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Biophysical delineation of grassland ecological systems in the State of Rio Grande do Sul, Southern Brazil

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ABSTRACT – Different types of grasslands cover much of the Earth's surface. At a closer look, these grasslands present unique and specific floristic and biophysical characteristics. Following an ecosystem approach, we propose a new regionalization of the grassland landscapes that correspond to two thirds of the surface of the state of Rio Grande do Sul. The biophysical factors that control energy and water availability for living organisms are the basis of our analysis. The dominant macroclimate is humid subtropical, but at a meso-scale (1:250,000), additional constraints such as relief and soils modulate this availability. With the support of Geographic Information Systems it was possible to delimit ten grassland ecological systems based on the flora and its relationship to the respective biophysical characteristics as derived from elevation, slope, and soil data. Our analysis adds the currently available floristic data on grasslands to previously established vegetation maps of the same geopolitical territory. Therefore, we extend the hitherto limited understanding of the complexity of the grassland systems. The results add new knowledge to the regionalization of the grassland vegetation of southern Brazil. The proposed delimitation provides a framework for various purposes, such as ecological and biodiversity studies, conservation and mitigation strategies, and sustainable land use.

Keywords: ecoregion, environmental management, landscape, regionalization, vegetation.

RESUMO – **Delimitação biofísica de sistemas ecológicos campestres no Estado do Rio Grande do Sul, sul do Brasil**. Diferentes tipos de campos cobrem uma grande parte da superfície da Terra. Sob um olhar atento, estes campos apresentam características florísticas e biofísicas únicas e específicas. Seguindo uma abordagem ecossistêmica, propomos uma nova regionalização das paisagens campestres que correspondem a dois terços da superfície do estado do Rio Grande do Sul, no sul do Brasil. Os fatores biofísicos que controlam a energia e a disponibilidade de água para os organismos vivos são a base de nossa análise. O macroclima dominante é subtropical úmido, mas em mesoescala, (1:250.000), condicionantes adicionais como relevo e solos modulam essa disponibilidade. Reclassificamos os dados de altitude, declividade e solos para relacionar os fatores biofísicos com a distribuição dos ecossistemas campestres. Com apoio de Sistemas de Informação Geográfica (SIG) foi possível delimitar dez sistemas ecológicos campestres com base na descrição florística e sua relação com as respectivas características biofísicas. Nossa análise acrescenta os dados florísticos atualmente disponíveis sobre os campos aos mapas de vegetação previamente estabelecidos do mesmo território geopolítico. Portanto, amplificamos a compreensão da complexidade até agora limitada dos sistemas campestres. Os resultados acrescentam novos conhecimentos à regionalização da vegetação dos campos do sul do Brasil. A delimitação proposta fornece uma estrutura para vários propósitos, como estudos de biodiversidade e ecologia, estratégias de conservação e mitigação, e usos sustentáveis do solo.

Palavras-chave: ecorregião, paisagem, planejamento ambiental, regionalização, vegetação.

INTRODUCTION

Grassland ecosystems occur in all continents but the Antarctic, covering between 41 and 56 million km² (White *et al.* 2000). They vary considerably from one region to another of the globe as an expression of their biogeographic history, as well as a consequence of distinct local environmental factors, such as climate, relief, and soil (Chebataroff 1968, Bailey 1987, Omernik & Griffith 2014, Olson *et al.* 2000). In South America, the tropical, subtropical, and temperate grasslands cover about 4.5 million km², in which 750,000 km² correspond to the Rio de la Plata Grasslands in Argentina, Uruguay, and Brazil (Soriano *et al.* 1992). The north-eastern corner of this grassland is located in Southern Brazil, covering 193,000 km², 68 % of the State of Rio Grande do Sul.

Palynological studies in Rio Grande do Sul showed that grasslands are the dominant vegetation in this area since the Pleistocene, 42,000 cal yr BP (Behling *et al.* 2004, Behling *et al.* 2005). By the end of the last glacial period, which indicates the beginning of the Holocene (11,500 cal yr BP), a cold and dry climate became gradually warmer. Around 4,000 cal yr BP, the increase in humidity allowed the establishment of shrub and tree vegetation. The end of the dry period and the humid conditions observed since 1,500 to 1,000 cal yr BP favoured the recent expansion of Araucaria forests over the grasslands on the top of the highlands (Behling *et al.* 2004, Behling *et al.* 2009). The state of Rio Grande do Sul, on the eastern coast of South America, at a mean latitude of 30° S, presents elements originated from three biogeographic provinces, namely Atlantic/Paranense (wet tropical), Chacoan (dry tropical), and Pampean (dry temperate) (Cabrera & Willink 1980). The climate fluctuations seem to have been the main factor controlling the vegetation presence in this landscape (Waechter 2002).

Several authors described the grasslands of Rio Grande do Sul in the last century, relating the local vegetation physiognomy to the respective landscape characteristics (Rambo 1956, Chebataroff 1968, Lindman 1974). These studies were followed by further floristical surveys, allowing the characterization of the flora of different plant communities and relating them to biophysical conditions (Kämpf *et al.* 1976, Boldrini & Miotto 1987, Boldrini 1997, Boldrini *et al.* 1998, Caporal & Boldrini 2007, Boldrini *et al.* 2008, Boldrini *et al.* 2009, Freitas *et al.* 2009). For the present study, the work of Boldrini (2009) is a milestone. She summarized the previous studies/surveys, identifying and describing eight different grassland ecosystems based on the association of plant communities to their respective local relief and soil conditions. Subsequently, Boldrini & Longhi-Wagner (2011) improved the floristic characterization. These studies represented a step towards a delineation of the grasslands, which recognized their unique characteristics and diversity.

In this work, we translate the relationships of grassland plant communities with the relief and soil of Rio Grande do Sul as described by Boldrini (2009) into a map of energy and water availability-conditioning ecosystems. We generated our ecosystems map using the approach of Bailey (1987), in which the relief- and soil-limiting availability of energy and water are proxies of the biophysical environment at the mesoscale. We described the spatial and biophysical characteristics of the territory by providing elevation, slope, and soil maps, which establish the limits of the occurrence of specific grasslands, and for understanding their spatial patterns, and their respective causal mechanisms (Bailey 2009). Boundary tracing requires the distribution of ecosystems as an expression of biophysical constraints and geospatial support. Most published studies have used basic maps containing the main features of the physical environment to draw limits. In general, the cartographic scale of such maps is small because they cover relatively large areas, restricting the level of achieved details (Hueck & Seibert 1981, IBGE 1986, Soriano *et al.* 1992). However, the increasing availability of digital geospatial data on different aspects of the Earth's surface, and the easy access to computational technologies for their processing, such as Geographic Information Systems (GIS), offer new mapping possibilities (Longley *et al.* 2013, Oyarzabal *et al.* 2018). These resources and the detailed description of the vegetation improve the knowledge of the spatial and temporal distribution patterns of biological species (Hirzel *et al.* 2002, Verburg & Veldkamp 2004, Sangermano *et al.* 2015).

In the present study, we propose a renewed delimitation of the different grassland landscapes, as applied to the territory of the state of Rio Grande do Sul, Brazil. We based our work on the characterization of grassland physiognomies as described by Boldrini (2009) and a hierarchical, ecological, mesoscale-level analysis, according to Bailey (1987). The fundamental assumption of our proposal is that the distribution of grassland ecosystems follows a set of environmental, biophysical rules. The elevation acts as a reducing factor of the air temperature related to the thermal conditions observed at sea level at the same latitudinal range (Almeida 2016). As the elevation increases, the atmosphere becomes less dense, gradually retaining less long-wave energy radiation. Lower temperatures at higher elevation limit the growth of plant species more sensitive to low temperatures, modulating the composition of plant communities present at different levels (Bonan 2015). The slope influences the proportion of rainwater that infiltrates the soil at a given location and the erosion rate due to runoff. The gentler the terrain slope, the higher is the chance for rainwater to infiltrate into the soil to the detriment of runoff (Wondzell *et al.* 1996, Wilson & Gallant 2000, Romano & Chirico 2004, Moeslund *et al.* 2013). Furthermore, the soil modulates the climatic elements through its physical characteristics and favours or limits the growth of some plants due to their physical and chemical features (Flores *et al.* 2007). With the help of soil information from previous published surveys and soil maps, we reinterpreted the soil classes into limiting factors for plant development.

With these rules, we interpreted the values of elevation, slope, and characteristics of soil types as biophysical proxies that reflect the availability of water and energy for defining the boundaries of the different grassland ecosystems. According to our present study, the grassland area of the state of Rio Grande do Sul, Brazil comprises ten grassland ecological systems. Our biophysical analysis adds the currently available floristic data on grasslands to the previously established vegetation maps of the same geopolitical territory (IBGE 2004), therefore expanding the understanding of the so far limited-perceived grassland complexity.

MATERIAL AND METHODS

The area of this study is the state of Rio Grande do Sul, whose extreme coordinates lie between the latitudes 27° 05' S and 33° 45' S, and the longitudes 49° 41' W and 57° 38' W (Fig. 1). In this latitudinal zone, on the eastern coast of the continent, the climate is subtropical humid with hot summers and, in the highlands, subtropical humid with mild summers, respectively *Cfa* and *Cfb*, according to Köppen's classification (Alvares *et al.* 2013). The state geology comprises a diversity of lithologies, including granite rocks of the Archean Eon, sandstone, and basalt of the Mesozoic Era, and sedimentary deposits of the Cenozoic Era. The relief varies from flat to steep and has elevation ranging from 0 m to 1,403 m. The integrated lithologies, elevation, and slopes generate various landforms corresponding to different geomorphological units (IBGE 1986).

The vegetation comprises ombrophilous and seasonal forests and different grassland typologies, which cover most of the state. According to the Brazilian Vegetation Classification System (IBGE 2012), in Rio Grande do Sul there are four forest and three grassland phyto-ecological regions, as well as areas of ecological transition ("Área de tensão ecológica") and areas of pioneer formations ("Área das formações pioneiras"). Although under the present climate conditions the energy and water availability throughout the year support forests, grasslands predominate in the state. According to Behling *et al.* (2009), grasslands have been in the region for as long as the forests. They correspond to the old-growth grasslands (Veldman *et al.* 2015, Bond 2016), and their occurrence can be evidence of a colder and drier climate in the past.

The sources used in this work comprise a set of open available digital geospatial data for the Brazilian state of Rio Grande do Sul. The used data include a digital elevation model (DEM), a soil map, and a map of phyto-ecological regions. The first data layer is a raster file, with a spatial resolution of approximately 90 m, continuously structured from 1° latitude to 1° longitude windows of the original SRTM – Shuttle Radar Topography Mission data (Weber *et al*. 2004). The second data layer is a vector polygon file of soils. The soil map units were structured from the original 1:250,000 scale sheets (SAA/RS-IBGE/SC 2003) of the Radambrasil Project (IBGE 1986), whose thematic richness is compatible with this scale (Sarmento *et al.* 2014). The third data layer is a vector polygon file of vegetation. Their correspondent phyto-ecological regions were structured from the original sheets, at scale 1:250,000, (SAA/RS-IBGE/SC 2003), as refined by Cordeiro & Hasenack (2009). We processed and analysed the geospatial data with the aid of the TerrSet Geographic Information System (GIS) (Eastman 2015), Cartalinx (Hagan *et al.* 1999), and ArcView

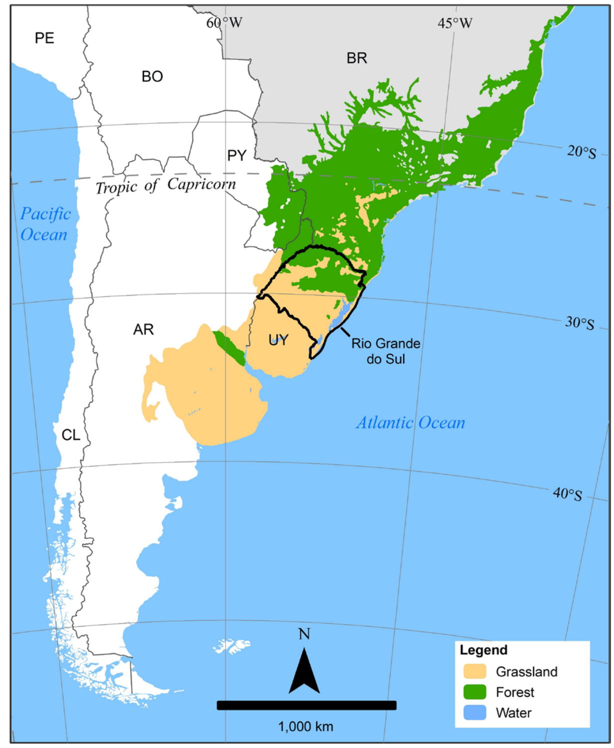

Figure 1. The study area of the State Rio Grande do Sul, Brazil, located at the subtropical eastern coast of South America, a latitude in which a transition from forest to grassland occurs southwards (adapted from Soriano *et al.* 1992 and Hueck & Seibert 1981).

(ESRI 2014) software. We used Navigation GPS (Global Positioning System) receivers to support field expeditions. Original geospatial data were harmonized with the Lambert Conical Conform cartographic projection, WGS84 datum, to enable subsequent data integration. Besides, vector polygon files such as soil and vegetation were also converted to raster using the same ~90 m resolution of the native DEM (digital elevation model) raster layer.

The DEM was the basis for two variables, an elevation, and slope class's map. The elevation classes resulted by reclassifying the continuous elevation values into a discrete map of elevation classes according to the Classification System of the Brazilian Vegetation for latitudes above 24° S (IBGE 2012). The continuous elevations of the DEM were also the basis on which continuous slopes were calculated using standard GIS procedures. The continuous slope values were then reclassified into class intervals, based on the relief phases used in soil surveys, according to the Brazilian Soil Classification System (EMBRAPA 2018). We overlaid the maps containing respectively elevation and slope classes. This new map allowed identifying all class combinations of both maps, which resulted in eight categories representing different relief compartments. These classes express the influence of elevation and slope as biophysical factors of the distribution of grasslands in the State Rio Grande do Sul. The criteria to evaluate biophysical characteristics of soils, such as moisture regime, depth, and fertility, were derived from the analytical and descriptive data of representative profiles of the soil survey report of IBGE (1986). As a result, we defined four functional soil groups representable at the mesoscale: 1) wet soils; 2) deep soils with high fertility; 3) deep soils with low fertility; 4) shallow soils. Departing from the soil maps, we reclassified the units of SAA/RS-IBGE/SC (2003) according to the functional class corresponding to the dominant soil type.

Some grassland was delineated based only on elevation and slope classes. Others required overlaying the functional soil classes. Additionally, to fulfil the boundaries in specific portions where the other three variables did not allow appropriations of subtle variations, we considered the land-use boundaries of a map by Cordeiro & Hasenack (2009). The phyto-ecological regions were used to create a mask to the areas originally occupied by grasslands in the state of Rio Grande do Sul (IBGE 1986, SAA/RS-IBGE/SC 2003). The mask includes the phyto-ecological regions Savanna, Steppe, and Steppic-savanna, and the Ecotones, and the Pioneer formation areas in which grassland vegetation is dominant. This is the comprehensive area in which we propose a new grassland landscape. With the definition of the boundaries of each grassland ecological system, it was possible to describe them according to the respective characteristics of dominant species and species richness, following Boldrini (2009).

The resulting map represents landscape typologies at the mesoscale level (Bailey 1987). To verify the consistency and the coherence of the limits of the ecological system defined above, we used the support of Landsat satellite images and GPS receivers for *in loco* observation of the respective dominant species. After verification was completed, the boundaries of the grassland typologies were merged with those of the forest regions (IBGE 2004) to generate a map of ecological systems of the entire state of Rio Grande do Sul.

RESULTS

The reclassification of the DEM (Digital Elevation Model) of the State Rio Grande do Sul resulted in four elevation classes and the reclassification of the continuous slopes resulted in four slope classes (Tab. 1). The combined map resulted in eight relief compartments (Tab. 2, Fig. 2A). The reclassification of the soil map based on biophysical functional classes allowed the identification of four functional soil groups (Fig. 2B). Figure 2C shows the area of the classified grasslands in grey. We divided the grassland region of Rio Grande Sul into ten grassland ecological systems with the same hierarchical level. At this level, the biophysical restrictions are associated with the elevation, reducing the temperature in one region, to slope or functional soil type, by diminishing the water storage capacity in another (Tab. 3). The map of (grassland) ecological systems is compatible with the scale 1:250,000 (Fig. 3).

The given name of the grassland ecological systems highlights the more evident physiognomic aspect of each one. In some cases, it refers to the floristic composition, while in other cases it highlights biophysical factors. For example, many herbaceous species are widely distributed in Rio Grande do Sul, but they may be either dominant or exclusive in certain areas, or less representative in others. Likewise, there are environments in which biophysical factors such as landform or soil express the physiognomy

Table 1. Elevation classes and their class name according to the Brazilian vegetation classification system for latitudes above 24° S (IBGE 2012), and simplified slope classes and their relevant phases in the Brazilian soil classification system (EMBRAPA 2018).

Elevation class	Name of elevation class	Slope class	Name of slope class
0 – 30 m	lowland	0 – 3 %	flat
30 – 400 m	sub-montane	3 – 8 %	gentle
400 – 1,000 m	montane	8 – 20 %	undulated
> 1,000 m	high-montane	> 20 %	strong undulated to steep

Table 2. Relief compartments were identified by combining elevation classes significant to vegetation (IBGE 2012) with simplified slope classes from relief phases (EMBRAPA 2018).

Elevation class	Slope class	Relief compartments
0 – 30 m	0 – 3 %	lowland, flat
30 – 400 m	3 – 8 %	sub-montane, gentle
30 – 400 m	8 – 20 %	sub-montane, undulated
30 – 400 m	> 20 %	sub-montane, strong undulated to steep
400 – 1,000 m	3 – 8 %	montane, gentle
400 – 1,000 m	8 – 20 %	montane, undulated
400 – 1,000 m	> 20 %	montane, strong undulated to steep
> 1,000 m	3 – 8 %	high-montane, gentle

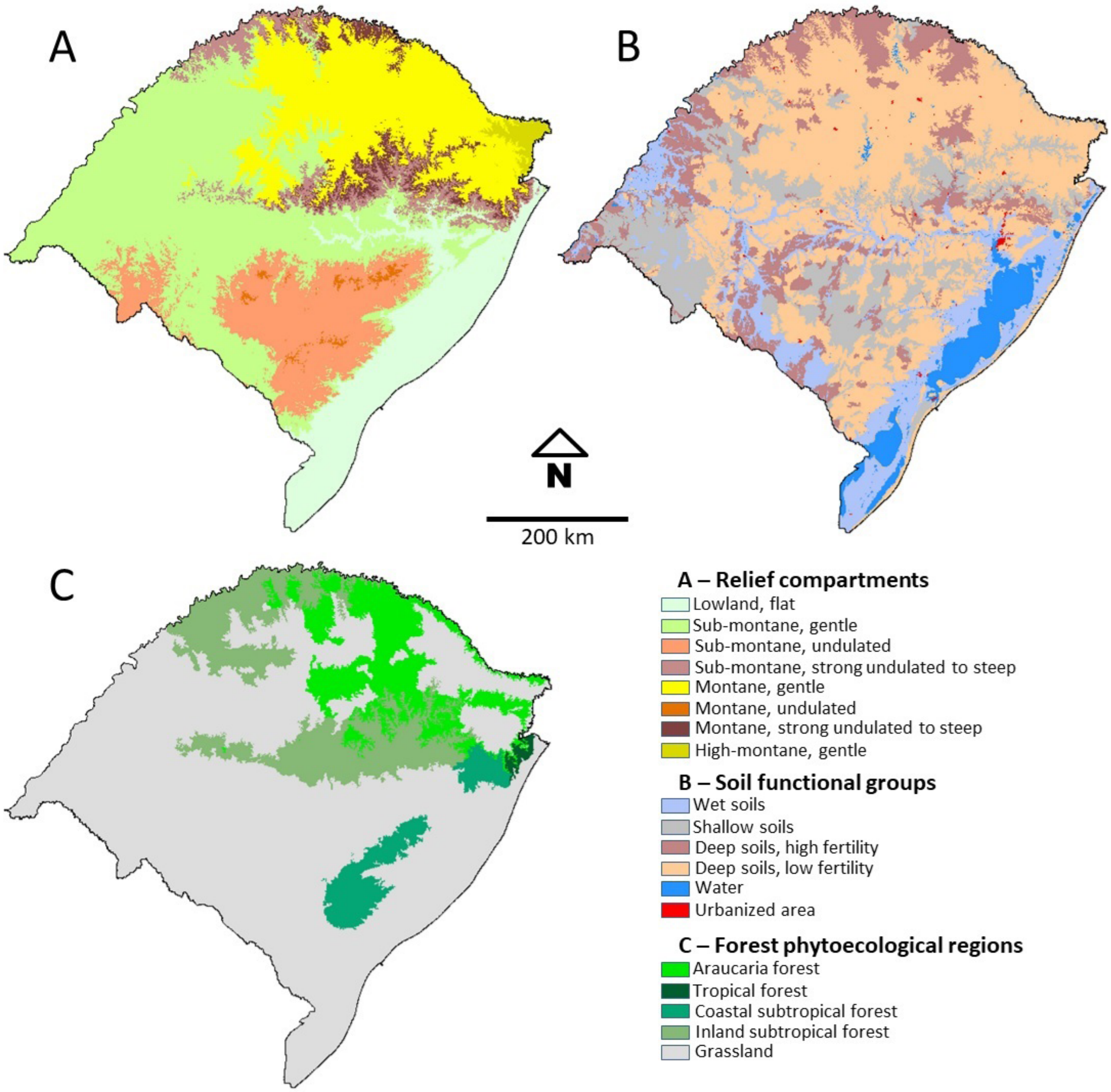

Figure 2. Geospatial data used to build up the map of ecological systems. **A**. Relief compartments, obtained by combining elevation classes significant to vegetation (IBGE 2012) with simplified slope classes from soil survey relief phases (EMBRAPA 2018); **B**. Soil functional groups based on hydromorphism, depth, and fertility, derived from the soils map (IBGE/SC-SAA/RS 2003); **C**. Forest phyto-ecological regions, according to IBGE (2004) and the target area of grassland of this work.

of the landscape better than vegetation. The terms inland or Atlantic in some grassland names geographically locate them close or distant to the coast, not necessarily meaning continentality in the climatic sense of the word. A short description of the different ecological systems (Detailed description of the flora in Supplementary Material 1):

HIG – The Highland grassland with dominance of erect species occurs on the highest portions of the basaltic plateau in the northeastern part of the state. Elevation ranges from 500 to 1300 m and slopes are gentle. Soils are deep and with low fertility, with Inceptisols ("Cambissolos") and Oxisols ("Latossolos") dominating. Dry grassland occurs in well-drained areas of the interfluve, and on less-dissected slopes, with a predominance of summer grasses. Wet grassland is in poorly drained areas, where soils have a high content of organic matter.

BUG – The Bush grassland with cactus and woody species occurs on the Uruguayan-sul-rio-grandense plateau, with elevation between 30 and 500 m, the slopes are undulating and both deep Ultisols ("Argissolos") with low fertility and shallow Lithic Entisols ("Neossolos litólicos"). The vegetation is characterized by two vegetation strata. The

Table 3. Area and proportions of grassland ecological systems delimited for the State of Rio Grande do Sul, Southern Brazil, and their general characteristics as a function of elevation, slope, and soils, and forest typologies according to IBGE (2004). (HIG: Highland grassland, BUG: Bush grassland, SAG: Sandy grassland, ARG: Aristida grassland, PAG: Park grassland, SSG: Shallow soil grassland, SHG: Shortgrass grassland, COG: Coastal grassland, ISG: Inland sub-montane grassland, ASG, Atlantic sub-montane grassland, ARF: Araucaria forest, CSF: Coastal subtropical forest, ISF: Inland subtropical forest, TRF: Tropical forest)

Vegetation type	Ecological systems	Elevation classes	Slope classes	Functional soil groups	Area (km²)	% of state RS
Grassland	HIG	montane and high-montane	gentle	deep soils, low fertility	16,341.12	5.81
Grassland	BUG	sub-montane	undulate	shallow and deep soils, low fertility	30,124.94	10.71
Grassland	SAG	sub-montane	gentle	deep soils, low fertility	4,674.58	1.66
Grassland	ARG	montane and high-montane	gentle	deep soils, low fertility	35,896.39	12.77
Grassland	PAG	sub-montane	gentle	wet soils	13,909.69	4.95
Grassland	SSG	sub-montane	gentle	shallow soils	13,685.47	4.87
Grassland	SHG	sub-montane	gentle	deep soils, high fertility	11,501.02	4.09
Grassland	COG	lowland	flat	wet soils	36,599.23	13.02
Grassland	ISG	sub-montane	gentle	deep soils, low fertility	35,546.96	12.64
Grassland	ASG	sub-montane	gentle	deep soils, low fertility	1,161.35	0.41
Forest	ARF	montane	undulate	deep soils, low fertility and deep soils, high fertility	29,885.21	10.63
Forest	CSF	sub-montane and montane	undulate	deep soils, low fertility and shallow soils	11,911.16	4.24
Forest	ISF	sub-montane	undulate	deep soils, low fertility and shallow soils	38,799.50	13.80
Forest	TRF	sub-montane and montane	strong undulate to steep	shallow soils and deep soils, low fertility	1,152.96	0.41
Total					**281,189.60**	**100.00**

upper one is formed by woody species dominated by Asteraceae species and the lower stratum by erect grasses such as *Aristida circinalis* Lindm., *A. spegazzini* Arechav., and *A. venustula* Arechav., and cactus species. The last ones have a high degree of endemism, especially on shallow soils.

SAG – The Sandy soil grassland with xerophytic vegetation occurs in the midwest of the state as a result of erosion of the layer of igneous rocks that covered sandy deposits of an ancient desert. The elevation is sub-montane (100-200 m), the slope is gentle and the soils are predominantly deep with low fertility dominated by Oxisols ("Latossolos") and Quartzipsamments Entisols ("Neossolos quartzarênicos"). This grassland has different species when compared to the other ones. Adaptations to an arid environment are frequent, as leathery, bright, or reduced leaves, with a very developed underground system, and have intense hairiness, which gives a grayish color to the landscape.

ARG – The Aristida grassland with summer cespitose and prostrate species covers the interfluves of the tributaries of the left margin of the upper Uruguay River valley. Elevation ranges from 100 to 500 m, slopes are gentle, and soils are deep with low fertility Oxisols ("Latossolos"). The vegetation is characterized by two vegetation strata, the upper one is formed by *Aristida jubata* (Arechav.) Herter and *A. laevis* (Nees) Kunth, and the under stratum is formed by rhizomatous grasses.

PAG – The Park grassland, with park-like vegetation is located on the floodplains of the middle Uruguay River at elevation between 0 and 150 m, with gentle slopes. The soil is predominantly wet, dominated by Ultisols (Nitossolos) and Alfisols (Plintossolos). The vegetation has similarity to the "espinal' found at the other side of the Uruguay River in the Argentinian Province of Corrientes. The lower stratum is continuous, made by a great diversity of grasses. Associated with this grassland matrix are some sparse woody Fabaceae like *Prosopis* spp. and *Vachellia caven* (Molina) Seigler & Ebinger.

PAG – The Shallow soils grassland with low, predominantly erect vegetation occurs on a low-lying basaltic plateau in the far west of the state at elevation between 100 and 300 m, The slopes are gentle and the soils very thin, with wide dominance of Lithic Entisols ("Neossolos litólicos"). Vegetation is associated with very shallow, stony basalt soils with low moisture retention. Water deficit in summer is quite peculiar in this stressful environment.

SHG – The Shortgrass grassland with many winter erect and summer prostrate grasses occurs in the south of the

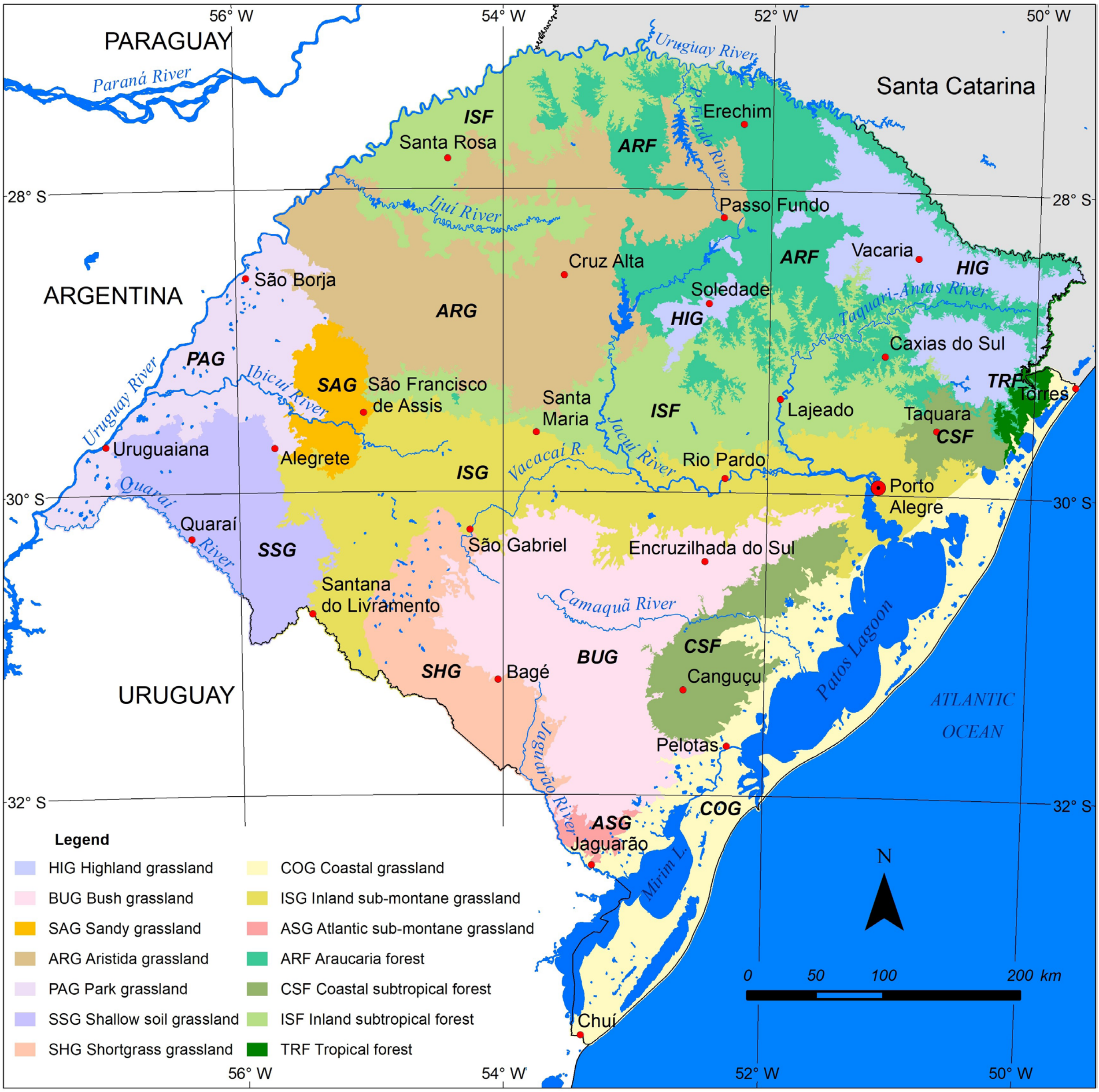

Figure 3. Grassland and forest ecological systems of the state of Rio Grande do Sul, Brazil, based on a biophysical landscape classification at mesoscale level, and compatible to scale 1:250,000. Files in Supplementary Material 2.

state on colluvium of the Uruguayan-sul-rio-grandense Plateau at elevation between 100 and 200 m. The slopes are gentle and the soils are deep with high fertility, dominated by Alfisols ("Planossolos") and Molisols ("Chernossolos"). The vegetation physiognomy is dominated by herbaceous species, essentially grassy ones, with a rhizomatous habit, and others with a tufted habit.

SHG – The Coastal grassland dominated by sedges and prostrate grasses occurs on sandy marine and lagoon deposits along the Atlantic Ocean. Elevation ranges from 0 to 30 m, the slopes are flat, and the soil is humid, dominated by Alfisols ("Planossolos") and Entisols ("Gleissolos"). A peculiar characteristic of this ecological system is the presence of numerous lakes and lagoons, which occupy 41% of the surface. Most of these water bodies are surrounded by wet areas. The main grass species in this grassland are small-statured plants, prostrate stoloniferous and rhizomatous, and plant species that promote high ground coverage. Many prostrate species of Asteraceae are dune fixers.

ISG – The Interior sub-montane grassland with a mixture of Poaceae and Asteraceae occurs along the middle and lower Jacuí River and its main right bank tributary Vacacaí River at elevation between 30 and 150 m. The slopes are gentle and soils are deep with low fertility dominated by

Ultisols (“Argissolos”). When grassland is well managed, the presence of uncovered soil is low, since dominant species in the lower stratum are prostrate. In overgrazed grasslands, the plant cover becomes scarce with large proportions of exposed soil where the seeds of the numerous Asteraceae settle.

ASG – The Atlantic sub-montane grassland with domain of summer grass species occurs in the extreme south of the state, the northernmost extreme of a grassland typology that is also present in Uruguay, on colluvial deposits at the eastern side of the Uruguayan-sul-rio-grandense granitic plateau at elevation between 30 and 150 m. The slopes are gentle and the soils are deep with low fertility, dominated by Ultisols (“Argissolos”). The vegetation of this grassland presents high grazing pressure with a constitution marked by summer species and scarce winter ones. With high grazing pressure, winter species are the first to be consumed because they have better forage quality, to the detriment of summer species. With high grazing pressure, bare soil occurs, and invasive species such as *Cynodon dactylon* (L.) Pers. and species with low fertility requirements, such as *Sporobolus indicus* (L.) R. Br., end up settling in these areas. Additional information can be found in Supplementary Material 1 and 2.

DISCUSSION

The main contribution of this work is the description of relevant biophysical factors considered in the characterization of grassland ecosystems at the mesoscale. The use of energy and water availability as conditioning factors in the description of ecosystems is a new way to look at the grasslands of the state Rio Grande do Sul, in Southern Brazil. This approach allowed us to discriminate different spatial units of the grassland ecosystems, expanding previous observations and descriptions (IBGE 1986, Boldrini 2009). Recent vegetation studies (in the region) confirm statements of several authors on the influence of relief and soil on the spatial distribution of herbaceous plant communities (Boldrini *et al*. 2009, Ferreira *et al.* 2010, 2020, Freitas *et al*. 2010, Setúbal & Boldrini 2012, Pinto *et al.* 2013, Menezes *et al.* 2015, Andrade *et al.* 2016, 2018, 2019, Menezes *et al.* 2022). Andrade *et al.* (2019) refers to 1,502 samples of 1 m² of the SISBIOTA Project (National System Research on Biodiversity – “Sistema Nacional de Pesquisa em Biodiversidade”), Ferreira *et al.* (2020) refers to 262 samples of 1 m² along five years of the PELD Project (Long Term Ecological Research-South Brazilian Campos – “Pesquisas Ecológicas de Longa Duração-Campos Sulinos”), and Menezes *et al.* (2022) refers to 1,080 samples of 1 m² of the PPBIO Project (Research Program on Biodiversity of the South Brazilian Campos – “Programa de Pesquisa em Biodiversidade nos Campos Sulinos”). Our identification of two new grassland ecological systems beyond those previously described (ASG and PAG) demonstrates the potential of geospatial analysis in the characterization of environments consistently and coherently. They allow to spatially combine existing formal knowledge about vegetation and environmental factors in discriminating different landscapes.

We listed and described the characteristic species of each grassland ecological system occurring in the state of Rio Grande do Sul, bringing together observations of more than 40 years of plant surveys (Supplementary Material 1). Although our list of species is not comprehensive, it reflects the differentiation of each grassland in terms of floristic composition. Andrade *et al.* (2019) classified the grasslands of Rio Grande do Sul into three types and ten subtypes, and Menezes *et al*. (2022) into three types and four subtypes, drawing our attention to the fact that the number of sample units, for more accurate classification, has to be larger by considering the different abiotic characteristics in more detail. In this work, with biophysical variables, we directed attention to the abiotic characterization of grasslands and delimitated them into ten ecological systems. These new spatial units would serve as a basis for identifying additional sampling areas for further characterizing grassland plant communities.

The names we attributed to the multi-physiognomic grassland typologies illustrate the different characteristics that need to be referred to when proposing a classification of such landscapes. For this reason, the naming of the grassland typologies followed the strategy of giving evidence to the most noticeable characteristic of each of them. For example, the Highland grassland (HIG) lies on the highest plateau of the state, and it is also isolated from the remaining grassland ecological systems by forests in steeper slopes. The Shallow soil grassland (SSG), on the other hand, denotes a marked influence of soil on the flora, where species adapted to water deficit settle, like *Chloris grandiflora* Roseng. & Izag., *Eustachys brevipila* (Roseng. & Izag.) Caro & E.A. Sánchez and *Aristida murina* Cav.. The Bush grassland (BUG) is the only one with undulated relief, whose variation of slope and aspect associated with soil heterogeneity results in a variety of plant species with the frequent presence of bush vegetation, like *Acanthostyles buniifolius* (Hook. ex Arn.) R.M. King & H. Rob, *Baccharis dracunculifolia* DC., *Aristida circinalis* Lindm., *A. spegazzini* Arechav., *A. venustula* Arechav., as well as Cactaceae and Fabaceae species. The Aristida grassland (ARG) received this name because, in this case, the vegetation is the hallmark of this grassland. *Aristida jubata* and *A. laevis* are the most frequent and more visible at a landscape scale. The Short Grass grassland (SHG) refers to numerous wintering species of *Nassella* (Trin.) E. Desv. and *Piptochaetium* J.Presl. In different places, one component of the ecological system is frequently more prominent than the others. This analytical framing led to nominating each of the ecosystems.

In our studies, we realized that to achieve the discrimination of grasslands at a level comparable to that for forest ecological systems, we need more data. It is probably because the composition and structure are easy to observe in forests compared to grasslands when mapping both vegetation cover, thus allowing discrimination in more detail. Our strategy here was to take advantage of the availability of ancillary data aiming to improve the discrimination of grasslands to a forest-equivalent level. We also combined the new-obtained grassland ecological systems with the previously-classified forest phyto-ecological regions (IBGE 2004) to capture an environment-regionalization that portrays the distributions of forest and grassland vegetation physiognomies in equivalent detail.

Currently, few portions of the state Rio Grande do Sul remain whose original vegetation cover has not been modified either by human settlements or agricultural use. It is hard to characterize the original vegetation in these altered areas. The ecological approach used here allows us to evaluate the local biophysical characteristics relevant for deriving adequate ecological restoration-strategies, and potentially sustainable land use. Because animal production is an economic activity of importance in the State Rio Grande do Sul, a renewed interest in the study of the native flora to understand the ecology of the grasslands arises, in order to apply this knowledge to improve the quality of native grasses for raising cattle.

Therefore, the ecological regionalization we present here can benefit multiple purposes, from biological conservation to land-use management. Because the natural vegetation is an expression of the biophysical conditions of a place, crops of economic interest may also respond accordingly. We believe that such regionalization is a relevant contribution to focus land-use policies on the natural potential of the respective land, either for economic purposes or conservation initiatives. The more we adjust land use with its natural biophysical potential, the more we approach a pertinent, sustainable use, and the less we will depend upon external energy and water sources to guarantee an equivalent output. In this way, we can devise environmental management strategies that harmonize conservation commitments with socio-economic pressures. Such data could be an additional piece of information to bring conservationists and farmers to a dialog based on the principle of sustainability.

It is also pertinent to confront the limits and characteristics of each ecosystem with its respective current or potential land use. For example, of the ten delimited grassland typologies described here, the Inland sub-montane grassland (ISG), the Coastal grassland (COG), the Aristida grassland (ARG), and the Bush grassland (BUG) occupy large extension of the state of Rio Grande do Sul. In some of them, various anthropic uses replaced a large proportion of the original grassland vegetation because of the favourable environmental conditions. On the other hand, in the Atlantic sub-montane grassland (ASG), which occupies a small area in the state, the conversion for anthropic uses is proportionally lower. This ecological system has a small spatial expression in that region, but it extends into larger contiguous areas in the neighbouring country of Uruguay.

We based our ecological approach at the mesoscale level (1:250,000) on the best available geospatial data set that uniformly covers the state of Rio Grande do Sul and on the previously described knowledge on grassland landscapes. We consider that discrete natural boundaries are an abstraction, a simplification of reality. They ideally indicate where natural elements tend to have a gradual spatial transition. These lines can change with the emergence of more detailed geospatial data or intensive knowledge about flora and fauna distribution.

We delineated and described ten different, typical grassland ecological systems based on the putative energy and water availability for the State Rio Grande do Sul, in Southern Brazil. These grasslands, combined with the previously described four forest phyto-ecological regions, resulted at the mesoscale level in 14 biophysics-conditioned ecological systems.

The characteristics of the flora present in each spatial unit show coherence with the geographical limits we propose. The biophysical attributes of a region influence the conditions for the status of natural ecosystems and limit the sustainability of anthropic activities. The proposed delineation of grasslands in ecological systems provides a framework for many purposes, like biodiversity and ecological studies, conservation and mitigation strategies, and sustainable land uses.

SUPPLEMENTARY MATERIAL

S1 – Description of the typical species that characterize the physiognomy of the ecological systems listed in Table 3 and presented in Figure 3.

S2 – Metadata of shape and kmz files of the ecological systems of the State Rio Grande do Sul, Brazil.

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