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Papers

Sandization: climatic dynamics, erosive-depositional, land uses, and land cover in the Brazilian Pampa at present

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Abstract

In the western part of the Rio Grande do Sul state - Brazil, there are sand spots (called areais) embedded in the Brazilian Pampa landscape. These sand spots, which are associated with unstable and/or stable aeolian deposits, are a legacy of drier climates from the past rather than the present one. Therefore, they provide important paleoclimatic evidence for understanding the evolution of this landscape. Currently, the sand deposits, which had their genesis in dry climates, are subject, at the same time, to wind action in the dry seasons, and surface and subsurface erosion in the rainy season, which remobilizes the unconsolidated sediments, initiating the sandization process and the formation of sand spots. In this study, we propose to identify, classify, and map these aeolian paleofeatures (stable aeolian deposits and sandstones), to understand their erosional and depositional dynamics, and to evaluate the contexts of evolution and agricultural pressure of grazing and monoculture systems in the study area, which characterize the Pampa. It can be stated that the stable aeolian deposits exhibit forms remodeled by pluvial and fluvial erosions, still presenting different degrees of morphological preservation concerning those of the recent past, which is why the present hills can be associated with Holocene longitudinal dune fields. As for agricultural dynamics, the conversion of these hills, mainly from pastureland, used for grazing, into tree and grain monocultures has intensified the pressure on water resources, herbaceous vegetation, and soils (Quartz Neosols), which are particularly sensitive to water and wind erosion.

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INTRODUCTION

In the open landscape of the Brazilian Pampa, the eolic deposits, especially the stable (not active) deposits, which are not yet in the process of sandization, are covered by vegetation typical of the native grasslands of this ecosystem. These formations are characterized as shrubby and herbaceous vegetation on the hills (coxilhas, in the regional denomination) of eolic sediments that are unconsolidated and therefore fragile, from lithological, pedological, and geoecological points of view.

In summary, the sand spots result from the reworking of sandy deposits of Quaternary superficial formations, resulting from current morphogenetic dynamics, in which the superficial hydric processes, particularly the concentrated runoff of ravine or gully types, associated with torrential rains, expose, transport, and deposit sand, giving rise to the formation of sand spots, which, in contact with the wind, tend to a constant removal (SUERTEGARAY, 1987; VERDUM, 1997; SUERTEGARAY et al., 2001; SUERTEGARAY & VERDUM, 2008).

In addition, it is recognized that these morphologies are degraded by the recent agricultural pressure exerted on the cover of native pastures on sandy soils (Quartz Neosols). The introduction of mechanized crops, such as wheat, from 1950 on, soybeans, from 1970 on, and forestry, from 2000 on, on the relief of sandy hills of "[...] easy management, covered by herbaceous vegetation typical of the Pampa, created a new landscape", especially by converting the field area into crops, "[...] in which, until then, extensive livestock farming predominated" (VERDUM, 2016, p. 50).

In the context of agricultural evolution, the South of Rio Grande do Sul is the region that traditionally develops extensive cattle-raising, but farmers have been changing the uses and management of their farms, with rice production in the floodplains and the establishment of artificial pastures and corn, wheat, and soybean crops on the hills, in addition to the planting of exotic tree monocultures, such as eucalyptus, also on the hills, which has been increasing recently. In this space, under the dynamics of a subtropical climate, the intensification of such crops is accompanied by pressures on water resources and soils, which are particularly sensitive to erosion, especially in the study area (CORBONNOIS et al., 2014).

Considering that, the following reflections arise: a) are the sedimentary dynamics originated, in part, from past geomorphological processes and, in another part, from recent aeolian actions, in conjunction with historical transformations by land occupation and use? and b) how are the construction and exhumation of new morphologies and old typical aeolian sediments occurring?

Therefore, with this study, we intend, initially, to identify, classify, and map the aeolian geomorphological paleofeatures of the west of Rio Grande do Sul, seeking to understand their erosive dynamics, to associate them with the contexts of evolution and agricultural pressure, especially, grazing and monoculture systems.

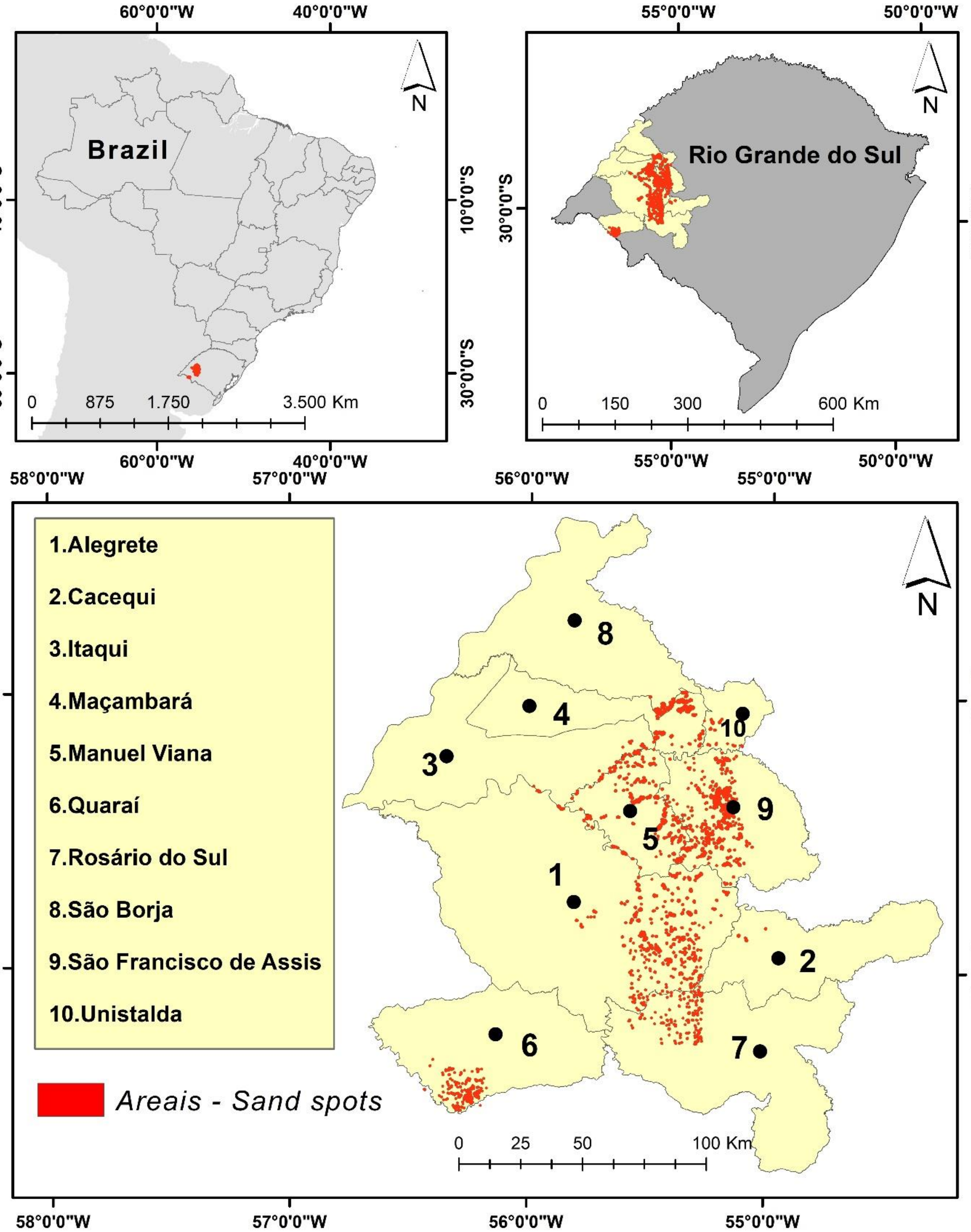
MATERIALS AND METHODS

Presentation and relevance of the study area

The occurrence of sand spots is limited to the 54ºW meridian, along the borders with Argentina and Uruguay. The sandization phenomenon covers ten municipalities from the West of Rio Grande do Sul (Figure 1) and has been studied for about four decades. However, there is still much research to be done on this subject, especially because of the importance of knowledge of this phenomenon for the proper development of agriculture, introduced in the region a few decades ago, and cattle ranching, the primary aptitude of the Pampa hill fields.

It should be notice that, except for the sand spots in the municipality of Quaraí, the sandy cores occur basically in the Ibicuí river basin, which belongs to the Uruguay Hydrographic Region (U050) and comprises an area of 36,397.69 km² (GUASSELLI, 2012).

Figure 1 – Location map of the municipalities with sandization processes, in which the sand spots are represented by red dots.



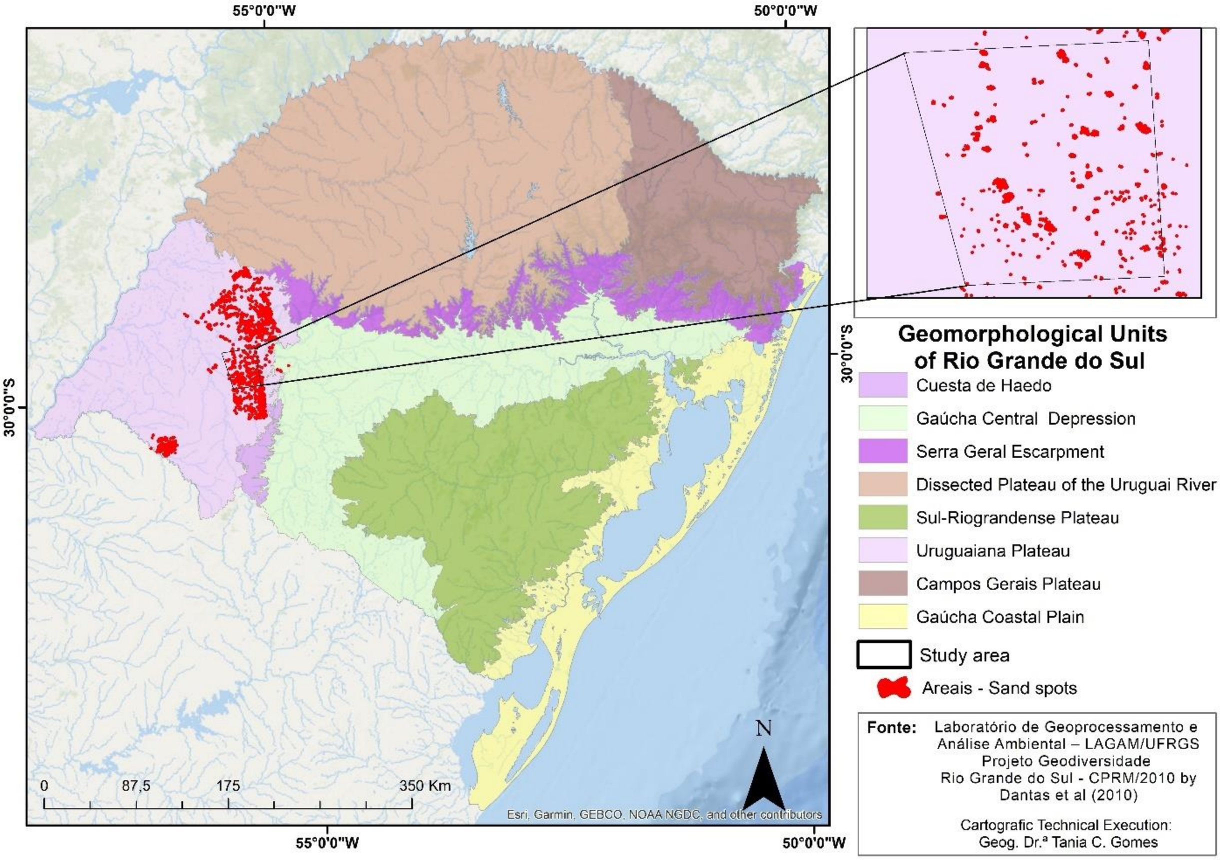
Source: Gomes (2019)

At the same time, it is emphasized that, currently, the region conjugates factors that favor the formation of sand spots, such as, for example, lowland topography, appropriate wind regime (in speed and direction), and availability of sandy sediments (quartz sand), exposed to the action of the winds, for transportation and later deposition. These aspects characterize the fundamental elements in the composition of the current landscape.

The sandization occurs over two geomorphologic compartments (Figure 2): a) the Cuesta do Haedo geomorphologic compartment, on the erosive escarpment of the Southern Plateau, characterizing areas with the presence of both rugged and witnessed reliefs; and b) the

Gaúcha Central Depression or Peripheral Depression, in which the landscapes of the Brazilian Pampa predominate, with the presence of hills (coxilhas) and witnessed hills (cerros), with altimetric levels of up to 200 m.

Figure 2 – Geomorphological units of Rio Grande do Sul and the experimental study area.



Fonte: Gomes (2019)

Thus, the sand spots occur predominantly in the hill compartments with fluvial sandstone substrate, interspersed by eolic deposits of the Guará Formation (Upper Jurassic) and eolic sandstones of the Botucatu Formation (Jurocretaceous), originating, in large part, from recent eolic deposits, admitting the fragility of the hill morphologies, due to the presence of rare herbaceous vegetation (or its absence), incipient soils, and Holocene unconsolidated superficial formations.

The chosen spatial section, with about 144 thousand ha (Figure 2), is located between the Alegrete and Manoel Viana municipalities, along the BR-377 highway, at coordinates 29°44'30" S; 55°37'0" W and 29°57'30" S; 55°22'0" W. This chosen area presents the typical forms of eolic action (abrasion and sedimentation) of the recent past and the complexity of the geomorphological processes analyzed in the research.

In this spatial area, it was identified a series of morphologies, associated with stable and/or unstable eolic deposits, active sands, and other geomorphological features will be detailed below.

Methodological and operational procedures

The methodological path applied to the mapping of surface formations and features

For spatialization of the surface formations, Pfaltzgraff (2003) emphasizes that the final product of mapping must contain detailed information on both residual and transported units, on the origin of the material, the outcropping substrate (with an indication of the lithological type), the neotectonic elements, the erosive features with regional significance, the relative chronology, the mineral resources, the relevant modeling features, and the physical characteristics of the materials.

Considering this, the interpretation key for the detailed mapping was elaborated (Chart 1). However, before this, it was necessary to carry out a broad survey of the methodologies applied to the mapping of surface formations, especially concerning stable inland continental aeolian deposits, including a bibliographic review of geology, geomorphology, and sedimentology studies, especially those related to the study area and fieldwork.

Chart 1 – Interpretation keys for mapping geomorphological features.

Attributes	Characteristics of the attribute	Materials and techniques applied
Stable wind deposits	Classification by texture, color, shape, altimetry, and the presence of vegetation cover	Digital photointerpretation in anaglyphs (visual interpretation and vectorization) (ILWIS 3.3 Academic and ArcGIS10.5 software)
Instable wind deposits (sand spots)	Active eolic deposits, classified by texture, color, and, mainly, the absence of vegetation cover	Digital photointerpretation in anaglyphs and validation in high spatial resolution images from Google Earth Pro and fieldwork (visual interpretation and vectorization) (ILWIS 3.3 Academic and ArcGIS 10.5 software)
Rock outcrop	Exposure of visible sandstones of the Guará or Botucatu formations, close to stable and/or unstable eolic deposits	Digital photointerpretation in anaglyphs in high spatial resolution images from Google Earth Pro and fieldwork (visual interpretation and vectorization) (ArcGIS 10.5 software)
Abrupt or tabular relief	Abrupt slopes and tabular forms visible on aerial photographs	Digital photointerpretation in anaglyphs and validation in high spatial resolution images from Google Earth Pro and fieldwork (visual interpretation and vectorization) (ArcGIS 10.5 software)
Deflation Basin	Depressions excavated by wind action are visible on aerial photographs and high spatial resolution images	Digital photointerpretation in anaglyphs and validation in high spatial resolution images from Google Earth Pro and fieldwork (visual interpretation and vectorization) (ArcGIS 10.5 software)
Ravine and gully erosion processes	Linear erosive incisions visible on aerial photographs and high spatial resolution images	Digital photointerpretation in anaglyphs and validation in high spatial resolution images from Google Earth Pro and fieldwork (visual interpretation and vectorization) (ArcGIS 10.5 software)

Source: Gomes (2019).

Therefore, for the choice of the spatial cutout, it was observed the grouping of the largest number of relevant attributes: the presence of sand spots themselves, sandstone-block outcrops, geological faults (as structural conditions of anchorage), lakes in deflation basin, buried or reactivating paleodrainages (valleys) (by wind deposits), wind origin deposits, among other characteristics.

The survey of these attributes subsidized the elaboration of the interpretation key for the mapping, applied from digital photointerpretation, that is, the visual classification of high spatial resolution images, made available by Google Earth Pro, and SRTM/TOPODATA images (30-meter spatial resolution), which were validated in the fieldwork.

The pre-processing of the digital photointerpretation base consisted of the transformation of aerial analog photos into digital, formed by stereoscopic pair through the anaglyph method, which can be directly manipulated in 3D digital means by any geoprocessing software.

The first analogical aerial photographs analyzed in the preview, from the year 1990 and on the scale of 1:60,000, were obtained from the 1ª DL – Divisão de Levantamento do Exército Brasileiro (1st Survey Division of the Brazilian Army) (DSG, 1990). After the delimitation of the experimental area, there were used aerial photographs (with a scale of 1:60,000, obtained in the years 1964/1965) (DSG, 1964) from the library collection of the UFRGS' Instituto de Geociências.

Then, both stable and/or unstable wind deposits were identified and vectorized, from the visual interpretation of qualitative information of the studied object, through 3D digital photointerpretation in previously prepared anaglyphs. Once the first considerations about the location and the morphological pattern of the wind deposits were made, it was performed the mapping of all the attributes and features to be qualified and/or quantified.

The methodological path applied to land use and land cover mapping

The mapping of land use and land cover was done by digital processing of two Landsat satellite orbital images: (i) one, from the Landsat 2's Thematic Mapper (TM) sensor (orbit/point), with an 80-meter spatial resolution and date of passage on 16/01/1982; and (ii) another, from the Landsat 8's TM sensor (orbit/point), with a 30-meter spatial resolution and with passage on 28/09/2016. Both are available at Instituto Nacional de Pesquisas Espaciais (Brazilian space research agency). All the processing applied to the use mapping was performed in ArcGIS 10.5 and QGIS3.22 software. In the ArcGIS 10.5 environment, the Basemap tool was also used to assist in the identification, vectorization, and quantification of sandization and/or active sand spots foci, through the visual interpretation of high spatial resolution images.

The classification and definition of the types of use were based on the land cover and land use classification system suggested by the Instituto Brasileiro de Geografia e Estatística (Brazilian statistical agency), which addresses a multilevel system of classification, with three levels of abstraction, giving rise to a basic classification system of land covers and uses, being possible to interpret many areas uses: anthropic and non-agricultural; agricultural anthropic; natural vegetation; waters; and other areas, such as conservation units, protection units, sustainable use units, indigenous lands, etc. (IBGE, 2013).

Thus, for the recent use mapping (TM-Landsat 1/2016), the classification of the areas occurred through the supervised classification method, in which about 80 samples per type of use were highlighted. For the image composition, it was used bands 1 to 6 (R(5)G(3)B(1)). The collection of samples of Field and/or Pasture types of use was performed with a larger number of samples of smaller sizes, considering the highest noticeable difference between the points on the aerial image.

The image processing was performed in ArcGIS 10.5, using the Spatial Analyst Tools / Image Classification extension. The 80 collected samples were then identified and grouped by land-use class with the Training Sample Drawing Tools. With the Create Signature File, the file with the collected samples was generated and the supervised classification was finalized, following the path: Image / Classification / Maximum Likelihood / Classification.

The mapping of the land uses in the 1982 image was performed, based on the interactive supervised classification, but its execution occurred with a larger amount of sample collection (on average, 100 per use), considering that this was performed with Landsat 2 satellite images, with lower spatial resolution and amount of bands. The composition of bands for classification was made in R(2)G(1)B(3).

The image processing in QGIS 3.22 software was performed using the Semi-Automatic Classification Plugin (SCP) / SCP: ROI Creation / SCP: Classification. With the SCP add-in enabled, the toolbars are activated to obtain the classification. In SCP: ROI Creation, the collection of samples was performed, linking them to the land use classes and exporting them to an ROI file, with shapefile format. Subsequently, in SCP: Classification, the land use shades are defined. Finally, by using the Classification Algorithm procedure, there are performed the maximum likelihood method, and the classification itself.

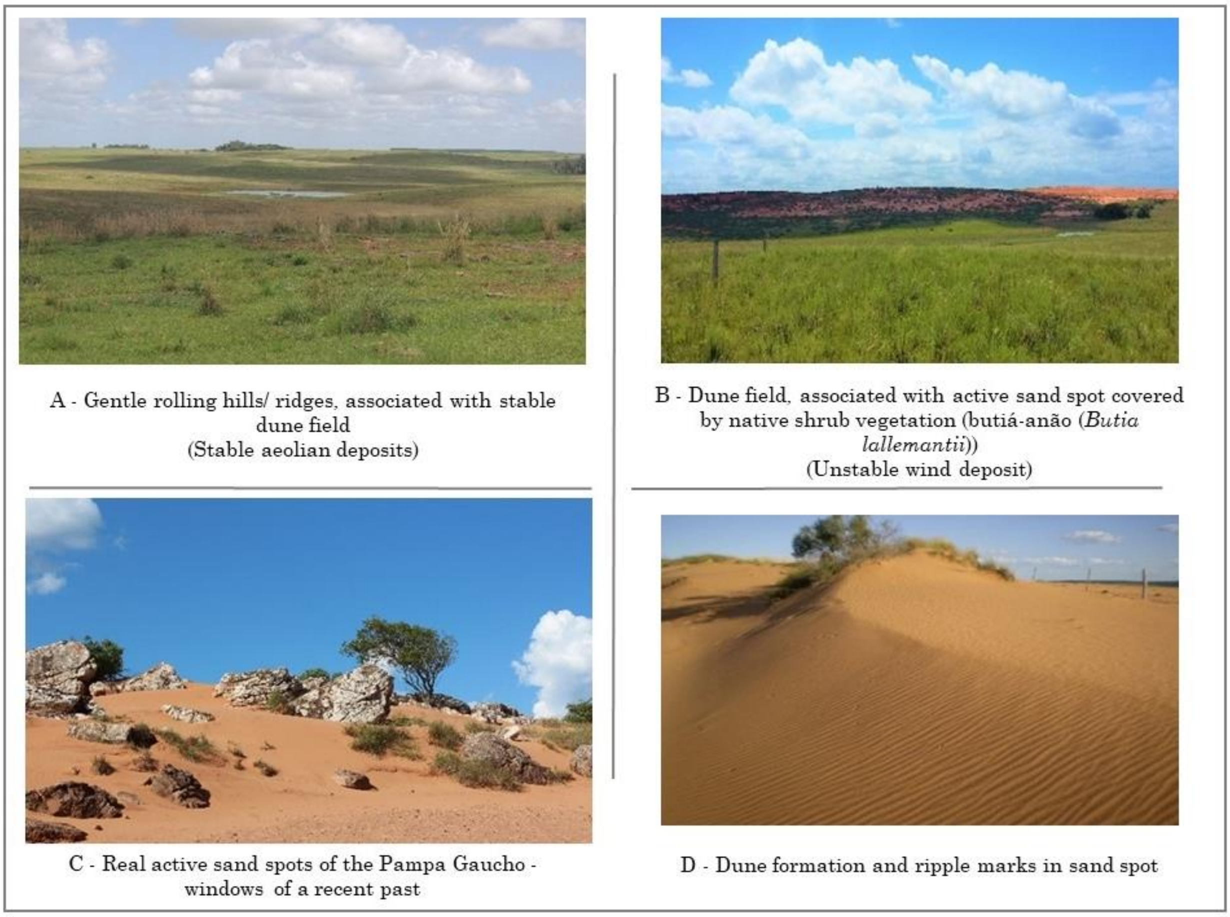
RESULTS AND DISCUSSION

Water and wind dynamics in the remobilization of sand spots

As already mentioned, the genesis of the sand spots is natural, since their formation results from the sandization process of unconsolidated sandy deposits, reworked by water and wind dynamics, throughout geological time. Thus, these aeolian deposits are subject, at the same time, to wind action, in dry seasons, and surface and subsurface water erosion, in rainy seasons, which remobilize the unconsolidated aeolian sediments, initiating the sandization process and the formation of sand spots (GOMES, 2019).

In general, aeolian deposits have no morphological pattern or a defined deposition orientation. However, stable aeolian deposits exhibit original forms, remodeled by pluvial and fluvial erosion, presenting different degrees of preservation, considering their aeolian morphology (ibid.) (figures 3A-3D).

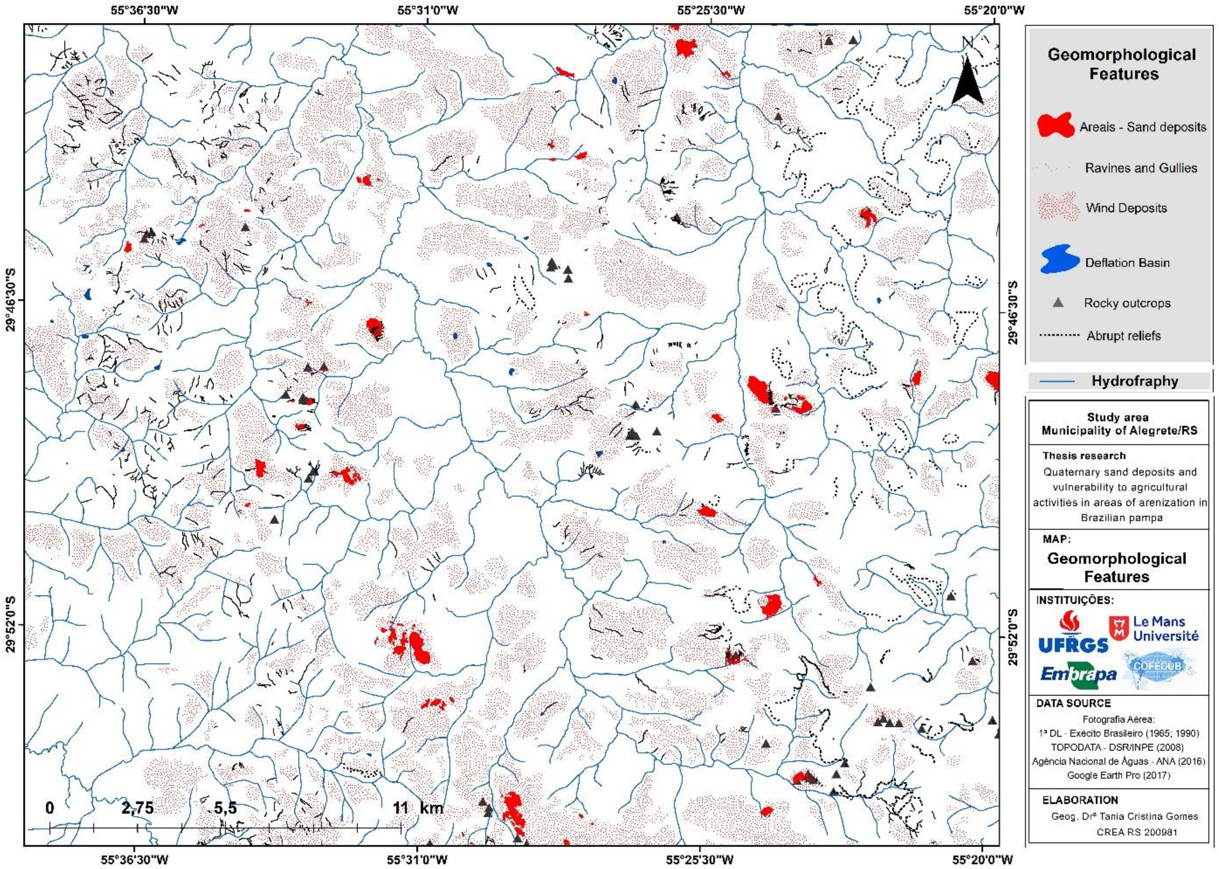
Figure 3 - Mosaic of hills on stable and/or unstable wind deposits (with active sand spots), associated with dune fields



Source: fieldwork records. A and B: Alegrete/RS (2017); C: São Francisco de Assis/RS (2014); D: Quaraí/RS (2007)

However, if we analyze the unstable deposits (sand spots reactivated by current climatic dynamics), it is possible to infer that these formations present a regional orientation. Also, at the regional scale, hills associated with Quaternary dune fields, mainly from Holocene, are observed, arranged in an elongated form from SE (windward face) to NW (leeward face), demonstrating the preferential paleowind direction, forming a depositional corridor (Figure 4).

Figure 4 – Map of geomorphological features.



Source: Gomes (2019)

The stable aeolian deposits, with herbaceous cover and rocky outcrops, can still identify abrasion on the windward face (SE) and provide wind deposition on the leeward face (NW). They can also present small deflated lakes (lunettes or PAN), which consist of areas depressed by wind abrasion, giving rise to small and visible deflated lakes, currently in the form of weirs. In addition, aeolian deposits can be associated with river channels buried by their sands. Currently, it is also possible to observe these eolic deposits blocking the drainage continuity, visibly embedded in humid areas.

Related to the context of current climate dynamics and changes in land use in the Pampa, whose primary aptitude is for livestock, the role of contemporary agricultural production is emphasized, in which tree and grain monocultures were installed a posteriori, bringing changes to the relationships between climate and meteorological dynamics, as well as the agricultural dynamics of the recent past (the 1970s) and the current ones, which potentiate the erosive/depositional processes on aeolian deposits, especially those devoid of protection from the vegetation cover.

For the analysis of erosive processes, from the perspective of dynamic geomorphology, it is relevant to observe daily and monthly precipitation data. The region can accumulate daily precipitation of up to 110 mm. Strong daily precipitation can occur in spring (September, October, and November), fall (March, April, May, and June), and in July, in the winter. The months of April and November present more intense daily precipitation, while the months of December, January, February, and August present a considerable reduction in precipitation. This rainfall behavior has different consequences, the main ones being the recharge of the underground reservoirs and the unleashing of the soil saturation phases and the concentrated surface runoff, the main erosive agent of the ravine type, closely linked to the genesis of the sand spots (VERDUM, 1997; SUERTEGARAY, VERDUM & GUASSELLI, 2001).

For the region with the presence of sandization processes, although the average annual precipitation (1,400 mm/year to 1,700 mm/year) is considered high, it occurs between 70 and 90 days, concentrated in a few days (between six and nine days per month) in autumn and spring months. The average annual temperature varies between 20 °C and 23 °C, with monthly average temperatures ranging between 11 °C and 14 °C in the coldest months and between 23 °C and 29 °C in the hottest months. These data show the poor distribution of rainfall in this climate typology, contrasting with the previous classification, which described the region as well-distributed rainfall (ROSSATO, 2011).

In the period between 2000 and 2017, monthly precipitation in the municipality of Alegrete (RS) was high (above 200 mm) and daily rainfall of 20 mm (of high erosive potential) may have occurred in the months of September, October, and November. Rainfall was also significant in March, April, and May. The months of April and November showed the highest volumes, reaching 661 mm in November, ratifying the premise of higher precipitation volume occurrence in these months. On the other hand, the months with the lowest precipitation (below 100 mm), in which daily rainfall of 3 mm (of low erosive potential) may have occurred, were June, July, and August (Figure 5).

Figure 5 – Volume of monthly precipitation between 2000 and 2017 in Alegrete (RS), Brazil (months with high precipitation in blue and months with low precipitation in red)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	106,4	95,5	257,2	118	240,6	197,6	76,53	64,15	213,2	187,4	233,5	123,6
2001	313,3	114,5	180,7	412,4	74,23	134,7	97,13	73,33	230,2	142,6	156,7	53,73
2002	54,18	119,6	321,3	319,3	200,9	157,4	229	183,4	277,3	463,3	242,5	306,6
2003	127,5	252,4	194,8	323,7	108,2	156,5	96,95	85,58	61	277	269,3	305,2
2004	53,8	68,4	28,88	160,3	48,28	91,85	62,15	40,63	111	197,6	177,1	103,1
2005	124,7	28,5	73,35	304,4	282,2	159,6	34,58	109,3	149,6	228,4	114,5	111,7
2006	80,33	17,1	91,33	127,6	92,23	122,3	68,18	43,08	118,1	184	221,3	199,2
2007	124,5	245,9	276,2	165,8	84,5	114,7	70,55	121,2	189,7	265,5	75,7	67,28
2008	84,38	129,8	46,23	148,6	98,88	147,9	150,8	91,95	89,83	291,6	46,4	18,7
2009	94,75	186,4	81,43	37,83	146,6	33,03	54,95	103,7	209,6	156,7	661,8	224,1
2010	484,5	212	51,33	147,4	143,3	43,68	362,9	28,3	237	51,33	45,95	116,5
2011	130,8	134,8	64,93	207,8	111,7	132,2	130,6	86,68	101,5	180,1	97,05	116,5
2012	26,95	103,2	32,6	140,5	24,05	61,4	56,65	102,3	114,2	434,3	46,78	367
2013	112,3	247,9	192,2	170,9	147,3	66,78	160,2	90,5	84,08	117,4	268,5	41,68
2014	195,8	165,8	206,6	86,6	222,4	159,3	196,2	24,5	213,9	207,8	134,9	226,3
2015	244	108,8	112,8	77,58	197,5	132,9	106,7	146,1	107,5	430,4	222,7	476,4
2016	118,9	152,8	212,3	300,1	101,4	88,28	127,3	97,8	23,13	266,4	189,6	126,1
2017	216,1	250,8	160,1	291,2	347,9	116,2						

Source: Gomes (2019).

The close relationship between current climatic conditions and erosional/depositional processes of sandization shows how the intensity of the occurrence of dry months or rainy episodes drives the erosional dynamics in the aeolian deposits, revealing sudden and powerful concentrated runoff phases, as well as the prevalence of wind action in dry periods, promoting morphogenetic processes on the fragile surfaces, from the lithopedological point of view, which are observed, especially, in ravine and gully type processes, associated with stable or unstable Holocene eolic deposits.

This is the general panorama of the current climatic conditions in the west of Rio Grande do Sul, a region that shelters large fields of coxilhas, covered by low-growing or small vegetation, except for riparian forest areas, along with the drainage network, and slopes, next to the testimonies reliefs. This landscape can be considered a relict, as well as stable continental eolic deposits, which, under contemporary climatic conditions, are subject to surface and subsurface erosive processes.

In periods of high precipitation on stable wind deposits with sparse vegetation cover, the process of concentrated subsurface runoff produces the transportation of sandy sediments in the subsurface (piping formation) and occurrence of subsidence steps by piping coalescence. In the sequence, these evolve into ravines and gullies, initiating the sandization process, with the formation of sand spots. These are subject to wind action in drought periods, causing remobilization, transportation, and deposition of sand, according to the aerodynamic and anchoring capacities of the spaces.

Agricultural transformations and sandization

Regarding agricultural dynamics, the region that traditionally developed extensive livestock farming has been experiencing transformations in the uses of its land, through the introduction/consolidation of rice production in the floodplains, artificial pastures, and corn, wheat, and soybean crops in the hills, as well as, lastly, the planting of new exotic tree monocultures, such as eucalyptus. The intensification of these crops is accompanied by pressures on water resources and Quartz Neosols (CORBONNOIS et al., 2014), which are particularly sensitive to erosion.

In this sense, to evaluate land degradation, and limitations and fragilities of the environment, as well as the pressure exerted by agricultural patterns on the environment, it was analyzed the phases of occupation of the territory, considering statistical data, such as those related to the area occupied by temporary crops and pastures, production of temporary crops, the relationship between the area occupied with pasture and heads of cattle, and the area occupied by owners and by tenants. The analysis of these data allows us to understand the differentiation of the forms of pressure, based on the diversity of historical processes, the persistence of agricultural practices, and the study of the intensification of extensive ranching and speculative mechanized agriculture (VERDUM, 1997).

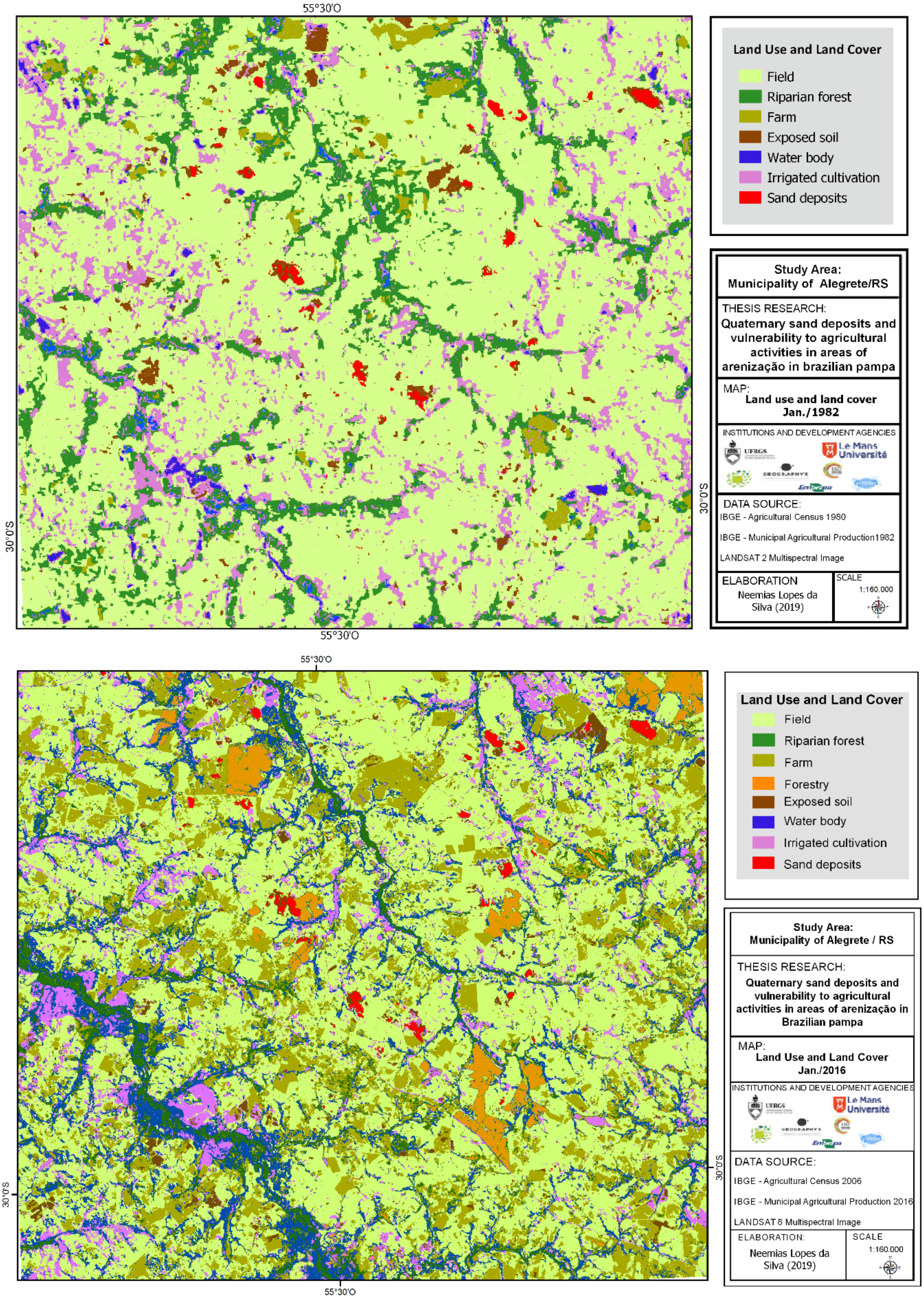
Thus, in the perspective of the diversity of historical processes, from the first forms of appropriation to the contemporary forms of exploitation of natural resources, from cattle raising and agricultural production, it can be said that the indigenous peoples transformed little the original landscape because the small native populations used only rudimentary tools, such as the polished stone ax (VERDUM, 1997).

Likewise, in the nineteenth century, it is not possible to speak of an organized territory or a more technified economic base that could conform to a kind of regional identity, because the conflicts and the indefinite political border between the Portuguese and Spanish crowns did not allow the organization of an agricultural area in the Rio Grande do Sul State at that time. However, already in the 20th century, one can state a consistent agricultural pressure on the Pampa, notably, from the 1970s on, with the establishment of mechanized crops, facilitated by the gentle relief of the hills covered by herbaceous vegetation and the easy management of soils, with modern agriculture, strongly motomechanized (VERDUM, 1997).

The natural pastures of grass-covered hills have always been used for raising cattle, whose tradition was introduced by the Jesuit missionaries, since the 17th century. Cattle breeding is still predominant today, however, the introduction of food crops, especially the development of agro-industrial cultures, since the 19th century, has changed the way the rural area is occupied. The cattle breeders from the Pampa started to share the space with farmers from the Southern Plateau (basaltic plateau), located in the North of the state, or have opted for grain cultivations. The migrant farmers introduced mechanized practices in the region, to develop monocultures, which accentuated the pressure of erosive processes on the herbaceous vegetation and friable sandy soils (Quartz Neosols) (VERDUM, 1997).

Thus, the land uses and land covers were mapped between the years 1982 and 2016, to check the increasing advance of agricultural activities over the Pampa native grasslands. The uses mapped were: Fields, Riparian forest, Farming, Exposed soil, Water bodies, Irrigated crops, and Sand (Figure 6).

Figure 6 – Maps of land use and land cover (1982 - 2016).



Source: Gomes (2019)

Among the different uses mapped, it can be observed that the area devoted to farming remained practically the same throughout the period analyzed (about 2.74% of the total area in 1982 and 2.52% in 2016). However, the field suffered a reduction of about 22%, going from 74% of the total area in 1982 to about 54% in 2016 (Figure 6 and Table 1).

However, there was a small increase in the area devoted to irrigated cultivation, which grew from about 13% in 1982 to about 14% in 2016. There was also an increase in the riparian forest class, which, in 1982, represented about 12% of the total area, and, in 2016, became 22%.

Table 1 – Area calculation by land use.

	January/1982		January/2016	
	Hectare	%	Hectare	%
Riparian forest	18,617	12.67%	32,554	22.86%
Water bodies	7,036	4.79%	7,155	5.02%
Fields	94,711	64.45%	74,456	52.05%
Farming	4,031	2.74%	3,600	2.52%
Irrigated crops – rice	19,533	13.29%	20,161	14.16%
Forestry	0	0.00%	2,796	1.96%
Exposed soil	2,344	1.60%	950	0.66%
Total	146,272	100.00%	141,672	100.00%

Source: Gomes (2019)

Forestry is observed only in the year 2016 because the incentive to plant exotic species began in the late 1970s when the first studies were conducted in the 1st phase of the Alegrete Pilot Plan. The actual planting of eucalyptus occurred later. Statistical data for the municipality of Alegrete, available in the IBGE's Agricultural Census, show an increase in the area occupied by crops (from 26,000 ha in 1970 to 107,000 ha in 2017) and a decrease in pasture areas (from 680,000 ha in 1970 to 575,000 ha in 2017).

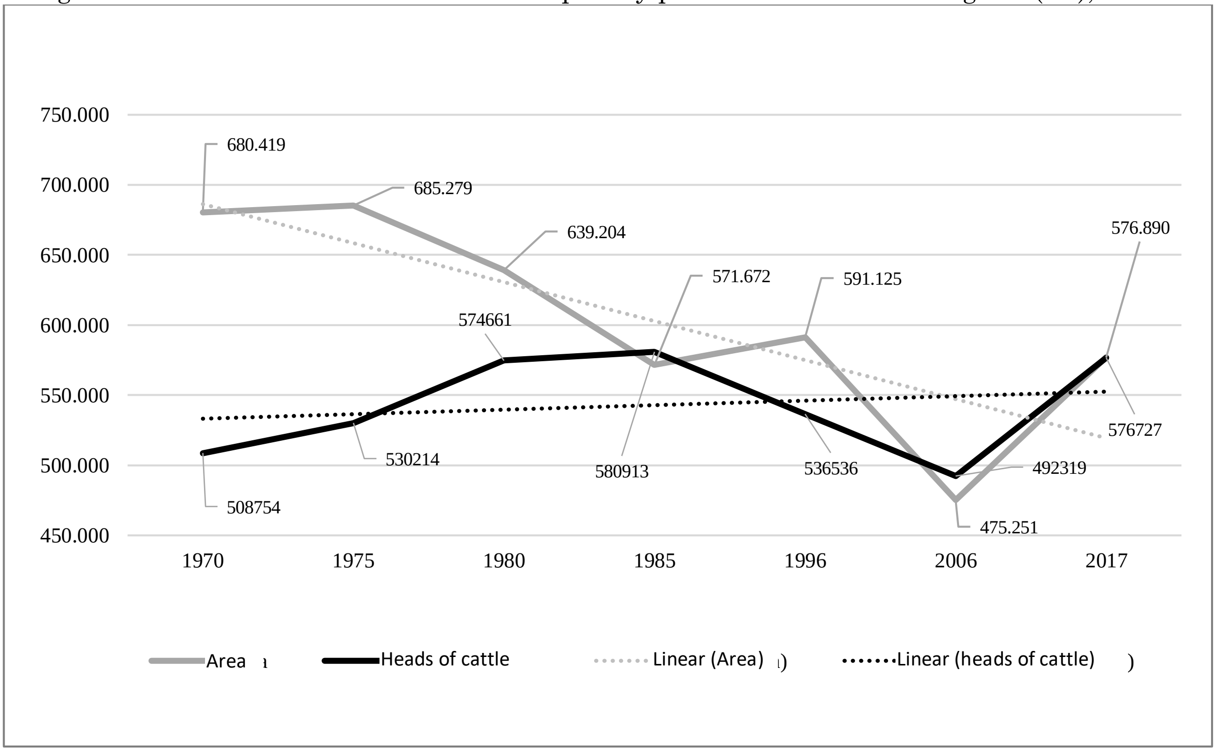
Regarding soybean production, it did not exist, in 1960, but, in 2017, it is the second-largest crop produced, increasing from only 162 tons, in 1970, to about 124,000 tons, in 2017.

Analyzing the production of other temporary crops in Alegrete municipality, it is identified that rice has been produced, since 1960, continuously increasing its yield. It was produced about 20 thousand tons in 1960 and about 480 thousand tons in 2017, according to IBGE's agricultural censuses.

The other crops (corn and wheat) have low production, besides suffering natural restrictions, specifically in the case of wheat, serving to supply only the local market. Alegrete presents a different profile from neighboring municipalities, in which soybeans have been replacing, even, rice crops and pastures, as shown in the numbers of rice production in the municipality. This temporary crop was the one that grew the most, possibly because of its location near the Ibicuí River and its tributaries, whose alluvial plains are favorable for this crop.

Data from the IBGE's Agricultural Census also show the evident decrease in the area occupied by pasture between 1970 and 1985. From the mid-1980s on, the crop activity gains area, until 1996, the point at which it again loses space. The resumption of the gain in the area allocated to pasture occurs from 2006, extending to the present day (2017).

Figure 7 – Relation between the areas occupied by pasture and cattle in Alegrete (RS), Brazil.



Fonte: Gomes (2019).

Cattle production remains constant and discrete, but growing, with a decline between 1985 and 2006 and a resumption until 2017. The overall issue is that the cattle production increased and pasture area decreased, over the years, causing pressure on the herbaceous vegetation cover and the soil, corresponding to a standard behavior in the region, since the neighboring municipalities present similar situations.

Another interesting fact concerns the acquisition of the machinery of mechanized agriculture. In 1960, at the beginning of the Green Revolution, Alegrete's farmers cultivated the land with 382 tractors and this number exceeds two thousand units in 2017. The other types of machinery, used in planting and harvesting, also remain at constant acquisition rates, according to the agricultural censuses of the IBGE.

Furthermore, the overlapping of both geomorphologic features and land use and land cover mapping establishes a relationship between linear erosive processes, uses, and conversion of uses. Table 2 shows the area occupied by each geomorphologic feature, relative to the distinct uses, however, it should be pointed out that there may be an area exaggeration in the result, as the calculations were made from raster and vector data, which may imply distortions in the final sum of the areas.

The Fields remains the most significant use, corresponding to about 52% of the total area, considering the natural characteristic of the Pampa. When we relate this use to wind and sand spots and erosive processes, we see that of the 74,456 hectares, 15,605.28 are wind deposits, with the occurrence of 59.13 hectares of sand spots and 465.03 hectares of erosive processes.

Table 2 – Land use and land cover vs wind deposits, sand spots, and processes.

WIND DEPOSITS			
	2016 (Landsat 8 – Jan.)*		
USE	Area of use (in ha)	Area of wind deposits in use	
		In pixels	In ha (0,09)
Fields	74,456	173,392	15,605.28
Irrigated crops	20,161	62,012	5,581.08
Water bodies	7,155	9,867	888.03
Exposed soil	950	6,384	574.56
Riparian forest	32,554	23,737	2,136.33
Farming	3,600	7,388	664.92
Forestry	2,796	8,152	733.68
ACTIVE SAND SPOTS			
	2016 (Landsat 8 – Jan.)		
USE	Area of use (in ha)	Active sand spot area in use	
		In pixels	In ha (0.09)
Fields	74,456	657	59.13
Irrigated crops	20,161	3,342	300.78
Water bodies	7,155	688	61.92
Exposed soil	950	4,918	442.62
Riparian forest	32,554	381	34.29
Farming	3,600	6	0.54
Forestry	2,796	7	0.63
EROSIVE PROCESSES			
	2016 (Landsat 8 – Jan.)		
USE	Area of use (in ha)	Area of erosive processes in use	
		In pixels	In ha (0.09)
Fields	74,456	5,167	465.03
Irrigated crops	20,161	1,903	171.27
Water bodies	7,155	843	75.87
Exposed soil	950	145	13.05
Riparian forest	32,554	1,829	164.61
Farming	3,600	173	15.57
Forestry	2,796	5	0.45

*Landsat 8 → 1 pixel = 0.09 há

Source: Os autores (2022).

Still concerning the overlapping of the mapping of geomorphological features with land use and land cover, observing the 26,557 hectares of field area converted into irrigated cultivation, farming, and forestry areas, which characterize uses that are not appropriate for the primary aptitude of the Pampa, it is possible to add 187.29 hectares of linear erosive processes in this converted portion.

The eolic and sand spots near the riparian forest and irrigated cultivation areas, mostly located on the banks of waterways, characterize fluvial deposits, composed of sediments originating from eolic and fluvial deposits, which are difficult to differentiate and classify because they are composed of eolic and fluvial sediments.

It can be said, finally, that the distinct uses of the areas on the hills, associated with wind deposits, determine both environmental and economic dynamics in the Brazilian Pampa. The conversion of use, especially from pasture land to crops, has intensified the pressure on water resources, on the herbaceous vegetation of the fields, and on the soils, which are particularly sensitive to erosion.

FINAL CONSIDERATIONS

The stable and/or unstable eolic deposits hold evidence of the water and wind dynamics in the remobilization of the sand spots, influencing the formation and transformation of the current landscape, harboring specific geomorphological characteristics of the Brazilian Pampa region, making it unique in the world.

The different uses of the hills, associated with stable and/or unstable eolic deposits, determine the environmental and economic dynamics of the Brazilian Pampa. As already mentioned, the Pampa's primary aptitude is livestock raising, and the conversion of use, especially of pasture land into crops, intensifies the pressure on surface and subsurface water resources, herbaceous vegetation, and soils most sensitive to erosion.

The fragility of the wind morphologies, associated with inadequate agricultural practices that are incompatible with cattle raising, potentiate the erosive-depositional processes on the wind deposits and reveal the relation between society/nature under new variables, especially those related to economic activities, linked to agriculture and cattle raising (extensive cattle raising and cultivation of monocultures), fundamental to the agribusiness sector.

In the future, it is important to study the occurrence/continuity of the migratory flow of farmers from the north of the State, especially soybean farmers, to west and southwest, to produce on leased land and, above all, as well as to examine the impacts of the practice of field conversion on the wind deposits studied, taking into consideration that the problem of sandization greatly affects small and medium producers, revealing an issue of induction to land concentration.

Finally, another important study to be carried out is the need to identify the hydric erosive processes still active in the drainage network, which seeks to reestablish their dynamics, before the deposition of sediments during periods of drought, which clog the valley bottoms and are often being resumed through the intervention of rural producers. In this sense, the generation and aggravation of erosive processes, in the form of ravines and gullies, can be unleashed and aggravated if there is no technical monitoring.

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AUTHORS' CONTRIBUTION

Tania Cristina Gomes conceived the study, conceptualized, collected and analyzed data and wrote the original draft, since the article sent for submission to the Sociedade & Natureza Journal, entitled **"**Sandization: climatic dynamics, erosive-depositional, land uses, and land cover in the Brazilian Pampa at present " "" is part of the thesis of the 1st author. The authors, Roberto Verdum and François Laurent, contributed as supervisors of the thesis that gave rise to this article, and in the article, they were responsible for the review reading, suggestions for alterations of all the steps carried out by the 1st author. Neemias Lopes da Silva contributed in the stages of technical procedures of acquisition, composition and processing of LANDSAT images and, choice of methodology, applied in the mapping of land use. It should be noted that all authors made substantial scientific and intellectual contributions to the present study.