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Avulsions drive ecosystem services and economic changes in the Brazilian Pantanal wetlands

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ABSTRACT

The Pantanal wetland is a mosaic of landscapes that brings together rich biodiversity with the valuable activities of fishing, tourism and ranching. Human occupation and land use in the headwaters have intensified the rate of channel avulsions in the lower reaches of the largest megafan on the Taquari River. This study evaluates the long-term changes of landscapes in the active depositional lobe of the Taquari megafan from the perspective of local communities of *pantaneiros*. Maps derived from multiple decades of multispectral Landsat data have proven useful for studying land cover changes through the relationship between dry (terrestrial vegetation and soil/dry pastures) and humid landscapes (open waters, aquatic macrophytes and wet soils), as well as through Sankey diagrams and spatiotemporal mapping with Boolean operations according to the rate of dryland recovery. We found that dryland recovery associated with an older and smaller avulsion (known as Zé da Costa) is analogous to that of a most recent and much larger avulsion (known as Caronal), which is still ongoing and has greater importance due to the scale of the impacts. Land value and fish capture depreciate as the partial Caronal avulsion still evolves, increasing the likelihood of environmental conflicts. While *pantaneiros* no longer profit from ecosystem services of provision (e.g., livestock or fishing), dryland recovery may deliver quantifiable ecosystem services of regulation. The strengthening of partnerships among stakeholders and the implementation of environmental compensation mechanisms are central for the best management of the Pantanal's megafans that ensure quality of life for all *pantaneiros*.

1. Introduction

The Pantanal wetlands gather lush ecosystems that are influenced by interannual and seasonal floods and droughts (Junk and Nunes da Cunha, 2005; Alho and Sabino, 2011). The spatial and temporal variabilities in physical, chemical, biological and socio-economic processes are modulated by the magnitude, duration and frequency of the floods in the Pantanal (Silio-Calzada et al., 2017; Ivory et al., 2019). The Pantanal wetland is an active lowland sedimentary basin surrounded by plateaus (Silva and Abdon, 1998; Assine et al., 2015a, 2015b, 2015c), where alluvial depositional systems are important drivers of landscape changes via channel aggradation (see the glossary in Section 3 of the Supplementary Material) and river avulsion dynamics often in response to climate change (Assine, 2005; Kuerten et al., 2013; Assine et al., 2015a; Rasbold et al., 2019). At geologic timescales, the history of river avulsions (see Section 3) shapes the configuration of fan and interfan environments (Assine et al., 2015b, 2015c). Recent unsustainable land use practices in upland catchments (e.g., on the plateau), and more frequent erosive summer rainfalls, have been jointly increasing the probability of river avulsions in the lowland plains (Bergier et al., 2018), particularly in the Taquari River megafan (Assine et al., 2015b, 2015c). These land-use changes can lead to dramatic consequences for the biodiversity, climate, socio-economy and ecosystem services in the lowlands.

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The Taquari megafan is the largest in Pantanal, covering an area of approximately 50,000 km^2 (Assine, 2005). Recurrent avulsions have formed many channel belts (Assine, 2005) and lobate landforms (Zani et al., 2012) within the active zone of deposition. As an example, in the 1980s, the Zé da Costa avulsion initiated near the upstream river mouth on the fan fringe and the complete process that shifted the river course endured only a decade, demonstrating the speed of the phenomenon (Assine, 2005).

During the late 1990s, an upstream and much larger avulsion, known as Caronal (Assine, 2005; Assine et al., 2005; Makaske et al., 2012; Zani et al., 2012), started with crevassing (see Section 3). The large avulsion is still in progress and may evolve to a complete avulsion, shifting the entire river course and changing its confluence ~100 km northwards with the Paraguay River (Assine, 2005; Assine et al., 2015a). Both avulsions likely resulted from an increase of riverbed elevation via sediment aggradation, which led to the failure of poorly vegetated levees and unconfined flow outside of the channel. Crevassing of marginal levees (see Section 3) during high fluvial discharge (see section 3) events caused diversion of water flow into the adjacent floodplain, eventually with sediment progradation (see Section 3) developed as crevasse splays (Assine, 2005; Makaske et al., 2012).

Numerical modeling has shown that both the size and duration of an avulsion depend on an intricate balance between water and sediment discharge, vegetation root strength, and substrate erodibility (Nienhuis et al., 2018). The Zé da Costa avulsion has stabilized via a new channel and formation of an avulsion belt (alluvial sand ridge) in about a decade. The Caronal avulsion is still in progress, and the new avulsion belt has been growing at a rate of about 23.5 km^2 per year (Stael et al., 2018a).

The Taquari River meander belt axially bisects the megafan into two large areas dominated by abandoned lobes (Assine, 2005; Assine et al., 2005): the Paiaguás (North) and Nhecolândia (South). These large areas are mainly flooded by pluvial runoff (see section 3) since water from the river rarely reaches these terrains (Assine et al., 2015b). The meander belt is a bypass zone that transfers waters from the catchment area on the eastern plateaus to the active depositional lobe, which is affected by annual river floods in terms of both geomorphology and plant ecology (Ivory et al., 2019; Louzada et al., 2020).

Variations in flood patterns and flooded areas have changed local morphologic landscapes in the Pantanal wetland, which constrain vegetation distribution, since wetter sites are colonized by aquatic vegetation (Coutinho et al., 2018), whereas drier sites are occupied by terrestrial vegetation (Tiner, 2016). During the formation of alluvial sand ridges and river rechannelization following an avulsion (the so-called process of landscape restoration), formerly dry sites become wet. Nonetheless, in the long-term, they eventually return to drylands (Nienhuis et al., 2018; Louzada et al., 2020). In this way, avulsions may play a critical role in reshaping ecosystem services (ES) (e.g. fish stocks, water quality, sediment control, food production) and economic activities (e.g. tourism and cattle ranching) in wetlands, such as the Pantanal.

The ES (Costanza et al., 1997; de Groot et al., 2002; de Groot et al., 2012) are intimately associated with strategic co-benefits of the 17 Sustainable Development Goals (SDG) of the United Nations (https://sdgs.un.org/goals). From those, the SDG No Poverty (SDG 1), Zero Hunger (SDG 2), Clean Water (SDG 6), Climate Action (SDG 13) and Life on Land (SDG 15) can be connected with ES of provision (SDG 1 and 2) and ES of regulation (SDG 6, 13 and 15) driven by avulsive processes in wetlands. Understanding river avulsion roles in ES and SDG is urgent due to changes in precipitation extremes that may intensify avulsion rates (Bergier et al., 2018; Thielen et al., 2020). Moreover, although wetlands occupy only 3% of the global surface area, they gather 43.5% of the global ES (Davidson et al., 2019).

The perception that river avulsions are major drivers of land use changes, and, consequently, drive ES changes that affect people in wetlands is not new (Junk and Nunes da Cunha, 2005; Junk et al., 2006). Nevertheless, the connections with SDG and empirical evidence are scarce. As the Zé da Costa and Caronal avulsions in the Pantanal are recent phenomena, they provide excellent natural laboratories to improve the understanding of the nexus between avulsions and their consequences over social, economic and ecological changes.

Socioeconomic studies of local people living in the Pantanal (*pantaneiros*) have provided evidence of the major impacts avulsions have for traditional ranching (Ioris, 2016; Guerreiro et al., 2019; Schulz et al., 2019) and fishing communities (Chiaravalloti, 2017; Louzada and Brito, 2018; Chiaravalloti and Dyble, 2019; Schulz et al., 2019). The risks to food security and relationship with social assistance from government programs in traditional communities are also threatened by Curado (2004) and Conceição et al. (2016). Nevertheless, the extent or time duration of those impacts are rather unclear, which make appropriate policy-making concerning the SDG and ES difficult.

Channel aggradation, crevassing, avulsion, rechannelization and new landscape development are interlinked processes that, depending upon spatiotemporal scales and discharge intensity, may take decades to centuries to occur (Overeem and Brakenridge, 2009; Paola et al., 2011; Nienhuis et al., 2018). A growing understand of these interlaced processes in Pantanal has been gradually achieved by multispectral and microwave remote sensing and Geographic Information System (GIS) (Souza et al., 2011; Evans and Costa, 2013; Miranda et al., 2018; Lisenby et al., 2019). In turn, this work aims to shed new light about the underlying nexus between SDG and ES (Costanza et al., 2014; Costanza et al., 2017; Yang et al., 2020) changes via decadal mapping of land cover changes in the active depositional lobe of the Taquari River megafan Louzada et al. (2020). We evaluate the nexus of land use changes with SDG and quantifiable ES of regulation (e.g. provision of habitats, maintaining biodiversity, prevention of water scarcity, SDG 6, 13 and 15), and provision (economic activities, SDG 1 and 2), like timber, pasture and fodder production (Tasser et al., 2020). The information presented and discussed here are then expected to be useful e.g. for policy-making via environmental compensation mechanisms.

2. Material and methods

2.1. Study area

The active (modern depositional) lobe of the Taquari River is located between latitudes 18° to 19°30′ S and longitudes 55°30′ to 57°30′ W in Mato Grosso do Sul state, municipality of Corumbá, surrounded by the abandoned lobes of Paiaguás (north) and Nhecolândia (south) (Fig. 1).

Paleochannels of abandoned depositional lobes are preserved on the surface of the Taquari megafan (Assine and Soares, 2004). The active depositional lobe covers an area of about 10,500 km^2 of the Taquari River megafan (Assine, 2005), and has a triangular shape, with an apex coinciding with the megafan intersection point (IP) (see Fig. 1). The active lobe extends from the west up to the Paraguay River trunk system (Assine et al., 2015a). The new channel of the Taquari River formed due channel splitting in the beginning of 2000s (topographic profile in Fig. 1) and currently can be navigated by small boats downstream to the Paraguay River.

2.2. Flowchart of methodology

The methodology summary is shown in Fig. 2 and a complete description is detailed in Section 1 of the Supplementary Material. In short, the study was addressed by the temporal classification of Landsat images, multicriteria analysis using Sankey diagrams and Boolean rules in ArcGIS 10.4.1, and SDG and ES relationships with changing landscapes of the Pantanal. (https://sdgs.un.org/goals).

3. Results

3.1. Geomorphological zonation

The active lobe of the Taquari River has a triangular shape (Zani,

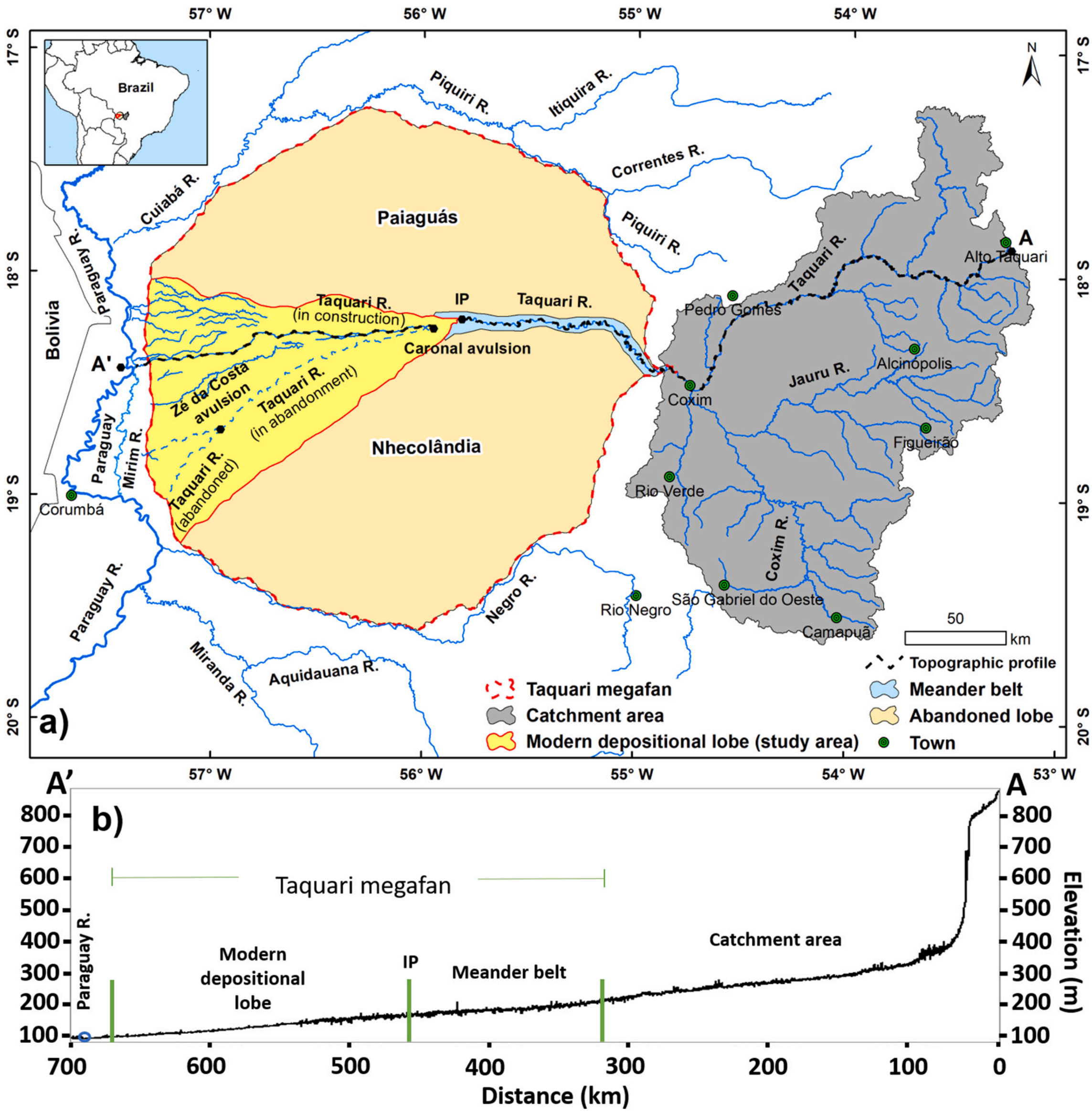

Fig. 1. The Taquari drainage basin (a), showing the upper bedrock (catchment areas in light gray) and lower alluvial reach (the megafan in orange/yellow) divided by the green marks. The active depositional lobe (yellow) is bordered by abandoned lobes of Paiaguás (north) and Nhecolândia (south) and starts after the intersect point (IP). The topographic profile (b) is a watercourse transect from A (catchments) to A' (confluence with Paraguay River). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2008; Assine et al., 2015a) and characterized by a complex landscape, which resulted from a superimposition of many different depositional features and channels, and paleochannels entangled by vegetated areas. NDVI data in 1:700,000 scale was useful for compartmentalizing the active lobe into major lobe zones (Fig. 3) related to distinct periods of channels activity and sand deposition forming lobed landforms (Buehler et al., 2011). These lobe zones are discernible because of differences in water content (NDVI ranging from −1 to 0.6) and greenness of landforms (from 0.6 to 1) (Assine et al., 2005). While the intra-depositional lobe A shows intermediate NDVI values, indicating some greenness, the intra-depositional lobe B shows high values of NDVI due to the presence of riparian forests of paleochannels (Fig. 3). On the other hand, the lobe C has predominantly lower NDVI values that reflects topographically low flooded areas, presently being filled by sediments brought by new anabranching fluvial channels derived from crevasses at the Caronal farm.

The association between NDVI and DEM data allows grouping generic lobed landforms by similarities in terms of the depositional processes (Zinck, 2013). Transverse topographic transects (Fig. 4) reveal that the landform features of three major depositional lobes are determined by the long-term dynamics of frequency and duration of avulsions, resulting in elevated, lobed landforms (Zani et al., 2012). The longitudinal slope decreases from east to west the transversal transects exhibits convex geometry, and the mean surface slope in each zone follows B > A > C.

The officially registered Taquari River (IBGE, 1982) in lobe B is topographically higher than C, where the river is braided at all transects (Assine, 2005). Other borders of the lobed landforms were delimited by relatively high elevations, probably associated to relicts of riparian woody forests (see e.g. A1 to A3 and B1 in Fig. 4), suggesting that subtle arching in crossed profiles is linked to an abandoned lobe (see e.g. Chakraborty et al., 2010).

3.2. Decadal map of the active lobe

The four decadal maps are presented in Fig. 5 overlaid by the

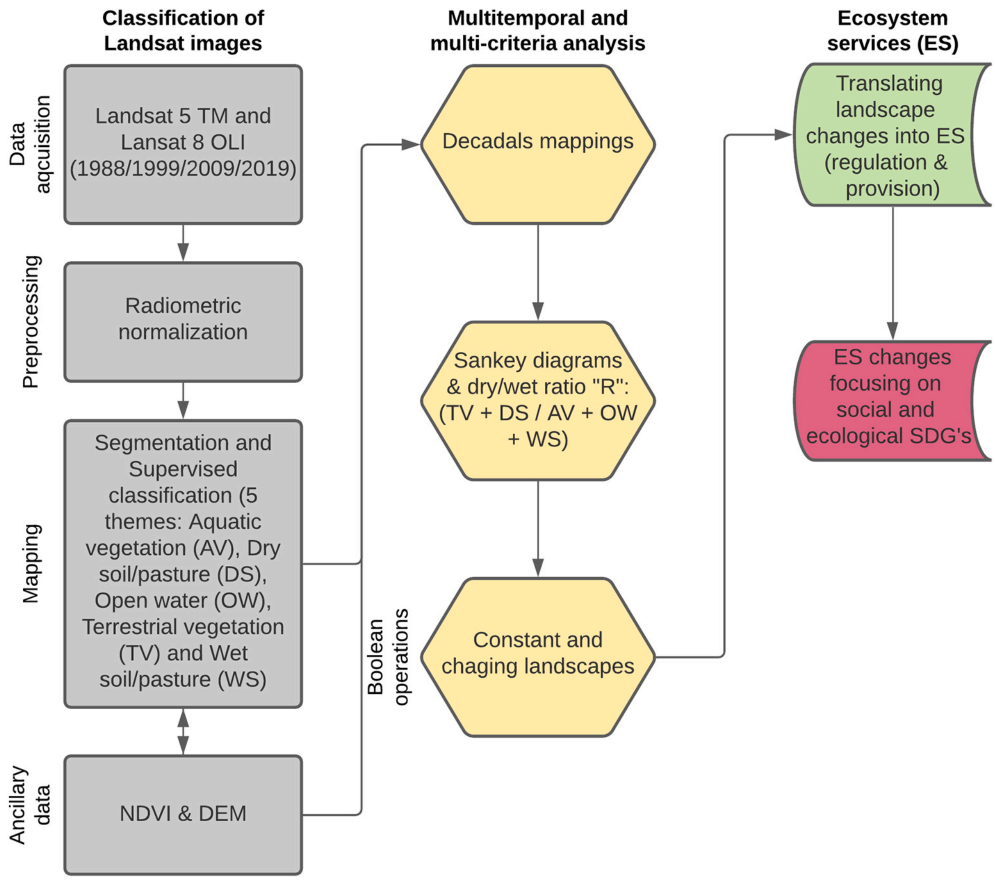

Fig. 2. Flowchart of methodology gathering the key processes to analyse the decadal landscape changes in the modern lobe of Taquari River megafan.

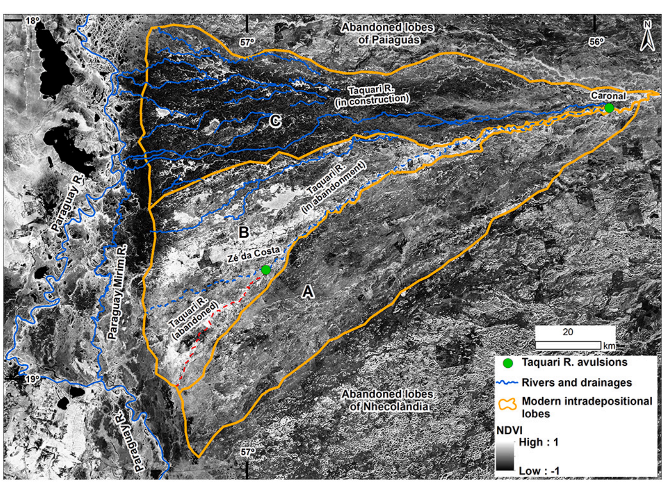

Fig. 3. Morphologic zonation of the active depositional lobe of the Taquari River: (A) Old lobe (nowadays inactive), (B) Pre-modern (in abandonment), (C) New lobe (in construction). (NDVI image from Landsat-8 OLI 2019 bands that ranges of 1 to terrestrial and − 1 to aquatic sites).

depositional lobes A, B and C. In 1988, the active lobe was a balanced mosaic of landscapes, except in the intra-depositional lobe B where terrestrial and aquatic vegetation, TV and AV, respectively, prevailed. Eleven years later, the large Caronal avulsion in lobe C stands out, reflecting the contrasting dryness of lobes B and A.

By 2009, crevasse splay growth (WS and TV) is clear in lobe C, along with the prevalence of downstream OW and AV. Alternatively, TV and DS dominated the landscapes of lobes A and B. Later in 2019, the crevasse splay in lobe C is even more evident, while TV and DS increased in lobes A and B, and AV markedly increased in lobes A and C. By considering Figs. 4 and 5, it can be interpreted that, in terms of deposition and landform changes, lobe A is older than B, whereas lobe C might be younger than A and B.

The Zé da Costa avulsion in lobe B is the best-studied case of a full avulsion in the region assessed via Landsat timeseries (Assine et al., 2005). By 1998, likely due to an ancient upstream crevasse (see Louzada et al., 2020), AV predominantly occupied the area inundated by the avulsion in 1999. The landscapes changed sequentially from AV to a mosaic of OW, WS and TV. After 21 years, the landscape was then dominated by terrestrial landscapes (DS and TV) and the river channel was reestablished by 2019. Since then, the Taquari River seems to be permanently moving its mouth in the direction of lobe C.

3.3. Temporal landscape changes in the active lobe

Temporal studies of landscape changes via Sankey's diagrams and R indexes are depicted for each intra-depositional lobe A, B and C in Fig. 6. The relative landscape changes for each decade are given in Table S5.

In lobe A, the most important landscape change from 1988 to 1999 was AV to WS (15.23%), while from 1999 to 2009 and 2009 to 2019 the change from WS to TV (14.1% and 11.9%, respectively) was remarkable.

Lobe B exhibited visible changes from AV to WS of 14.8% in the period 1988–1999, a consequence of morphologic changes associated with the Zé da Costa avulsion. Another key change from AV to TV (10.8%) is perceptible, likely due to avulsion backswamp development and stabilization of terrestrial pioneer species (see e.g. Marchetti et al. (2020) for similar processes). At lobe B, during the transition between 1999 and 2009, TV switched to WS (17.4%), counterbalanced by changes of WS to TV (11.2%). The more recent transition at lobe B

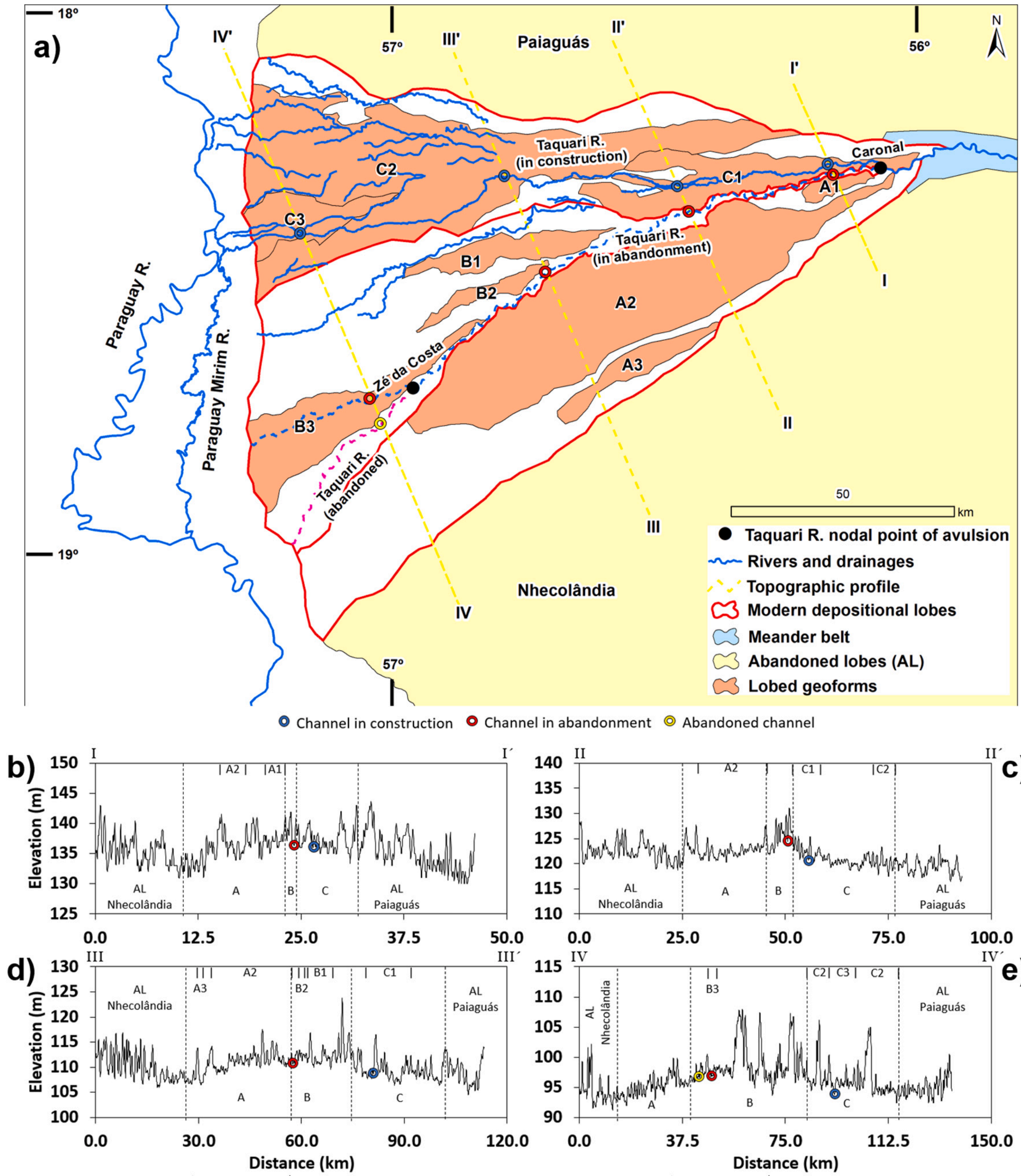

Fig. 4. Lobed landforms on the active lobe of the Taquari River megafan were mapped using NDVI and DEM data (a). The topographic profiles are shown in (b), (c), (d) and (e) (transects I-Í, II-IÍ, III-IIÍ, and IV-IV́), which were built using data from DEM (source: TOPODATA project). For clarity, a 300-m running average kernel was applied for transects II-IÍ, III-IIÍ, and IV-IV́. Blue circle is the Taquari River in construction by the crevasse on Caronal farm, red circle is the official river in abandonment and the yellow circle is the Taquari River abandoned before the avulsion on Ze da Costa region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

consolidated the full avulsion and terrestrial land recovery from WS to TV (21.61%) that culminated in a northward shift of the Taquari River channel (Louzada et al., 2020).

From 1988 to 1999, lobe C exhibited a balanced mosaic of the five mapped landscapes, in which the most important changes were WS to OW (8.1%) and DS to TV (7.1%). Since then, the region has been draining waters from the Caronal avulsion (Assine et al., 2005). During the transition between 1999 and2009, the most relevant changes were WS to TV (12.1%) followed by AV to OW (11.8%). More recently, lobe C abandoned any sign of rapid land recover, with landscape changes of OW to AV (16.2%), TV to AV (13.7%) and TV to WS (12%), leading to the formation of deadwood and permanent shallow floodplains (La Rovere and Mendes, 2000).

On the other hand, R index evolution in lobe B indicates land formation ($R > 1$). The same can be assumed for lobe A due to TV increases. In lobe C, however, the enduring inundated area by the Caronal avulsion provides an $R < 1$, with the predominance of AV and WS landscapes (Fig. 6).

3.4. Spatiotemporal landscape dynamics in the active lobe

Permanent and transitional landscapes in the active lobe of the lower Taquari River are shown in Fig. 7. while the percentage of areas are shown in Tables S9 and S10. Permanent landscapes were mapped with

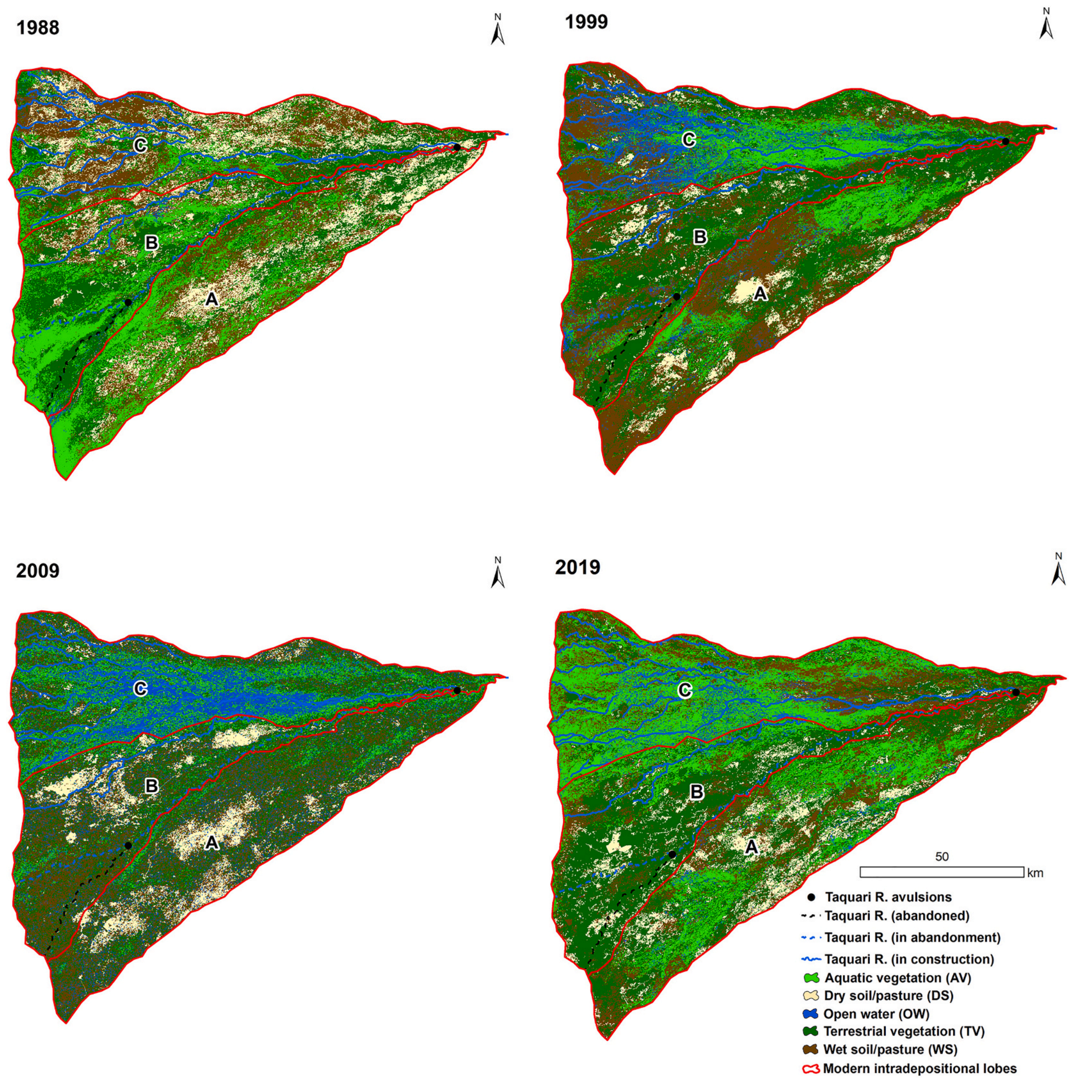

Fig. 5. Decadal maps of major landscapes in the active lobe of the Taquari River.

the Boolean rule 1988 U 1999 U 2009 U 2019 for each thematic class. As proposed by Adami et al. (2008), the location of permanent landscapes is associated with the topographic sequence from riparian forests (TV) to marsh sites (WS) and OW. Nevertheless, OW sites (i.e., the river channel), as expected for distributary drainage basins, showed the highest average elevation in recently abandoned channels of the Taquari River (see Fig. S3).

Transition landscapes have been labeled arbitrarily according to the rate of land formation (recovery) as fast, moderate, slow, and very slow. The Boolean rule for each transition was based on information obtained from Figs. 5 and 6. Very slow rate class merges all pixels in 1988 (TV U DS U AV U OW U WS) that remained wet (AV U OW U WS) from 1999 to 2019. The slow rate class aggregates only wet pixels until 2009 that turned out dry (DS U TV) by 2019. The moderate rate class gathers wet pixels up to 1999 that dried in both 2009 and 2019. Lastly, the fast rate class combined all wet pixels in 1988 that remained dry in 1999, 2009 and 2019. The relative distributions of the spatiotemporal classes for each lobed landform (see Fig. 3) are presented in Fig. 8.

By exploring DEM variability, it is possible to infer similarities that aggregate the lobed landforms into five groups:

1. A1, the most elevated and more homogenous;
2. A2 and C1, the highest in the terrain following A1;
3. A3, B1, and B2, situated in the middle region;
4. C2, more heterogeneous, over proximal, mid and distal portions; and
5. B3 and C3, featured in distal and less elevated areas.

The preceding groups, however, are rather evident from the perspective of spatiotemporal changes of landscapes, including permanent and background (undetermined changes) classes. For instance, higher proportions of permanent sites characterize A1, while A3 and B1 showed the highest percentage of fast transitioning sites. Equivalent relative proportions of slow and moderate transition sites merge B2 and B3 lobed landforms. On the other hand, C1, C2 and C3 can be joined due to high proportions of very slow sites. Otherwise, A2 is comparable to A1 with respect to permanent classes, but has analogies with C1 and C3 regarding very slow sites.

4. Discussions

4.1. Temporal dynamics of landscapes in the active lobe

Changes in avulsive rivers generally are controlled by channel patterns including depth, regional relief and topographic gradient, which are affected by differential subsidence, climate and base level changes (Allen, 1978). In addition, a key variable influencing channel length is water velocity.

Vegetation is also a decisive factor, where channel narrowing can

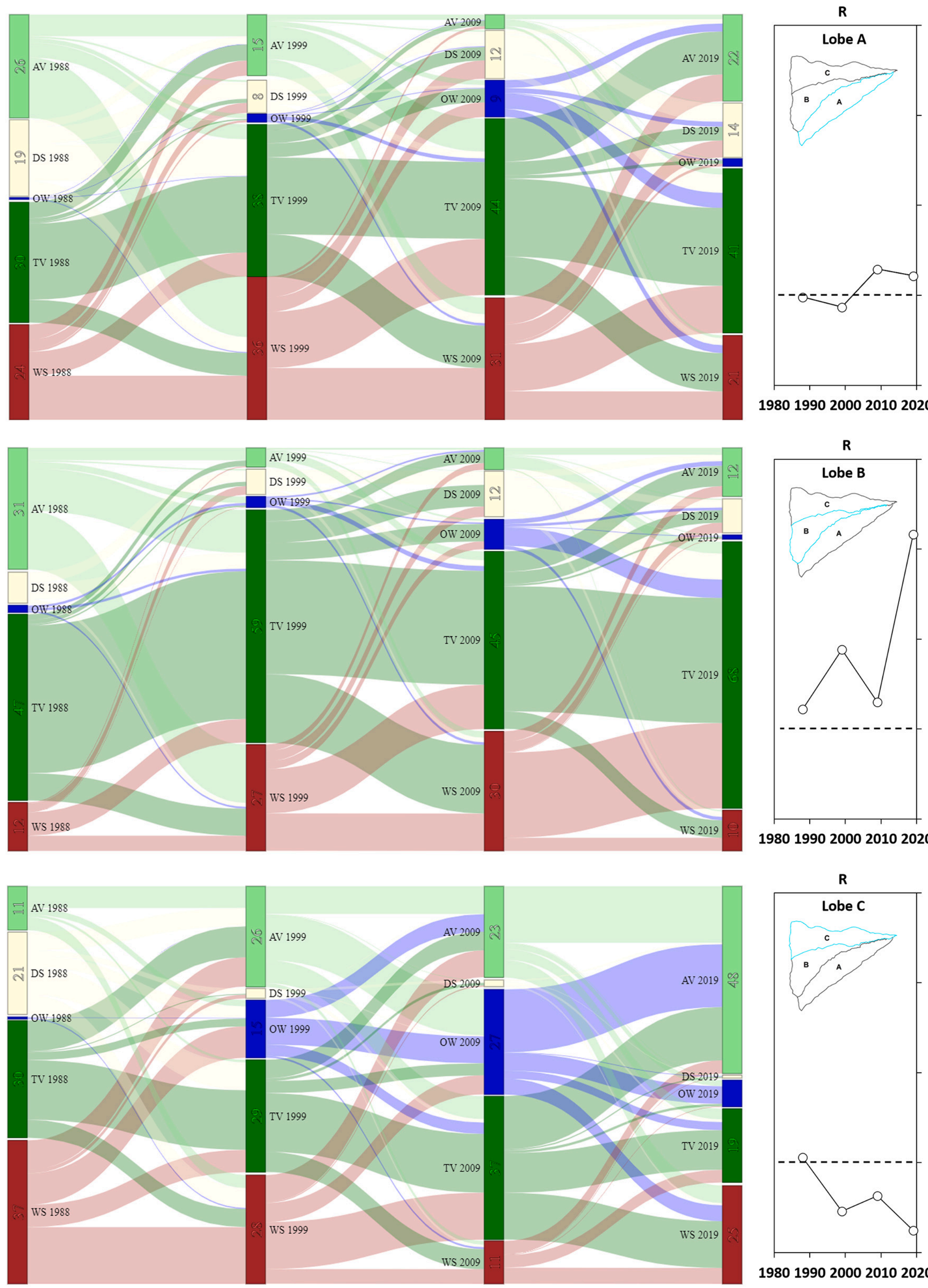

Fig. 6. Sankey diagrams and R indexes for intra-depositional lobes A, B and C of the Taquari River megafan. The ordinary values of fluxes by landscapes are shown in Tables S6, S7 and S8.

result from levee protection by the roots of riparian species (Coulthard, 2005; Nienhuis et al., 2018; Marchetti et al., 2020). Thus, at local scales, vegetation influences flow velocity and depth (Tal and Paola, 2010). Moreover, Bertoldi et al. (2011) suggest a two-way interaction, the simultaneous increases of stabilized levees by plant roots and of the roughness effect due to the retention of inorganic and organic (usually refractory) sediments.

Some opportunist riparian species play a role in the development of anabranching patterns at distributary river systems (Gibling et al., 1998), where plant growth, sand deposition (Weissmann et al., 2013; Nienhuis et al., 2018) and channel formation are all concurrent (Tooth et al., 2008; Tal and Paola, 2010). The understanding of those

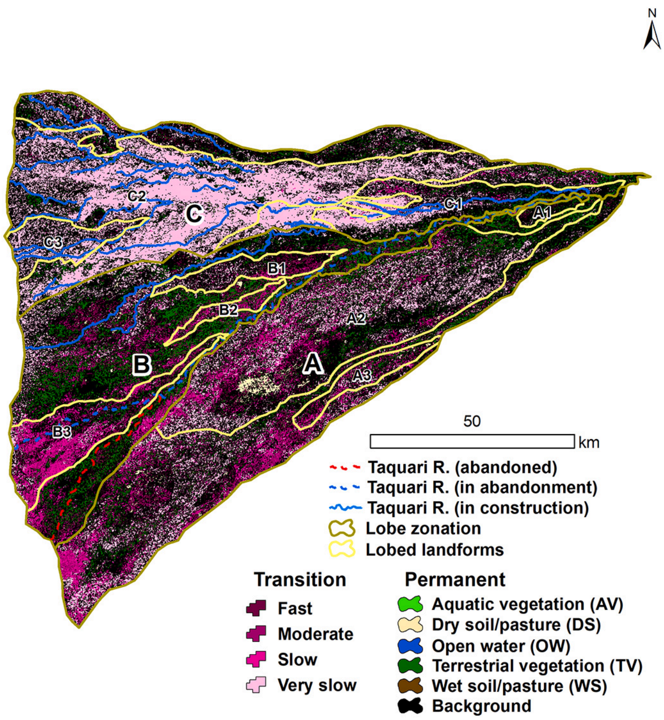

Fig. 7. Spatiotemporal mapping of permanent and transition landscapes from 1988 to 2019.

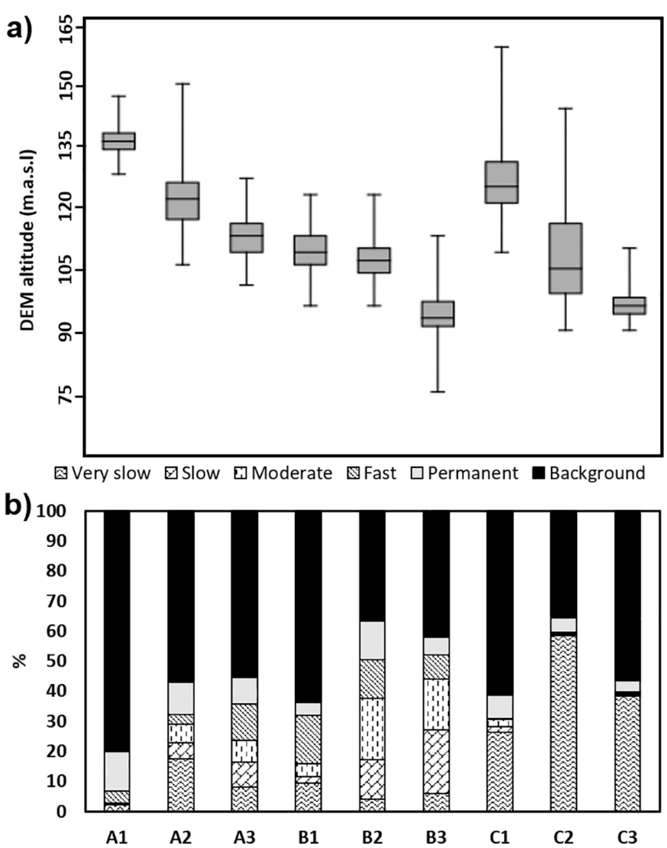

Fig. 8. The box plots of altitude (DEM) (a), and relative distribution of spatiotemporal classes in the lobed landforms at the active lobe of the Taquari River megafan (b).

interactions and feedback has been crucial for forecasting the geomorphic evolution of complex distributary river systems (Piégay et al., 2000; Nardin and Edmonds, 2014; Piliouras et al., 2017).

For the Zé da Costa avulsion, the abandoned lobe comprises stable TV in higher terrains (See Fig. 4), whereas lobe B3 contains topographically lower sites with slow to moderate rates of landscape changes. On the abandoned lobe, aggradation caused a channel super-elevation (see Fig. S4), hence less area available for sediment accommodation (Weissmann et al., 2013), forcing the avulsion in the direction of B3. Furthermore, the previous AV area in 1988 at B3 likely aided in developing an organic-rich substrate (Pott and Silva, 2015; Coutinho et al., 2018; Lo et al., 2019) for terrestrial woody species (see Fig. S5). For instance, AV decay can provide suitable conditions for the development of riparian forests (Piégay et al., 2000), thus increasing root roughness for the development of a single river channel (Coulthard, 2005; Luhar et al., 2008; Tal and Paola, 2010). Corenblit et al. (2020) recorded similar results in bio-stabilization by vegetation in a rectified channel in France.

A combination of channel aggradation, splay progradation and vegetation feedback in the Caronal (the huge lobe C) in the long-term can reproduce the full avulsion observed at Zé da Costa. The crevasse in the Caronal point has been responsible for continuous splay progradation induced by annual floods (Makaske et al., 2012). Consider that, within the avulsion, alluvial sand ridges and river rechannelization have an aggradation phase in dry seasons and an aggradation plus progradation phase during floods in rainy seasons by correlation with flow rate. By also including the root vegetation feedback, the Caronal avulsion in lobe C indeed resembles the Zé da Costa avulsion but at earlier stages (lobe B3) (Fig. 8).

While similar in terms of driving physical processes, lobes C and B3 have differences regarding process timespans due to scale, so it is very likely that these processes are scale invariant and produce self-affine patterns (Rodríguez-Iturbe and Rinaldo, 2001). Land formation and river rechannelization (full avulsion) in lobe B3 required about a decade, due to its lower size comparative to lobe C, for which much longer time might be necessary due to its larger scale. Therefore, in view of scale invariance properties and differences in characteristic timespans, it is possible that the year 2019 at lobe C is to some extent equivalent to the year 1988 at lobe B3 (see Figs. 5 and 8).

Overall, Zé da Costa and Caronal avulsions show in common a channel shifting towards to the north, with preferential crevasses on right-side levees (Assine, 2005; Makaske et al., 2012). In both cases, an intermediate phase with an anabranching (multichannel) river seeks its 'best route' according to the highest gradient (Smith et al., 1989). For the case of Zé da Costa, the search for the best route 'rapidly' concluded, with coupling to the channel named Negrinho River (Louzada et al., 2020), which connects to the Paraguay Mirim River, an abandoned channel of the Paraguay River (Macedo et al., 2014).

Harvey (2012) has shown that aggradation regularly occurs at distal portions of megafans, whereas progradation produces a type of avulsion belt with characteristic elongated alluvial ridges (Assine, 2005). At lobe C, the successive splay progradation at a rate of 23.5 km^2 per year (Stael et al., 2018a) have been possibly aided by wet-tolerant native grasses. Nevertheless, the roots of these grasses are too scant to stabilize soil erosion (Marchetti et al., 2013; Nienhuis et al., 2018; van Toorenenburg et al., 2018). Furthermore, most crevasses happened on the right levee towards the Paiaguás (Makaske et al., 2012; Stael et al., 2018a), where the mean altitude is lower than that at Nhecolândia. Unmanaged cattle grazing (see Fig. S5) and fishermen-induced crevasses may lessen roughness protection by natural vegetation. Therefore, the combination of unsustainable practices and successive layers of sand deposition with reduced vegetation at lobe C might be delaying an already very slow landscape restoration process due to scale (Fig. 8). Furthermore, it has been shown that, in the absence of flood pulses, grasses inhibit channel development (Piliouras et al., 2017).

On the outer borders of the lobe C, stable landscapes are hallmarks of ancient depositional lobes elevated on the terrain. In contrast, the shallow inundation at lower sites can provide suitable conditions for macrophyte proliferation (Silva et al., 2008; Marchetti et al., 2016). Over dry seasons, the growth of aquatic vegetation is synchronized with the accumulation of sediments, which is less evident during wet seasons due to progradation (Piégay et al., 2000; Tiner, 2016; Lo et al., 2019; Lacourse et al., 2019).

Our measurements of landscape dynamics at the borders of lobe C with lobes A and B suggest that land formation and river rechannelization will be confined in this area, due to the tendency of increasing stabilization in the inundated floodbasin (Buehler et al., 2011). Indeed, lobe C is a semi-confined system, in which the new river mouth might be located at lobe C boundaries with the Paraguay trunk system (megafan fringes), most likely in the upper Paraguay Mirim River.

Information about time duration of land formation and river rechannelization are somewhat scarce (Assine, 2005; Marchetti et al., 2020). As we have shown, the time duration of a full avulsion may largely rely on scale. Table 1 gathers estimated sizes (S in km^2) and time duration (Td in years) for full avulsions in the Pantanal and other analogous distributary systems.

Data in Table 1 corroborate our scale-free hypothesis, indicating that the time duration relates to avulsion size as $T_d = 0.79S^{0.59}$ with $r^2 = 0.70$. The scaling equation can be simplified to $T_d \sim \sqrt{S}$ by conjecturing that time duration scales with the square root of the avulsion size. As the avulsion size in lobe C has 3728 km^2, the conjecture and regression equations give a total characteristic time duration ranging between 61 and 98 years.

Geotagged digital pictures taken in 2020 revealed a set of anabranching channels in the mid portion of lobe C (Fig. S6), which is likely an intermediate stage of land formation and river rechannelization. Based on the previous scaling relations and modern dynamics at lobe C, between 38 and 75 years may be required to complete the full avulsion. Nonetheless, mid and distal portions of the active lobe comprise the largest water mass to drain, which is also influenced (dammed) by the fringes of Paraguay River trunk system (Junk and Nunes da Cunha, 2005; Assine et al., 2015a). Therefore, the continuous sediment supply (Weissmann et al., 2013), aided by a definitive abandonment of the parent channel might accelerate the completion of the full avulsion (Hooke, 2003).

4.2. *Ecosystem services (ES) and implications of our findings for "pantaneiros"*

Changes in landscapes due to avulsions have resulted in ecological and social implications, changing the balance in ES of regulation and provision. As previously noted, cattle breeder landowners and fishers (*pantaneiros*) can affect and be affected by river avulsion in the Taquari River megafan. At lobe C, the secular activities of cattle breeding have been prevented and the riverine population dependent on fish was forced to migrate due to losses in the ES of provision. In addition, the permanent flood has depreciated land price substantially (Lourival et al., 2008), and government public policies have been demanded ever since (Jongman, 2005). One possible strategy to cope with that problem is the monetary valuation of ES of regulation. That can be estimated as the net decadal change in ES, or simply ΔES (in US$/year) for each studied lobe. Values of ΔES are obtained by combining the net change areas (in km^2)

Table 1
Size and time duration of full avulsions in Pantanal and other regions.

	T_d (years)	S (km^2)	Reference
Sarda (India)	66	1615	Mitra et al. (2005)
São Lourenço (Brazil)	25	1008	Assine et al. (2014)
Saskatchewan (Canada)	80	399	Farrell (2001)
Taquari River (Brazil)	20	495	Louzada et al. (2020)
Mara (Tanzania)	15	163	Bregoli et al. (2019)
Thomsom (Australia)	4	21	Brizga and Finlayson (1990)

of each mapped class (Fig. 9) with their respective ES value given in Table S2. The estimated values of ΔES are shown in Fig. 9 and calculations are provided in Table S8.

Changes of ΔES in lobes A and B indicate an increase of monetary values of terrestrial ES, agreeing with R index changes shown in Fig. 6. On the other hand, ΔES associated with aquatic environments gained importance in lobe C, particularly in the decade 2009/2019. The net balance of ΔES for all classes at each decade change suggests a generalized loss of ES of regulation in the decade 1999/2009, but an increase of about 322,773 US$/year of ES of regulation at lobe C (Fig. 9). Because lobe C gathers most farmlands with losses in ES of provision (Araujo et al., 2018), the quantified gains in the annual ES of regulation during the last decade could be taken as an approximate reference for public policies mechanisms of environmental compensation for both livestock farmlands and fishermen.

Table 2 summarizes the main classes in the respective lobes linking ES with SDG (Campbell et al., 2018; Yang et al., 2020). A key connection is the land restoration by unconsolidated sediments transported by the river discharge, which are deposited (progradation). The organic fraction of the new land soil, or deposited in shallow lakes, as well as layers of underground soil in alluvial processes, can be targeted as an important carbon sink (Stallard, 1998), intensified in tropical lakes over the last century (Anderson et al., 2020). Indeed, soil formation is a crucial interface of geochemical processes and biodiversity, it is not surprising that Keesstra et al. (2016) pointed out soil science at the core among major SDG 1, 2, 3, 6, 13 and 15 (Yang et al., 2020).

AV and OW (major part of lobe C) are other fundamental sources of ES that provide SDGs, especially clean water and increased biodiversity. Confirming our explanations, recent efforts by the Brazilian government to map natural resources highlight the Pantanal with a well-preserved biome (IBGE, 2020a) that is fundamental for the delivery of regulatory and provisioning ES (IBGE, 2020b).

It is critical to integrate information about the active lobes of the Taquari River in land use policy strategies for reducing poverty and increasing food security in the region, such as by using economic incentives for improving sustainable chains and by creating programs of payments for ecosystem services that consider families under risk of food insecurity as priority beneficiaries. This is particularly critical for traditional communities in lobe B (e.g. Bracinho) that remain heavily dependent on government welfare programs such as "Bolsa Família" (Conceição et al., 2016). However, we recognize the social imbalances in the region and low levels of environmental awareness among local decision-makers are still challenges to be overcome for implementation of large scale programs of payments for ecosystem services (Schulz et al., 2015).

In the absence of national actions, regional proposals, like a recent municipal bill 2598/2017, has defined an area of 11,150 km^2 as the "Taquari Region", equivalent to the lobe C. The territorial planning aims to ensure the quality of life and the integration of *pantaneiros*, by outlining remaining elevated areas for Legal Reserve Compensation, through the issuance by competent body of the Legal Reserve Quotas within the Federal Law 12,651/2012 (Forest Code) for the preparation of the Rural Environmental Registry (in Portuguese, *Cadastro Ambiental Rural* or CAR). Alternatively, inundated areas affected by avulsions that are unfit to issue Environmental Reserve Quotas via CAR will be considered priority for payment for ecosystem services of regulation (e.g. sediment retention and water purification) made by affected *pantaneiros* through monetary compensation while unterminated the full avulsion.

This bill mechanism seems appropriate because neither cattle nor fish protein can be obtained from those once very productive lands. In lobe C, the ichthyofauna community has been severely impacted, with an increased predominance of small, low-value pioneer fish species (e.g. *Cichla piquiti*) (Resende et al., 2008; Súarez et al., 2013) due to flow and depth water changes, reflecting negatively on the '*piracema*' – larger fish migration and reproduction (see for example at the Pilcomayo River in

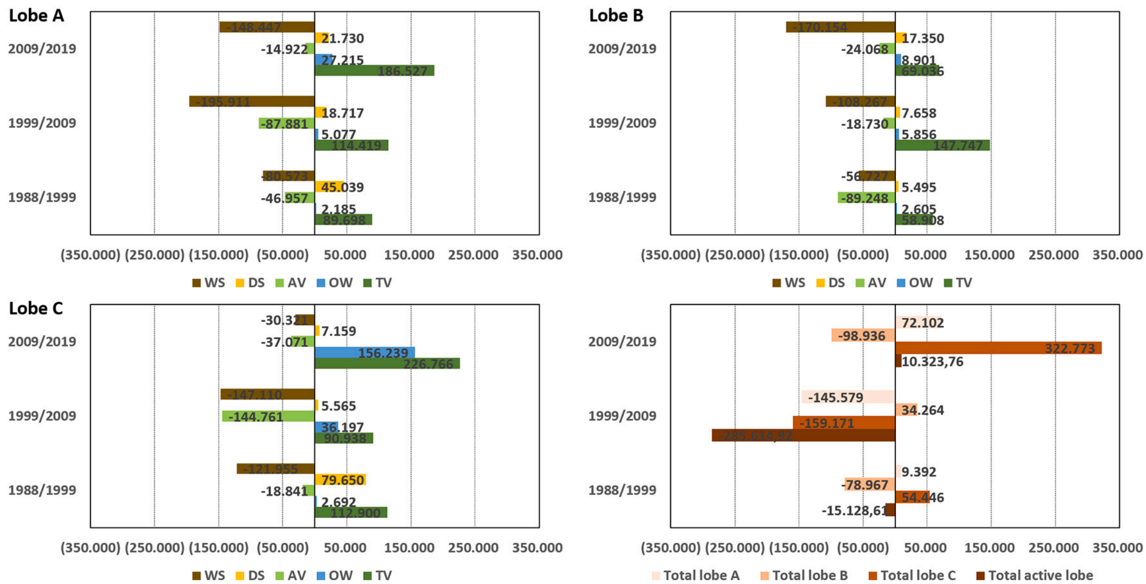

Fig. 9. Long-term changes in ΔES of regulation (in US$/year) calculated for each decade of change. The landscapes were AV (aquatic vegetation), DS (dry soil/ pasture), OW (open water), TV (terrestrial vegetation) and WS (wet soil/pasture).

Table 2
Relation between major landscape classes in lobes, ES and SDG.

Lobe	Class	ES	UN SDG
A, B	TV	Regulation (carbon retention, biodiversity)	Climate action (13) & Life on land (15)
A, B	DS	Provision (livestock and fish)	No poverty (1) & Zero hunger (2)
C	AV	Regulation (carbon and sediment retention, biodiversity)	Clean water (6), Climate action (13) & Life on land (15)
C	WS	Regulation (land restoration, carbon retention, biodiversity)	Climate action (13) & Life on land (15)
C	OW	Regulation (water supply, biodiversity)	Clean water (6) & Life on land (15)

Martín-Vide et al., 2014).

Despite the lack of research available on *pantaneiros* in the lower Taquari River, historical communities (e.g. Colônia Bracinho, Cedro, São Domingos, and Miquelina) in lobe B3 are, in general, very poor, sustained by subsistence crops and fisheries. They have been severely impacted by the flood in the 2000s (Curado, 2004), and have recently experienced aridification and social isolation due to difficulty accessing urban areas for health assistance. As a result, that community has been changing lifestyle by working on cattle farms that could expand production (Louzada et al., 2020), or migrating to adjacent urban areas, particularly Corumbá and Ladário municipalities (Louzada and Brito, 2018; Silva et al., 2018).

On the other hand, the avulsion in lobe C created new opportunities based on the sustainable collection of *Cayman yacare* eggs for a local industry of leather and meat (Stael et al., 2018b). Moreover, the avulsion also increases opportunities for the sectors of sport fishing and wildlife contemplative tourism. Nevertheless, future scenarios of changes on rainfall intensity and land use may enhance *pantaneiros* vulnerability due to increased likelihood of river avulsions in rainy summers (Bergier et al., 2018) or wildfires in drier winters (Marengo et al., 2021), but particularly due to the lack of consistent planning and implementation of sustainable land use practices at major rivers′ catchments (Bergier, 2013; Ivory et al., 2019; Oliveira et al., 2019). Therefore, the strengthening of partnerships among stakeholders and the implementation of environmental compensation mechanisms are central for the best management of Pantanal's megafans that ensure quality of life for the entire *pantaneiros* community (Schulz et al., 2015, 2019).

5. Conclusion

Major landscape changes in the active lobe of the Taquari River megafan are induced by avulsive river systems. By means of historical images, it was possible to identify the underlying mechanisms responsible for shaping the most important patterns (lobed landforms) in the landscape. We empirically confirmed that the aggradation, progradation and root vegetation feedback act synergistically in moving the main river channel within the active lobe, as a natural strategy to accommodate sediment in the plains. We also suggest that full avulsions could be self-affine processes, for which the characteristic timespan varies with scale as a power law. If that is correct, then the complete avulsion of Caronal region might occur from 2058 to 2095. However, unsustainable anthropic influences in river catchments and in the plains may postpone full avulsion, maintaining river instabilities in the active lobe, with severe implications for *pantaneiros*. While river recanalization is underway, gains in ecosystem services of regulation can monetarily compensate the losses in ecosystem services of provision due to man-induced avulsion by land use in the river catchment at the plateau. The turnover on environmental agenda is to make the lands affected by the Taquari avulsions more attractive for the *pantaneiros* to also solve their social inequalities.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crsust.2021.100057.

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