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Vegetation dynamics on mosaics of Campos and *Araucaria* forest between 1974 and 1999 in Southern Brazil

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Abstract: A mosaic of Campos grassland and *Araucaria* forest characterizes the vegetation of the Southern Brazilian highland plateau. Palaeoecological evidence indicates that forest expansion over grassland initiated after the mid Holocene, when climate changed towards present day cool and moist conditions. In this paper, we discuss landscape level changes that occurred on vegetation patterns after grazing and fire exclusion in a mosaic of Campos and *Araucaria* forest in Southern Brazil. The analysis of aerial photographs from 1974 and 1999 showed alterations on grassland communities under grazing and fire exclusion, especially pronounced shrub establishment near the edge of the forest. Considering the change in the cover of vegetation classes relative to the total altered cover in all classes from 1974 to 1999, the most prominent alterations were: 48% from grassland with tussock grasses dominance (GRA) to grassland with shrubs (GSR), 24% from GRA to grassland with tall shrubs (GTS), 16% from GSR to GTS and 9% from GTS to forest (FOR). Considering the alteration relatively to the vegetation cover in 1974, the most relevant changes were: 44% from GSR to GTS and 94% from GTS to FOR. These observations support a directional forest expansion over grassland under grazing and fire exclusion.

Abbreviations: ANT – anthropogenic vegetation, FOR – forest, GRA – grassland, GSR – grassland with shrubs, GTS – grassland with tall shrubs.

Nomenclature: Cronquist (1984).

Introduction

The occurrence of natural grassland under humid climatic conditions that would potentially support forest cover is an ecological puzzle (Lindman 1906, Walter 1967, Box 1986, Pillar and Quadros 1997, Pillar 2003). A mosaic of Campos grassland and forest formations characterizes the Southern Brazilian highland plateau (Rambo 1956a, 1961, Klein 1975). The lower altitude slopes (<500 m above sea level) are potentially covered by dense ombrophilous forest (Atlantic rain forest) in the east and by subtropical, seasonal forest, with origins in the Paraná River basin, at the southernmost edge of the plateau (30º S latitude) and westbound and southbound river valleys. At higher altitudes, Campos grassland predominates, intermingling with riparian forest and patches of mixed ombrophilous forest with the conspicuous *Araucaria angustifolia* as emergent tree (*Araucaria* forest). It is an interesting question whether forest expands over grassland under these conditions.

Phytogeographic (Rambo 1953, 1956ab, Klein 1975) and palaeopollen evidence (Behling 2002, Behling et al. 2004) indicate that Campos are relics of cooler and dryer glacial and postglacial phases that preceded the present-day forests, and are not the result of climate-driven shrinking of the forest or anthropogenic forest destruction. Furthermore, fire and grazing regimes may have contributed to the maintenance of grassland and differential forest expansion patterns, resulting in the actual vegetation mosaic (Behling 1995, 1997ab, 2002, Behling et al. 2004, Pillar and Quadros 1997, Pillar 2003). The expansion of *Araucaria* forests from refugia in deep valleys and riverine areas over Campos is seen as a recent process starting ca. 4000 years before present (BP) and accelerated around 1000 years BP, probably in response to the emergence of a moister climate (Behling 2002, Behling et al. 2004). The climate, compared to the current conditions, was colder and drier until about 10,000 years BP, warmer and drier from 10,000 to about 4000 years BP and followed by a cool and moist climate to the present. Presently, in the state of Rio Grande do Sul the mean annual precipitation varies from 1235 mm in the south to 2162 mm on the north-eastern plateau; mean annual temperatures range from 15 to 20 ^{o}C, with mean temperatures in the coldest month ranging from 11 to 14 ^{o}C. It is unclear, however, if and under which conditions of fire and grazing regimes and landscape features *Araucaria* forest expansion over Campos could occur.

Kadmon and Harari-Kremer (1999) pointed to the relevance of historical aerial photographs in vegetation dynamics studies. These records provide the best source of information available to study long-term dynamics, since they combine high spatial resolution, large spatial extent and long term coverage. Landscape level studies, based on aerial photographs, indicated woody expansion over grasslands in several ecosystems, mainly savannas (Archer et al. 1988, Bowman et al. 2001, Carmel and Kadmon 1999, Silva et al. 2001) and grassland-forest ecotones in subtropical wet regions (Mast et al. 1997). Furthermore, they conclude that fire and grazing are important factors inversely proportional to the expansion of woody vegetation.

In this paper, based on historical aerial photographs, we analyze vegetation dynamics that occurred after grazing and fire exclusion in a study site presenting a mosaic of Campos and *Araucaria* forest, in the highland plateau of Rio Grande do Sul state in Southern Brazil.

Methods

Study site

We considered a 540 ha mapped polygon limited by coordinates 50°22’69” W, 29°47’66” S; 50°22’68” W, 29°49’29” S; 50°19’61” W, 29°47’64” S; and 50°19’58” W, 29°49’27” S, at the eastern edge of the highland plateau, from ca. 650 to 900 m above sea level, in the municipality of São Francisco de Paula, Rio Grande do Sul state, Brazil (Fig. 1). The area belongs to the Center for Research and Nature Conservation Pró-Mata – CPCN Pró-Mata (466 ha) and to Três Estrelas Farm (74 ha). This site is a mosaic of *Araucaria* forest and Campos grassland, partly forming a nearly isolated patch surrounded by forest. The grassland within CPCN Pró-Mata has not been burned or grazed since 1994. In contrast, the grassland in Três Estrelas Farm has been managed with extensive cattle grazing and periodic burning.

Vegetation mapping

Aerial photographs taken in 1974 (1:20,000) and in 1999 (1:10,000), obtained from the state road department (DAER) and Catholic University of Rio Grande do Sul (PUCRS) respectively, were used for vegetation description. First, the vegetation patches in 1974 and 1999 were identified and classified into physiognomic categories using stereoscopy. *In situ* verifications were made in 2001. Second, vegetation maps were digitized based on one aerial photograph from 1974, previously georeferenced with 20 control points, and on a mosaic of rectified aerial photographs from 1999. Conspicuous landmarks, such as roads and isolated trees, were used to ensure georeferencing accuracy. The vector files generated were converted to a raster system, with resolution of 1 m^2. The IDRISI32 software was used for cross tabulation and data extraction (Eastman 2001).

Data analysis

A comparative approach was used to identify vegetation cover changes, based on the parameters described below. Areas classified as anthropogenic vegetation (0.8 ha) in any year were not considered for the analysis.

The map of stable vegetation class *i* is:

$$S_i = C_{i1} \cap C_{i2}$$

where S_i is the mapped vegetation class *i* in 1974 (C_{i1}) that remained as such in 1999 (C_{i2}).

The map of expanded vegetation class *i* is defined as:

$$E_i = C_{i2} - S_i$$

Figure 1. Location of the study area in South America.

Table 1. Cover of vegetation classes (i) in 1974 (1) and 1999 (2); absolute and relative terms of stability (CS_i), expansion (CE_i) and retraction (CR_i). Vegetation classes: Grassland (GRA), Grassland with shrubs (GSR), Grassland with tall shrubs (GTS) and Forest (FOR).

	CC_{i1}	CC_{i2}	CS_i	CE_i	CR_i	$\frac{CS_i}{CS_.}$	$\frac{CS_i}{CC_{i1}}$	$\frac{CE_i}{CE_.}$	$\frac{CE_i}{CC_{i1}}$	$\frac{CR_i}{CR_.}$	$\frac{CR_i}{CC_{i1}}$
	(ha)					(%)					
GRA	148.6	134.5	134.2	0.3	14.5	25.8	90.3	1.7	0.2	72.9	9.7
GSR	7.2	13.3	3.7	9.6	3.4	0.7	52.0	48.5	134.4	17.3	48.0
GTS	1.9	8.0	0.1	7.9	1.8	0.1	5.8	39.7	407.5	9.2	94.2
FOR	381.5	383.4	381.3	2.0	0.1	73.4	100.0	10.1	0.5	0.6	0.1
Total	539.2	539.2	519.3	19.8	19.8	100.0	------	100.0	-----	100.0	-----

where E_i is the mapped vegetation class i in 1999 that was not in the same class in 1974.

The map of retracted vegetation class i is obtained as:

$$R_i = C_{i1} - S_i$$

where R_i is the mapped vegetation class i in 1974 that was not in the same class in 1999.

The map of alterations from class i to class j is:

$$A_{ij} = C_i \cap C_j$$

where A_{ij} is the mapped vegetation class i in 1974 that was class j in 1999 ($i \neq j$).

Based on these maps, cover values of S_i, E_i, R_i and A_{ij} were obtained for each vegetation class i and class combination ij (CS_i, CE_i, CR_i and CA_{ij}). Dividing these by their corresponding totals ($CS_.$, $CE_.$, $CR_.$ and $CA_{..}$) generated relative terms in the context of all vegetation classes for each parameter. Note that $CE_. = CR_. = CA_{..}$ since retraction in one class corresponded, by definition, to expansion in another. Furthermore, dividing CS_i, CE_i, CR_i and CA_{ij} by the cover of class i in 1974 (CC_{i1}) generated relative terms for stability, expansion, retraction and alteration in the context of each vegetation class.

Results

The vegetation was categorized into five physiognomic classes (Table 1; Figs 2 and 3), which occurred in both years, as follows. Grassland (GRA): herbaceous stratum with tussock grasses dominance, mainly *Andropogon lateralis,* 10 to 60 cm high. Grassland with shrubs (GSR): shrub patches of *Calea phyllolepis* and *Baccharis* spp. within a grass matrix as in GRA, 50 to 130 cm high. Grassland with tall shrubs (GTS): patches of *Baccharis uncinella* (dominant species) and *Baccharis mesoneura*, 150 to 300 cm high, forming a shrub canopy above a grassy or shrub-grassy stratum as in GRA or GSR. Forest (FOR): *Araucaria* forest, with high abundance of broadleaf species (e.g., *Myrcia* spp., *Ilex* spp., *Nectandra* spp. and *Ocotea* spp.). Anthropogenic vegetation (ANT): plantation cropland in 1974 and afforestation in 1999, which were not considered in the analysis.

The general trend was high vegetation stability, since 519 ha was covered by the same vegetation class from 1974 to 1999. Comparing the stable cover of each vegetation class with the total stable cover, FOR (73%) and GRA (26%) had the highest values. Considering stability in the context of each class, FOR and GRA had high stability (more than 90%), GSR intermediate stability (52%) and GTS low stability (6%) (Table 1; Fig. 2).

Despite the small total altered area (ca. 20 ha), alteration of vegetation classes differed sharply (Table 1; Fig. 2). The expansion of GTS and GSR corresponded respectively to about 40% and 48% of the total expanded cover. Compared to 1974, GTS cover in 1999 expanded about 4 times and GSR about 1.3 times in the same period. Considering the retracted cover, GRA represented 73% of the total retracted cover, while GTS (94%) and GSR (48%) had the highest retraction compared to 1974.

The cross tabulation of the vegetation maps evidenced twelve vegetation directions, which account for three quarters of the possible combinations (Fig. 3). Four directions correspond to stable covers, as already described. The other directions indicate changes in vegetation cover class (Table 2). GRA to GSR (48%), GRA to GTS (24%) and GSR to GTS (16%) were the most relevant directions relatively to the total altered cover, while GTS to FOR

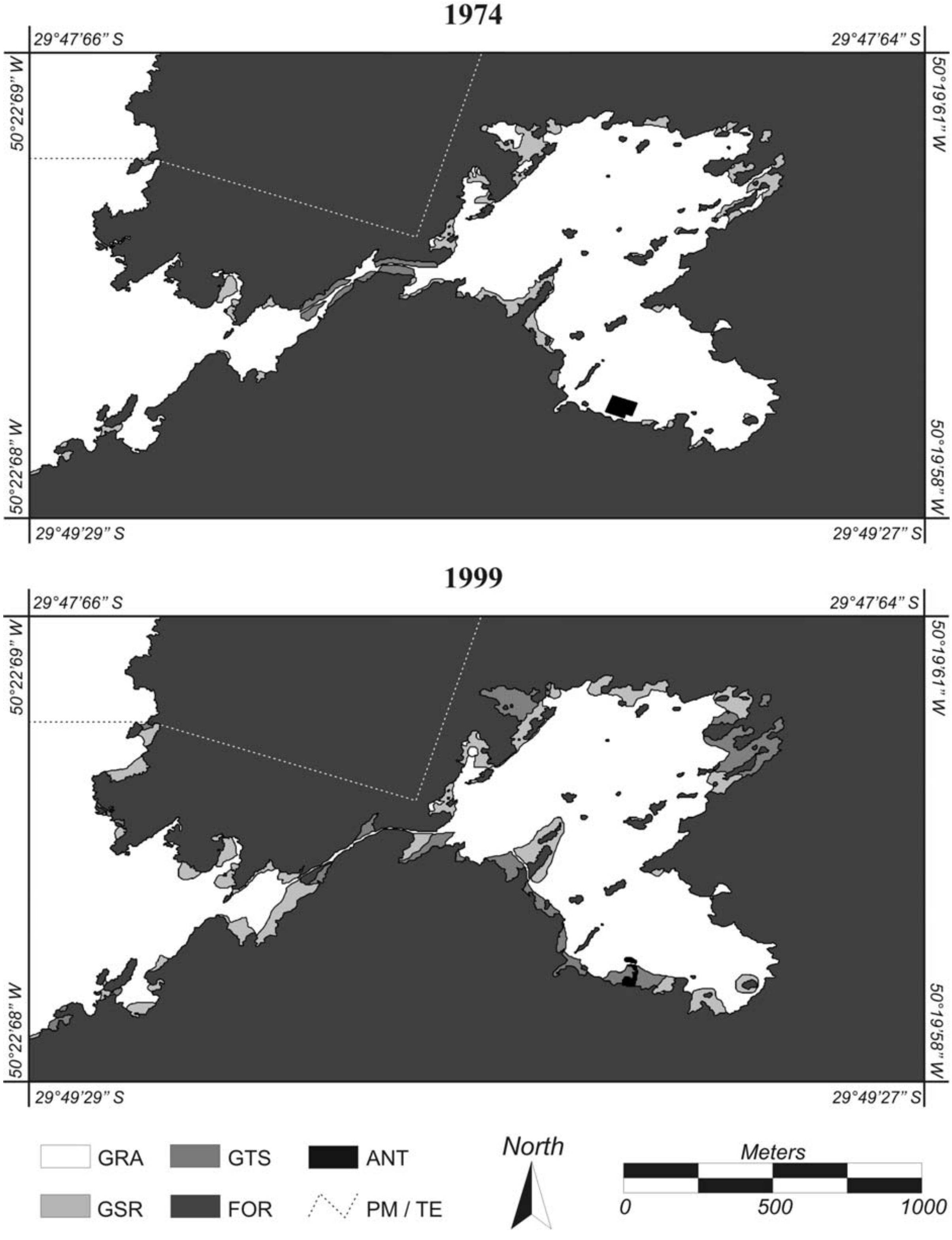

Figure 2. Vegetation maps of 1974 and 1999. Legend: Grassland (GRA), Grassland with shrubs (GSR), Grassland with tall shrubs (GTS), Forest (FOR), Anthropogenic vegetation (ANT), and boundary between CPCN Pró-Mata and Três Estrelas Farm (PM / TE). The farm is located at the northwestern sector.

Table 2. Alteration direction cover (*CA*) of vegetation classes (from *i* to *j*, $i \neq j$) from 1974 to 1999, compared to cover of class *i* in 1974 (CA_{i1}) and total cover of alteration directions ($CA_{..}$). Vegetation classes: Grassland (GRA), Grassland with shrubs (GSR), Grassland with tall shrubs (GTS) and Forest (FOR).

	$\frac{CA_{ij}}{CA_{..}}$ (%)	$\frac{CA_{ij}}{CC_{i1}}$ (%)
GRA to GSR	48.2	6.4
GRA to GTS	23.7	3.2
GRA to FOR	1.0	0.1
GSR to GRA	1.4	3.8
GSR to GTS	16.0	44.2
GTS to FOR	9.2	94.2
FOR to GRA	0.3	0.1
FOR to GSR	0.3	0.1

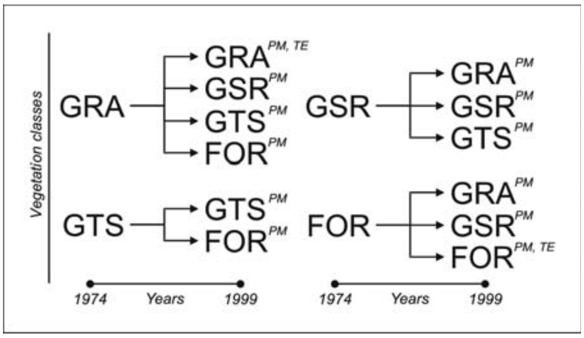

Figure 3. Directions of vegetation dynamics from 1974 to 1999 occurred at CPCN Pró-Mata (PM) and Trȩs Estrelas Farm (TE). Vegetation classes: Grassland (GRA), Grassland with shrubs (GSR), Grassland with tall shrubs (GTS), Forest (FOR).

(94%) and GSR to GTS (44%) were the most relevant ones relatively to the vegetation cover in 1974. Alterations on FOR were small compared to the total altered cover, as well as to its cover in 1974.

The high substitution rate (94%) from GTS to FOR should be considered carefully. It is possible that some GTS areas in 1974 were actually intermediate stages of forest recovery process, due to deforestation in the narrow grassland belt along a road leading to the isolated grassland area, having faster arboreal establishment than natural shrubby herbaceous vegetation.

CPCN Pró-Mata and Três Estrelas Farm differed markedly in vegetation dynamics patterns. The twelve vegetation directions were present in the former, while only the stable directions GRA to GRA and FOR to FOR occurred in the latter (Figs 2 and 3).

Discussion

Forest (FOR) and grassland (GRA) patches were highly stable except at their edges. It is evident in the CPCN Pró-Mata area that under grazing and fire exclusion since 1994 most of the vegetation alterations occurred at the edges between forest and grassland where other grassland cover classes (with short or tall shrubs) were observed. Furthermore, the direction alterations were predominantly towards the increase of shrub and, to a lesser extent, towards the increase of forest cover.

Studies concerning vegetation dynamics on landscape scale produced similar results, albeit in different ecosystems (Bowman et al. 2001, Carmel and Kadmon 1999, Mast et al. 1997, Silva et al. 2001). In general, these studies ascribe wood shifts over grassland areas in favorable climatic conditions, and consider grazing and fire as hindering the expansion of woody vegetation. Our records support these results since Três Estrelas Farm (managed with frequent fire and cattle grazing) showed high stability compared to CPCN Pró-Mata (under conservation since 1994).

It is well known that grazing and fire exclusion leads to an increase in shrub cover in Campos (Boldrini and Eggers 1996, Pillar and Quadros 1997). Grazing influenced the Campos flora evolution; fossil records indicate the existence of large grazing mammals (Equidae, Camelidae and Cervidae) in this region until 8000 yr. BP (Bombim and Klamt 1975, Kern 1994). After domestic cattle were introduced in the Campos early in the 18^{th} Century (Porto 1954), it is likely that shrub cover decreased in general. Charcoal records from peat in mires show that Campos burning was common in the plateau region since 7,000 yr. BP and that *Araucaria* forest was not flammable (Behling 1995, 1997ab, Behling et al. 2004). Furthermore, experimental evaluation supports that Campos is resilient after disturbance by fire (Quadros and Pillar 2001). Klein (1960) argues that adaptations to dry climate conditions (e.g., xylopodia) would favor grassland maintenance under fire regimes, hindering forest expansion.

Considering that palaeopollen data (Behling 2002) substantiate forest expansion in the highland plateau since 4,000 yr. BP under the prevailing cool and moist climate conditions, we postulate that the observed shrub increase near the forest edge is a first step towards forest expansion. Grassland was probably highly stable between 1974 and 1994, due to the prevailing intense grazing and frequent burning regime (as observed on Três Estrelas Farm). Since grazing and fire exclusion started in 1994, the main vegetation changes actually occurred during a five-year period until 1999.

Shrub establishment on grassland and possibly later arboreal colonization characterized a directional process on patches near to forest edges, suggesting a general trend from natural grassland towards forest. Our records represent the initial landscape level dynamics of *Araucaria* forest expansion over Campos grassland after grazing and fire exclusion. More extent landscape data sets, as well as community and population level studies would provide more conclusive results concerning the dynamics of these forest-grassland transitions.

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