire regime and/or spread *Araucaria* woodland. The here proposed research aims to add new information to disentangle these possible drivers and thus add to a better understanding of this highly divers and threatened ecoregion.

A high resolution study of the Holocene vegetation and fire dynamics is necessary to establish the leads and lags between vegetation and fire.

Objectives

The overall aim of the research proposed in this project is to obtain a **regional understanding of the interplay of climate change, natural fire dynamics, human land-use and vegetation change** in one of the world's biodiversity hotspots, the Mata Atlântica. By exploring the hypothesis that grassland (campos) and forest represent two fire mediated alternative stable states within the *Araucaria* region of southern Brazil it will be possible to gain a more general understanding of the dynamics of subtropical ecosystems. This understanding will enable us to anticipate possible consequence of climate change and make suggestions on how to preserve the biodiversity.

To focus the research, the project will aim at disentangling the causes and document the dynamics of the late Holocene forest expansion, which may have been climatic or human induced and the dynamics may have been determined by system internal feedbacks. These different explanations can be formulated as three **competing hypotheses:**

H a) Insufficient moisture availability restricted the forest expansion in the *Araucaria* region during the early Holocene. Slowly increasing precipitation resulted initially in a higher productivity of the grassland, increasing the amount of available fuel. The resulting frequent fires limited the expansion of forest. Through chance or due to the succession of a few consecutive years without fire, groups of trees established in moist places, stabilized and expanded into the grassland. In addition to the fire frequency, increased biomass production or growth rate of trees may have defined the width of the tension zone between forest and grassland (Murphy & Bowman 2012). Thus gradually increasing precipitation would also increase the growth rate of trees favouring their establishment before a new fire kills the saplings. In particular *Araucaria angustifolia* trees have bark that is resistant to fire once they have grown tall enough and are often seen as a pioneer in previously disturbed areas.

H b) Precipitation alone limited the expansion of Araucaria forest during much of the Holocene and only a shift to moister conditions between 4 ka and 3 ka (e.g. Razik et al. 2013) permitted the spread of forest from previously established gallery forests along rivers and streams (Behling et al. 2004). This hypothesis assumes that fires were not restricting the expansion of the fire-resisting *Araucaria angustifolia* and that climate alone determined the response of the vegetation without internal feedback mechanisms.

H c) *Araucaria* seeds were such an important food source for the local population that woodlands of *Araucaria angustifolia* were planted to support the growing human population. Fires were set by humans and are largely unrelated to increase fuel availability or drought.

The available **pollen diagrams** from the *Araucaria* forest region come from small peat bogs, where shifts in sediment accumulation often hamper the analysis of dynamic processes. Moreover, sediment accumulation over the early and mid-Holocene often only amounts a few centimetres and is thus too low to obtain enough samples to characterize the fire regime and evaluate vegetation dynamics. It is therefore crucial to study sediments that allow a high resolution analysis and while lakes are rare in the region Lake Dourada (25°14'26"S 50° 2'59"W) represents one of the rare exceptions.

Previous investigations on Lake Dourada obtained a 12.2 m long sediment core that was studied sedimentologically and samples were analysed for their diatom content (Melo et al. 2000, Moro et al. 2004). These analysis and two radiocarbon dates at 11.9 and 10.6 m with ages of 13 ka and 9.7 ka indicate a constant sedimentation and demonstrate that this sediment record is an ideal choice for a high resolution analysis. Preliminary pollen analysis was conducted on samples from the same core. Although this analysis was never published, they showed excellent pollen preservation and the presence of pollen from *Araucaria* for the early Holocene (Behling personal communications).

The lake is situated at an elevation of 800 m, mean annual temperature is 18 °C and annual precipitation 1542 mm. While Lake Dourada will be the prime target for the high resolution investigation, other small basins that exist in the surroundings will be investigated as additional sources of information. The natural vegetation is classified as grassland dominated, with groups of trees and riparian forests, and thus ideally suited to study the dynamics of grassland versus forests, testing whether the alternative stable state theory can describe this system.

Counts of **charcoal particles** are available for existing palynological investigations and provide trends for the overall change in fire activity, indicating that increased burning started at different times during the Holocene and even the Late-Glacial (e.g. Jeske-Pieruschka & Behling 2012). While the slow sediment accumulation of existing records does not permit detailed insights into the fire regime, the analysis of a 10 m long sediment core, proposed here, will allow evaluating the fire frequency for the Holocene on a high resolution. It will be possible to resolve critical periods to a decadal and potentially even sub-decadal resolution. Applying cross correlations between charcoal and pollen analytical results will make it possible to study the long term fire ecology (e.g. Tinner et al. 1999) of this fire prone ecosystem and evaluate the role of fire in inhibiting the spread of trees.

Work programme

Lake Dourada offers a unique chance to carry out high resolution palaeoeclogical investigations. The results from previous investigations (Melo et al. 2000, Moro et al. 2004) will be an added benefit for the here proposed analysis. The size and depth of the lake allow coring with a hand operated Livingstone corer from a raft. Several overlapping cores will be collected from the basin. The cores will be described and documented photographically. A master sequence will be selected avoiding core breaks. Prior to any destructive analysis the cores will be scanned with the XRF-core scanner at GEOPOLAR, Bremen University. These results will provide high resolution environmental information aiding the subsequent analysis interpretations and potentially yield important proxies for past moisture availability that can be used as forcing parameter in vegetation modelling. Previous analyses indicate changes in the composition of authigenic minerals potentially due to changing moisture availability and thus lake water salinity (Moro et al. 2004).

As it is not feasible to analyse 10 m of core at decadal resolution, the cores will be initially sampled for pollen at 25 cm intervals and if macroscopic plant remains can be detected without sampling for it this material will be used for radiocarbon dating. The cores will be left intact for as long as possible and reference sections will be retained. Based on initial results and a preliminary age-depth model the further sampling strategy will be decided, including high resolution sampling across periods of forest expansion, as well as periods of apparent stability for comparison. Sampling for pollen will be carried out volumetrically, density and loss on ignition will be determined from the same depths. The full sequence will be sampled contiguously. After all high resolution sampling is completed large volume samples will be taken to search for macrofossils that are apt for radiocarbon dating to establish a precise chronology.

Pollen preparation will follow the standard procedures (e.g. Bennett and Willis 2002) including the addition of *Lycopodium* tablets to estimate pollen accumulation rates. Pollen identification will be supported by the extensive reference collection held at the Department of Palynology and Climate Dynamics as well as a digital collection of images from fossil pollen types and local expertise provided by Hermann Behling. Samples for macro-charcoal analysis will be prepared following Rhodes (1998), using potassium hydroxide and weak hydrogen peroxide solution and gentle sieving through a 150 µm mesh. Residue not passing through the sieve will be examined using a stereomicroscope at 40x magnification. The concentration of charcoal partials will be converted to an accumulation rates as a proxy for past biomass burning.

Based on at least 15 radiocarbon age determinations an age-depth relationship will be constructed through Bayesian age modelling with Bacon (Blaauw & Christen 2011). Exploratory data analysis will be employed to visualize the major trends in the data. Canonical ordination will be used to explore trends between pollen charcoal and XRF data. These analyses will be carried out in R (R Development Core Team, 2013) using mainly the Vegan package (Oksanen et al. 2011). To establish the fire history, the charcoal time series will be analysed using CharAnalysis 0.9 software (Higuera et al., 2009; 2010; http://CharAnalysis.googlepages.com). Cross correlations will be carried out between proportions and accumulation rates of important pollen types and charcoal accumulation rates.

This high resolution multi proxy analysis will provide a milestone in palaeoecological research for the Mata Atlântica biome and thus the results will be publishable in leading disciplinary as well as interdisciplinary journals. A minimum of two manuscripts are envisaged to result directly from this work package.

Bibliography

Behling H, Bauermann SG, Neves PCP (2001) Holocene environmental changes in the Sao Francisco de Paula region, southern Brazil. Journal of South American Earth Sciences 14 (6):631-639.

Behling H, Negrelle RRB (2006) Vegetation and pollen rain relationship from the tropical Atlantic rain forest in southern Brazil. Brazilian Archives of Biology and Technology 49 (4):631-642.

Behling H, Pillar VD (2007) Late Quaternary vegetation, biodiversity and fire dynamics on the southern Brazilian highland and their implication for conservation and management of modern Araucaria forest and grassland ecosystems. Philosophical Transactions of the Royal Society B-Biological Sciences 362 (1478):243-251.

Behling H, Pillar VD, Orloic L, Bauermann SG (2004) Late Quaternary Araucaria forest, grassland (Campos),fire and climate dynamics, studied by high-resolution pollen, charcoal and multivariate analysis of the Cambara do Sul core in southern Brazil. Palaeogeography Palaeoclimatology Palaeoecology 203 (3-4):277-297.

Bennett K, Willis K (2002) Pollen. In: Tracking environmental change using lake sediments. Springer, pp 5-32.

Blaauw M, Christen JA (2011) Flexible paleoclimate age-depth models using an autoregressive gamma process. Bayesian Analysis 6 (3):457-474.

Blanco, CC, Scheiter S, Sosinski E, Fidelis A, Anand M, Pillar VD (2014) Feedbacks between vegetation and disturbance processes promote long-term persistence of forest–grassland mosaics in south Brazil. Ecological Modelling 291:224-232.

Bunting MJ, Middleton R (2009) Equifinality and uncertainty in the interpretation of pollen data: the Multiple Scenario Approach to reconstruction of past vegetation mosaics. Holocene 19 (5):799-803.

Cruz FW, Burns SJ, Karmann I, Sharp WD, Vuille M (2006) Reconstruction of regional atmospheric circulation features during the late Pleistocene in subtropical Brazil from oxygen isotope composition of speleothems. Earth and Planetary Science Letters 248 (1-2):495-507.

Cruz FW, Karmann I, Viana O, Burns SJ, Ferrari JA, Vuille M, Sial AN, Moreira MZ (2005) Stable isotope study of cave percolation waters in subtropical Brazil: Implications for paleoclimate inferences from speleothems. Chemical Geology 220 (3-4):245-262.

Davis MB (2000) Palynology after Y2K - Understanding the source area of pollen in sediments. Annual Review of Earth And Planetary Sciences 28:1-18.

Flantua SGA, Hooghiemstra H, Grimm E, Markgraf V (2013) Updated Latin American Pollen Database: Version 2013 in preparation for NEOTOMA. PAGES News 21(2):88.

Gaillard MJ, Sugita S, Bunting MJ, Middleton R, Brostrom A, Caseldine C, Giesecke T, Hellman SEV, Hicks S, Hjelle K, Langdon C, Nielsen AB, Poska A, von Stedingk H, Veski S, Members P (2008) The use of modelling and simulation approach in reconstructing past landscapes from fossil pollen data: a review and results from the POLLANDCAL network. Vegetation History and Archaeobotany 17 (5):419-443.

Giesecke T, Ammann B, Brande A (2014) Palynological richness and evenness: insights from the taxa accumulation curve. Vegetation History and Archaeobotany 23:217-228.

Giesecke T, Fontana SL, van der Knaap WO, Pardoe HS, Pidek IA (2010a) From early pollen trapping experiments to the Pollen Monitoring Programme. Vegetation History and Archaeobotany 19 (4):247-258.

Giesecke T, Hickler T, Kunkel T, Sykes MT, Bradshaw RHW (2007) Towards an understanding of the Holocene distribution of *Fagus sylvatica* L. Journal of Biogeography 34 (1):118-131.

Giesecke T, Miller PA, Sykes MT, Ojala AEK, Seppa H, Bradshaw RHW (2010b) The effect of past changes in inter-annual temperature variability on tree distribution limits. Journal of Biogeography 37 (7):1394-1405.

Grace J, San Jose J, Meir P, Miranda HS, Montes RA (2006) Productivity and carbon fluxes of tropical savannas. Journal of Biogeography 33 (3):387-400.

Higgins SI, Scheiter S (2012) Atmospheric CO2 forces abrupt vegetation shifts locally, but not globally. Nature 488 (7410):209-212.

Higuera PE, Brubaker LB, Anderson PM, Hu FS, Brown TA (2009) Vegetation mediated the impacts of postglacial climate change on fire regimes in the south-central Brooks Range, Alaska. Ecological Monographs 79 (2):201-219.

Higuera PE, Gavin DG, Bartlein PJ, Hallett DJ (2010) Peak detection in sediment-charcoal records: impacts of alternative data analysis methods on fire-history interpretations. International Journal of Wildland Fire 19 (8):996-1014.

Hirota M, Holmgren M, Van Nes EH, Scheffer M (2011) Global Resilience of Tropical Forest and Savanna to Critical Transitions. Science 334 (6053):232-235.

Iriarte J, Behling H (2007) The expansion of Araucaria forest in the southern Brazilian highlands during the last 4000 years and its implications for the development of the Taquara/Itararé Tradition. Environmental Archaeology 12 (2): 115-127.

Jeske-Pieruschka V, Behling H (2012) Palaeoenvironmental history of the Sao Francisco de Paula region in southern Brazil during the late Quaternary inferred from the Rincao das Cabritas core. Holocene 22 (11):1251-1262.

Jeske-Pieruschka V, Fidelis A, Bergamin RS, Velez E, Behling H (2010) *Araucaria* forest dynamics in relation to fire frequency in southern Brazil based on fossil and modern pollen data. Review of Palaeobotany and Palynology 160 (1-2):53-65.

Ledru MP, Mourguiart P, Riccomini C (2009) Related changes in biodiversity, insolation and climate in the Atlantic rainforest since the last interglacial. Palaeogeography Palaeoclimatology Palaeoecology 271 (1-2):140-152.

Lenton TM, Held H, Kriegler E, Hall JW, Lucht W, Rahmstorf S, Schellnhuber HJ (2008) Tipping elements in the Earth's climate system. PNAS 105 (6):1786-1793.

Matthias I, Semmler MSS, Giesecke T (2015) Pollen diversity captures landscape structure and diversity. Journal of Ecology. 103: 880-890.

Matthias I, Giesecke T (2014) Insights into pollen source area, transport and deposition from modern pollen accumulation rates in lake sediments. Quaternary Science Reviews 87 (1): 12-23.

Matthias I, Nielsen AB, Giesecke T (2012) Evaluating the effect of flowering age and forest structure on pollen productivity estimates. Vegetation History and Archaeobotany 21 (6):471-484.

Melo MS, Giannini PCF, Pessenda LCR (2000): Gênese e evolução da Lagoa Dourada, Ponta Grossa, PR. Revista do Instituto Geológico, São Paulo 21(1/2), 17-31.

Miller PA, Giesecke T, Hickler T, Bradshaw RHW, Smith B, Seppa H, Valdes PJ, Sykes MT (2008) Exploring climatic and biotic controls on Holocene vegetation change in Fennoscandia. Journal of Ecology 96 (2):247-259.

Moro RS, Bicudo CED, de Melo MS, Schmitt J (2004) Paleoclimate of the late Pleistocene and Holocene at Lagoa Dourada, Parana State, southern Brazil. Quaternary International 114:87-99.

Murphy BP, Bowman DMJS (2012): What controls the distribution of tropical forest and savanna? Ecology Letters 15, (7) pp. 748–758.

Oksanen J, Blanchet FG, Kindt R, Legendre P, Minchin PR, et al. (2011) vegan: Community Ecology Package.

Overbeck GE, Muller SC, Fidelis A, Pfadenhauer J, Pillar VD, Blanco CC, Boldrini, II, Both R, Forneck ED (2007) Brazil's neglected biome: The South Brazilian Campos. Perspectives in Plant Ecology Evolution and Systematics 9 (2):101-116.

R Development Core Team (2013) R: A language and environment for statistical computing. R Foundation for Statistical Computing.
Ratajczak Z, Nippert JB (2012) Comment on "Global Resilience of Tropical Forest and Savanna to Critical Transitions". Science 336 (6081).
Razik S, Chiessi CM, Romero OE, von Dobeneck T (2013) Interaction of the South American Monsoon System and the Southern Westerly Wind Belt during the last 14 kyr. Palaeogeography Palaeoclimatology Palaeoecology 374:28-40.
Scheffer M, Carpenter SR (2003) Catastrophic regime shifts in ecosystems: linking theory to observation. Trends in Ecology & Evolution 18 (12):648-656.
Scheiter S, Higgins SI (2009): Impacts of climate change on the vegetation of Africa: an adaptive dynamic vegetation modelling approach (aDGVM). Global Change Biology 15, 2224-2246.
Scheiter S, Higgins SI, Osborne CP, Bradshaw C, Lunt D, Ripley BS, Taylor LL, Beerling DJ (2012): Fire and fire-adapted vegetation promote C4 expansion in the late Miocene. New Phytologist 195, 653-666.
Staver AC, Archibald S, Levin SA (2011) The Global Extent and Determinants of Savanna and Forest as Alternative Biome States. Science 334 (6053):230-232.
Sternberg LDL (2001) Savanna-forest hysteresis in the tropics. Global Ecology and Biogeography 10 (4):369-378.
Tinner W, Hubschmid P, Wehrli M, Ammann B, Conedera M (1999) Long-term forest fire ecology and dynamics in southern Switzerland. Journal of Ecology 87 (2):273-289.
Van Nes EH, Holmgren M, Hirota M, Scheffer M (2012) Response to Comment on "Global Resilience of Tropical Forest and Savanna to Critical Transitions". Science 336 (6081).
Wang R, Dearing JA, Langdon PG, Zhang EL, Yang XD, Dakos V, Scheffer M (2012) Flickering gives early warning signals of a critical transition to a eutrophic lake state. Nature 492 (7429):419-422.
Wang XF, Auler AS, Edwards RL, Cheng H, Ito E, Solheid M (2006) Interhemispheric anti-phasing of rainfall during the last glacial period. Quaternary Science Reviews 25 (23-24):3391-3403.
Wang XF, Auler AS, Edwards RL, Cheng H, Ito E, Wang YJ, Kong XG, Solheid M (2007) Millennial-scale precipitation changes in southern Brazil over the past 90,000 years. Geophysical Research Letters 34 (23).
Warman L, Moles AT (2009) Alternative stable states in Australia's Wet Tropics: a theoretical framework for the field data and a field-case for the theory. Landscape Ecology 24 (1):1-13.