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A GIS-based assessment combined with local ecological knowledge to support the management of *Juncus acutus* L. spreading in the floodplain of a protected coastal lagoon

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ABSTRACT

The floodplains of brackish coastal lagoons are subject to a highly dynamic hydrological regimen mainly due to their intermittent connection with the ocean. Coastal lagoons generally support fisheries, while livestock ranching and human settlements are found in the floodplain. Therefore, it is common practice to artificially open the sand barrier to avoid floods and manage fish stocks. Saltmarsh species are subject to grazing pressure and to changes in flooding and salinity regimens, affecting plants' community structure. In the Laguna de Rocha Protected Landscape, a shallow brackish coastal lagoon located in Uruguay (South America), livestock ranchers complain about the spreading of the native cyperacea *Juncus acutus* L. The plant forms dense mats in the outermost zones of the floodplain, apparently displacing natural grasslands where the cattle graze. Also, stakeholders have encouraged the park authorities to artificially open the lagoon to obtain short-term benefits for fisheries and cattle raising. The study evaluated the increase in the surface area occupied by *J. acutus* and analyzed the possible causes of this increase as a basis for suggesting management actions. Historical and current aerial and satellite images, historical hydrological and climatic data and local ecological knowledge about the biology of the species and its spatial distribution over time were analyzed. The results indicate that *J. acutus* expanded in the floodplain of Laguna de Rocha, possibly starting ca. 2000, to cover less than 100 ha of the study area at low and high density. The results confirm most of the information obtained from the local stakeholders, whose local ecological knowledge was highly useful in understanding some local processes and providing information regarding periods for which data were not available. The expansion of *J. acutus* can be explained by a multiplicity of causes that acted synergistically to favor the species through a series of changes in the management of the sand barrier, livestock management and climate variability. However, a quantification of the economic effects of *J. acutus* on cattle feeding and fisheries is needed. Possible actions to control *J. acutus* expansion involve management of the grazing pressure using sheep, burning with fire, mechanical removal and avoiding artificial opening of the lagoon to allow larger and longer floods to occur and permit recovery of the previous, more natural hydrological regime. Our results suggest that it is important to be cautious before taking management actions to avoid costly solutions that are only short-term palliatives that could trigger other unforeseen environmental impacts.

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1. Introduction

Littoral wetlands (or riparian systems) are transitional semi-terrestrial areas that are regularly influenced by freshwater (and also brackish water); they usually extend from the edges of water bodies to the edges of upland communities (the floodplains of rivers and lagoons) (Naiman, Décamps, & McClain, 2005) and are among the most dynamic and productive ecosystems (Cronk & Fennessy, 2001). At the floodplains of brackish coastal lagoons in South America, saltmarshes are usually found (Isacch et al., 2006). Saltmarshes are influenced by physical factors including a highly dynamic hydrological regimen (mainly due to intermittent connection with the ocean and wind influence in coastal lagoons), the salinity gradient, and peat accumulation (Pennings & Callaway, 1992) as well as by precipitation (Boorman, 2003). The littoral saltmarshes of coastal lagoons can vary from freshwater to brackish or very saline conditions over short time periods. Therefore, plant species must continually adapt to flooding and to abrupt changes in salinity (Cronk & Fennessy, 2001; Pennings, Grant, & Bertness, 2005 and references therein). Littoral wetlands are also subject to various human uses, of which livestock ranching is one of the most extensive (Boorman, 2003; Di Bella, Jacobo, Golluscio, & Rodríguez, 2014). Ranchers manage these ecosystems to favor species that are palatable to cattle; drainage (Esteves et al., 2008; Isaach, 2008) and burning with fire are common management practices (Boughton, Quintana-Ascencio, Bohlen, Fauth, & David, 2016; Kirkman, 1995). In choked coastal lagoons, the opening of the sand barrier that temporarily separates the lagoon from the sea is usually artificially manipulated to regulate the water level (Gale, Pattiaratchi, & Ranasinghe, 2007; Pollard, 1994; Chávez, Mendoza, Ramírez, & Silva, 2017; Conde et al., 2019). Generally, flooding is avoided so that cattle can feed in wetlands, and land is progressively reclaimed from the lagoon.

All these human pressures are present in Laguna de Rocha Protected Landscape, a brackish coastal lagoon in Uruguay, South America. The surrounding lands are mainly dedicated to livestock ranching on natural grasslands, with increasing agricultural activity in non-flooded areas. Livestock ranching in Uruguay (and in Laguna de Rocha) is conducted on natural grasslands, being compatible with biodiversity protection under appropriate management practices (Blumetto et al., 2015; Modernel et al., 2016). Management in this protected area, must be judicious because it must balance the public interest in biodiversity protection with private interests of the land owners, under a lack of economic incentives for ecosystem protection. Cattle pasture up to the lagoon shores and also feed in wetlands. Ranchers value these ecosystems but manage them in an attempt to favor palatable species, not always with the expected results or using the practices most suitable for a protected area. Nevertheless, stakeholders such as ranchers and fishermen have long-term involvement with the area and profound knowledge of its species and ecosystems. Their knowledge is very valuable for understanding ecosystem changes and their causes and consequences as well as for developing management alternatives.

Under this scenario, the management of Laguna de Rocha is based on the social-ecological systems framework, which understands ecosystems and human society as an integrated system with reciprocal feedbacks and interdependence (Folke et al., 2010). The vision statement that guides the management plan of this Protected Landscape aims at promoting responsible ways of life, through a participatory management based on agreements and consensus. The protected area may ensure a healthy habitat for humans through the socioeconomical and cultural development of its community, and the conservation of biodiversity and the cultural values, sustaining a landscape with its own identity (MVOTMA, 2016a). Local knowledge and the participation of stakeholders in the decision-making process are key aspects for the management of this area. At this scale, participation has been described as essential for successful and sustainable coastal management (Berkes, 2009; Christie et al., 2005). Particularly in protected areas, this may help keep dominant interests from prevailing over less-influential stakeholders (Gönenç & Wolflin, 2004) and to incorporate a larger diversity of perceptions in management plans, thereby leading to legitimized decisions and reduced conflict (Larson & Edsall, 2010; Shackeroff, Campbell, & Crowder, 2011). Active transformation can promote changes at small scales that facilitate the achievement of desired goals, avoiding abrupt disruptions that may lead to social resistance or conflicts (Folke et al., 2010).

For active transformation the local ecological knowledge is invaluable. This knowledge is transmitted orally or through imitation and demonstration, is a consequence of day-to-day practice, tends to be empirical, is repetitive, is in constant production and reproduction, and is shared to a high degree throughout the community, and its distribution is fragmentary and holistic (Ellen & Harris, 2000). In the field of ecology and conservation, studies incorporating local ecological knowledge (LEK) have played an increasingly important role in the last 30 years (Brook & McLachlan, 2008). To approach cases in which conservation is integrated into traditional forms of use of natural resources, the integration of LEK as one of the indicators used is a key methodological strategy (Tomasini & Theilade, 2019). This type of approach also permits the incorporation of genealogical, intergenerational or personal diachronic perspectives. The articulation with more "hard" approaches makes possible the development of predictions and future scenarios to improve natural resources management and the wellbeing of the inhabitants of the studied landscapes (Tattoni, Ianni, Geneletti, Zatelli, & Ciolli, 2017).

Juncus acutus is spreading on the flood plain of Laguna de Rocha, causing great concern among livestock ranchers. This is a non-palatable species for cattle, it forms large, dense monospecific patches parallel to the lagoon margins, obstructing access to the lagoons, reducing the surface area of the grasslands and changing the habitat available for other native species. The species, which is semi-cosmopolitan and native to South America (Snogerup, 1993), is commonly found in the saltmarshes of Uruguay. It flourishes in spring and summer (Lombardo, 1982) and reproduces mainly by seeds and rhizomes; it has high dispersion potential due to its abundant seed production and high germination rate (Brown & Bettink, 2006; Jones & Richards, 1954), making it a strong competitor and causing it to displace other species (Parsons & Cuthbertson, 2001). Plants of the family Juncaceae can develop rich seed banks that remain latent for decades (Snogerup, 1993) and that can be transported by water (Parsons & Cuthbertson, 2001) and germinate mainly in spring and summer (Jones & Richards, 1954; Parsons & Cuthbertson, 2001). The salinity tolerance of *J. acutus* seeds can be high (Boscaiu, Ballesteros, Naranjo, Vicente, & Boira, 2011); however, *ex situ* experiments showed that germination is maximal under freshwater conditions and that it progressively decreases as salinity increases (Boscaiu et al., 2011). Germination is partially inhibited by decreasing light and by temperatures lower than 10 °C (Martínez-Sánchez, Conesa, Vicente, Jiménez, & Franco, 2006).

Flooding and the salinity gradient are the main abiotic factors that determine vegetation zoning in saltmarshes (Pennings et al., 2005), along with a great influence of microtopography and altimetry. In South American saltmarshes, flooding tolerance clearly determines the zoning of *Spartina* species (Isaach et al., 2006), and *J. acutus* is frequently found in the outermost zone (Isaach et al., 2006; Di Bella et al., 2014), because it cannot tolerate permanent flooding (Bettink, 2009; Snogerup, 1993) and prefers brackish conditions (Greenwood, 2008). This pattern is also found in North American saltmarshes (Pennings et al., 2005) but for a different species of Spartina spp. and Juncus (*J. roemerianus*). Saltmarshes in South America are very sensitive to changes in sea level, precipitation, geomorphology, and salinity and to human impacts (Bonifacio-Costa & Marangoni, 2010; Schaeffer-Novelli et al., 2016). For example, in Laguna de Mar Chiquita and Bahía de Samborombón (Argentina), *J. acutus* is expected to colonize the upper zones of the flood plain due to changes in precipitation and sea level rise (Canepuccia et al., 2008; Volpedo & Fernández-Cirelli, 2007), negatively affecting cattle farming.

Juncus acutus also provides important ecosystem services. It protects soils against hydrological erosion (Isacch, Escapa, Fanjul, & Iribarne, 2010; Marangoni & Costa, 2010), it can be used as feed (Erdem & Cetinkaya, 2016) and as a natural fiber to make ropes and paper (El-Sayed, 2004), and it has medicinal properties (Daoudi, Benboubker, Bousta, & Aarab, 2008). Saltmarshes are important refuges for threatened mammals and crabs of prime importance in energy and carbon fluxes in saltmarshes (Bortolus & Iribarne, 1999).

The aim of this article is to evaluate the increase in surface area occupied by *J. acutus* in the floodplain of Laguna de Rocha, to analyze the possible causes for its expansion, and to suggest management actions. We analyzed historical and current aerial and satellite images and characterized the local ecological knowledge about the biology of the species and its spatial distribution over time on the SE coast of the lagoon. We also analyzed historical records of air temperature, precipitation and water level of the lagoon and looked for relationships with the observed changes. The approach used in this study and its results provide important input for designing management strategies for this species in Laguna de Rocha and other saltmarshes with similar problems worldwide.

2. Study area

Laguna de Rocha (Uruguay; 34° 35′ S - 54° 17′ W) has a surface area of 7 km^2, an average depth of 0.6 m (Fig. 1), and a catchment surface area of 1214 km^2. The climate in Uruguay is subtropical and humid, with four well-defined seasons, and precipitation is homogeneous throughout the year (the climate is Cfa according to the climate classification of Köppen and Geiger (1936)). Due to its outstanding biodiversity and cultural value, multiple protection categories have been declared for Laguna de Rocha. It has been designated a Biosphere Reserve (MAB-UNESCO Program), a Ramsar Site and part of the National System of Protected Areas.

The periodic connection of the lagoon with the ocean occurs directly through a breach that opens on the sand bar (Fig. 1); thus, its salinity ranges from freshwater to marine conditions (Rodríguez-Gallego et al., 2015), but no hypersaline conditions were reported for this lagoon. Hydrology is the driving force determining the dynamics of the aquatic communities (Bonilla, Conde, Aubriot, & Perez, 2005; Conde, Aubriot, & Bonilla, 2000; Meerhoff, Rodríguez-Gallego, Giménez, Muniz, & Conde, 2013; Rodríguez-Gallego et al., 2015; Segura et al., 2011). The lagoon is artificially opened by the local municipality to reduce flooding in livestock ranching fields and in two small towns. The artificial opening of the sand barrier is currently regulated by the management plan of the protected area, and it is permitted only when the water level of the lagoon reaches a certain level, mimicking the natural opening as much as possible (Conde et al., 2019). Nevertheless, there has been no long-term assessment of the impact of this hydrological modification.

The flood plain of the lagoon is very flat, and following rains the soils can be saturated with freshwater for long periods, generally during the colder months. Also, when the water level of the lagoon rises due to rains, flooding can persist for several weeks. When the sand bar is opened, marine water enters the lagoon and floods the littoral wetlands. Further, salinity can concentrate in the soil due to evaporation during the summer months. Freshwater floods are larger and of longer duration than brackish water floods; therefore, freshwater and saltmarsh vegetation coexist. At the outermost area of the littoral zone, uliginous grassland harboring freshwater species such as *Bacopa monieri* and *Hydrocotile articarpa* can be found. The middle zones are covered by dense patches of *Juncus acutus*, and strips of *Spartina densiflora* are also found surrounding the lagoon's shores. Grassland featuring salinity-tolerant species of short grasses such as *Paspalum vaginatum* and *Stenotaphrum* secundatum, among others, is the dominant matrix.

The study site belongs to one establishment (named Tropicalia) (Fig. 1) in the SW zone of Laguna de Rocha. It was selected because it was pointed out by local stakeholders as the site with the greatest increase in the coverage of *J. acutus*.

3. Methods

3.1. Spatiotemporal analysis of *J. acutus* cover

To analyze the increase in *J. acutus* cover and abundance, two sites in the study area were selected. The first was located in a semi-enclosed bay, and the second was located on the southwest shore of Laguna de Rocha (sites 1 and 2, respectively; Fig. 1). Both sites harbor dense *J. acutus* patches whose cover has increased dramatically with time; for site 1, precise topographic information is also available. Orthogonal aerial photographs taken in 1943 (scale 1:40,000 from the Military Geographic Service) and 1967 (scale 1:20,000 from the Aerial Force) and Google Earth images obtained in 2010 and 2013 were selected based on the image quality. Images between both periods had to be discarded due to low resolution and the presence of cloud cover. All images were georeferenced in WGS 1984 UTM 21 South using free Geographical Information System software. Analog stereoscopy was conducted to precisely identify *J. acutus* patches in photographs, while satellite images

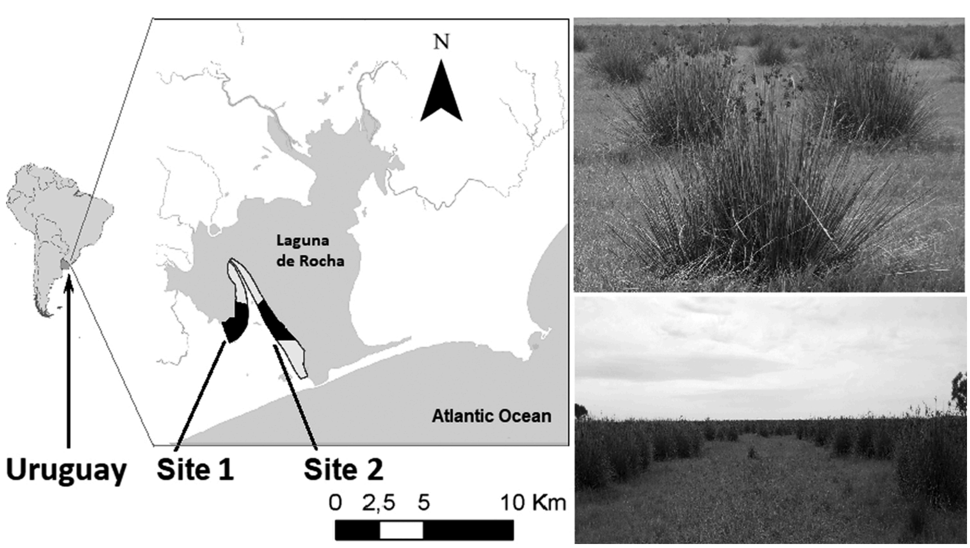

Fig. 1. Map of the study area in Laguna de Rocha. The polygons indicate the two sites at which the temporal and spatial changes of *J. acutus* were analyzed. Panoramic images of the species stands are shown.

were visually inspected using a combination of zoom, image colors and texture.

For each image and site, a preliminary map was first manually digitized and used to identify *J. acutus* and *Spartina densiflora* Brong cover, patches of bare sandy soils, small temporal ponds, natural channels and reference points (fences or isolated trees). At each site, a subarea was delimited and used to determine *J. acutus* cover (see black patches in Fig. 1), which was visually categorized into four classes. Cover was determined by zooming in and out on the images up to a scale of 25 × 25 m and polygons of each class were manually digitalized on screen. Class 1 includes the densest patches in which *J. acutus* mats cannot be differentiated. Class 4 includes patches that contain disperse mats in a grass matrix, and classes 2 and 3 are in-between situations. An exhaustive field inspection of both sites was conducted to validate the 2015 preliminary map and cover classification and to determine whether certain coverages that were observed in older images but not in recent ones were definitely absent. The presence of the species on the preliminary map corresponded with the field survey in all inspected sites (20 points in the field) due to the high quality of the image, which allowed distinguishing *J. acutus* mats without error (no systematic determination of the cover classification error was conducted).

3.2. Temporal changes in climatic and hydrological variables

To evaluate whether the changes in *J. acutus* distribution have been influenced by climate or hydrology, we analyzed the available long-term databases of air temperature (mean annual temperature from 1961 to 2013) and precipitation (daily precipitation from 1956 to 2011), both obtained from the National Meteorological Service (INUMET) from Rocha Station, and the water level of the lagoon (obtained from the National Hydrology Service – DINAGUA; data were available for the period 1956–2005). For the annual precipitation regimen, the moving average was calculated. For this, the annual accumulated precipitation was estimated and then the average was calculated every ten years.

The water level of the lagoon was referenced to the official zero (OZ), an official reference datum that is defined as the average sea water level in the Port of Montevideo. To determine changes on the duration of different water levels between decades a permanence curve of water levels was calculated for the entire period and for individual 10-year periods. Additionally, changes in the water level over a year were analyzed between decades by plotting the mean daily water level every 10-years periods.

Finally, to locate *J. acutus* in relation to flooding curves, the species presence obtained for all images was superimposed by SIG with the detailed topographical information described in Conde et al. (2015). Three water levels were selected: < 0.30 m, 0.30 m - <0.87 m and >0.87 m from the OZ.

3.3. Local ecological knowledge of J. acutus in Laguna de Rocha

To obtain a detailed description of *J. acutus* coverage over different time periods and in different zones of the lagoon as well as phenological observations and management information, a total of eight semi-structured interviews were conducted. This type of interview allows the investigator to focus on the topics of interest with high specificity while also allowing the incorporation of thematic variants that may not have been foreseen (Sandoval-Casilimas, 1996). For the interviews, visual stimuli were used (Muniz, Santos, Paiva de Lucena, Bezerra, & Albuquerque, 2014). The use of the images during the interviews was a key tool to identify the spatial extent of significant topics such as: 1) the temporal and spatial distribution of the species; 2) the consequences of the expansion; 3) the ecology of *J. acutus*; 4) other relevant variables of the ecosystem; 5) the causes of the expansion; and 6) the management of the species.

The local stakeholders included in this study were three livestock ranchers, three artisanal fishermen, one ranger and an ornithologist. These stakeholders use, observe and manage this wetland ecosystem in different ways. The ranchers and fishermen interviewed were the oldest local inhabitants who still live or work in the lagoon. The ranger had worked in the area for 20 years and the ornithologist conducted field work in the study sites for 10 years. Ranchers know most deeply the zones within their own properties, the fishermen know best the areas closest to where they fish, and so on. In addition to this spatial bias, there is a temporal one: the observations of these stakeholders were limited to a particular period of time. Therefore, for this analysis, only the zones and periods that the stakeholders knew well were considered (Fig. 7).

4. Results

4.1. Juncus acutus spreading

The image analysis showed an evident increase in *J. acutus* cover from 2010 but no relevant changes between 1943 and 1967 or between 2010 and 2013. Fig. 2a shows 1967 and 2013 images, which are the available images were the maximum expansion of the species can be observed. In the older aerial images (years 1943 and 1967), it was difficult to distinguish small patches or narrow strings of *J. acutus* from other tall emergent species, even using stereoscopy. In contrast, in the 2013 image the surface areas of the most dense covers of *J. acutus* (classes 1 and 2) were 11.6 and 31.1 ha in the subareas of sites 1 and 2 (Fig. 1), respectively, while for lower cover classes the surface areas were 46.0 and 11.8 ha, respectively (Fig. 3). Colonization was observed in sandy and bare soil patches and in areas with very short and sparse vegetation in both sites and over the original herbaceous vegetation (Fig. 2a). The surface area occupied by bare and sandy soils decreased from 37 to 18 ha (48.6 %) in site 1 and from 47 to 12 ha (74.5 %) in site 2 between 1967 and 2013, mainly due to colonization by this species. At site 1, the *J. acutus* strip was wider, but the lowest cover (class 4 and 3) predominated. In contrast, at site 2, the strip occupied by this species was narrower, and it was covered by the densest classes (class 1 and 2) (Fig. 3).

When mapping *J. acutus* in sites with precise topographic surveys and were previous studies determined water levels of different recurrence time, it can be observed that the species was located between the flooding curves 0.30 m and 0.87 m from the OZ (Fig. 2b).

4.2. Temporal changes of climatic and hydrological variables

The mean annual temperature was 16.3 °C during the studied period (1971–2011). The moving average temperature for successive 10-year periods showed a gradual increase (data not shown), but the maximum increase (0.7 °C) relative to the mean annual value for the entire period was recorded for the 1994–2004 period. After that, the moving average of the mean annual temperature remained stable.

The mean annual precipitation from 1956 to 2011 was 1175 mm, with marked variability between years (Fig. 4). The moving average for periods of 10 years indicated a slight increase in precipitation, mainly from the 1990s. Precipitation occurs throughout the year and shows high monthly variability between years. In contrast, evapotranspiration showed a clear cycle in which the highest values occurred in summer (data not shown).

The water level records illustrated the cycle of lagoon refilling due to runoff, sand bar breaching and discharge into the ocean (Fig. 5a). In this cycle, the water level rises gradually until it reaches a critical level approximately 1.4–1.8 m from the OZ; it then suddenly decreases, indicating breaching of the sand bar. Fig. 5b shows the water level permanence curve. The black line shows the permanence curve for the entire period, and the dotted lines indicate the permanence curves at intervals of 10 years. The permanence of higher water levels (permanence of up to 10 %) was larger for earlier decades (before 1986) than for more recent periods (after 1986). The permanence of lower water levels showed an inverse pattern. This means that prior to 1986 the

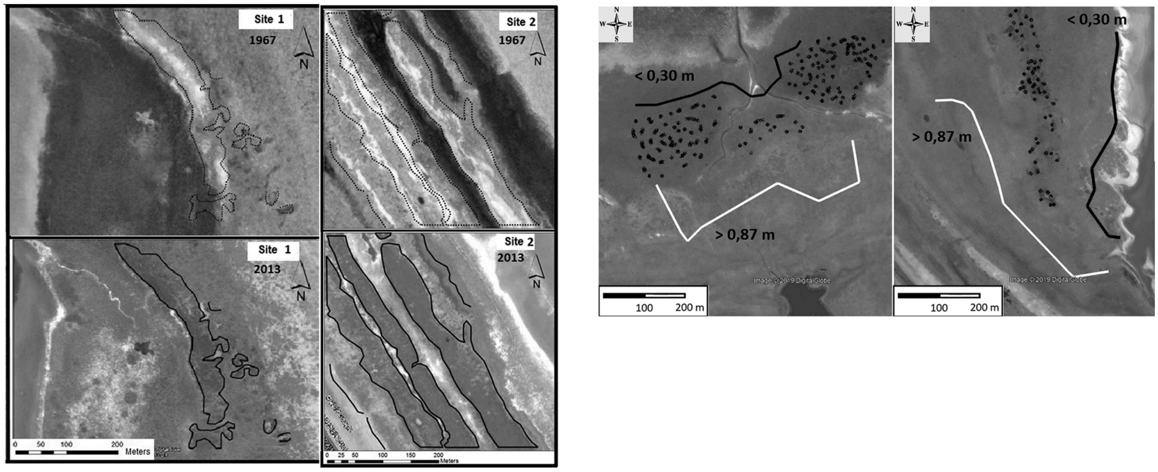

Fig. 2. A) Images of sites 1 (left) and 2 (right) in 1967 (top) and 2013 (bottom), respectively. The black polygons in the 2013 images show the current distribution of dense mats of *J. acutus*, which is shown in dark gray. The same polygons are indicated by a dotted line in the upper images to indicate the changes from 1967. In all images, light gray mainly represents sandy and naked soils. B) Location of *J. acutus* within the flooding curves in 2013 image. The white and black lines indicate the flooding curves at >0.87 m and <0.30 m, respectively, from the OZ. The black dots represent *J. acutus* vegetation in 2013. The image on the right is located on site 1, while the left image is located at ca. 1300 m to the South along the lagoons shore, at the closest site with precise topographic description. The data were taken from Teixeira et al. (2013) and Conde et al. (2019).

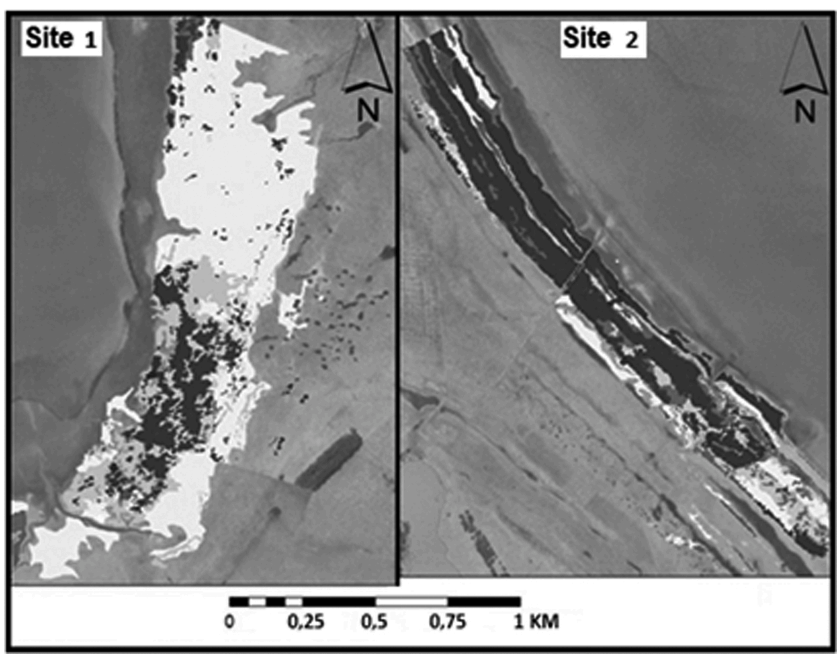

Fig. 3. Cover of *J. acutus* in sites 1 and 2 superimposed on the 2013 image. Dark gray represents the densest class (1), with decreasing tonality up to class 4.

highest water levels were maintained for more days; in other words, floods were longer. The crossover between the permanence curves occurs near a water level of 0.87 m from the OZ.

One of the most notable changes was the decrease in the percentage of time during which the water level remained below 0.3 m; it decreased from 65 % in 1956–1966 to 54 % in 1996−2005. When lower water level values were analyzed, this decrease was even more marked (Fig. 5b). For water levels > 0.87 m, the percentage by which this level was exceeded remained stable at approximately 11 % of the year during the entire studied period. The percentage of time during which the water level remained between 0.3 m and 0.87 m increased progressively from 24 % to 35 % from the first to the last decade. For the entire period (1956–2005), the water level fell within this range 30 % of the time.

The mean daily water level also differed by decades (Fig. 6). In the earlier decades, the water level achieved higher values for shorter periods, in comparison to recent decades. In contrast, during more recent decades the curves became flatter, indicating that the flooding was less severe but of longer duration; this is consistent with the permanence curves. However, the annual average water level in each decade increased with time; the first two decades showed an average annual water level that was lower than the historical level (0.33 m from the OZ), while in the last three decades it exceeded it. The annual average water level increased from 0.09 m in the period 1956–1966 to 0.39 m from the OZ in the last decade. The maximum increase (0.19 m) was observed between 1966 and 1976 (water level: 0.21 m) and between 1986 and 1996 (water level: 0.40 m from the OZ). In other words, although the lagoon does not achieve water levels as high as those recorded during the first decades on record, on average the system shows higher water level values along the year. Furthermore, the variability in the water level clearly decreased along the decades, showing

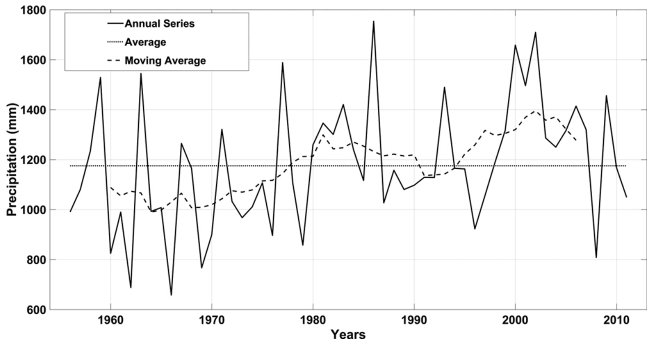

Fig. 4. Annual precipitation at Rocha Station of INUMET. The average precipitation for the entire period is indicated by the dotted line; the moving average every 10 years is also shown.

more values closer to the average throughout the year.

4.3. Local ecological knowledge of J. acutus distribution and lagoon dynamics

The interviewees had different spatiotemporal relationships with Laguna de Rocha. Depending on the tasks each interviewee performs in the lagoon, they know some zones better than others. Livestock ranchers offered information related to two periods of time: 1964–1999 and 2000−2014. The oldest record of the species was a small population recorded in 1972 at the NW section of the lagoon (Fig. 7b). For the second period, the interviewees indicated the presence of two other populations, one in the south in 2000 and another in the NNW in approximately 2005. The three ranchers indicated that the population of *J. acutus* began to increase around 2000 and that it has expanded continuously since then (Fig. 7b). The fishermen also offered information related to two periods of time: 1945–1999 and 2000−2014. According to them, the presence of the species was first noted in approximately 1945, mainly in the N-NW, S-W and E zones of the lagoon; it was also observed at other sites, but always in small patches consisting of few mats (Fig. 7a). They remarked that the species began to spread after 2000 in all the sites where it was previously recorded as well as to new ones (e.g., in the sand bar margin and to other sites of the NW semi-enclosed bay Bolsón de Los Noques). The biologist and the ranger offered information of a shorter period of time (2000–2014) and of localized zone of the lagoon (S and SW zones).

All stakeholders have a large amount of information of the site and knowledge about *J. acutus* biology and the causes of the expansion as well as about the dynamic changes that occur in the lagoon. Table 1 summarizes the local ecological knowledge of all interviewees on *J. acutus* biology and ecology, spreading causes, affectation to production activities and on biodiversity.

5. Discussion

This study documents that in the floodplain of Laguna de Rocha, *J. acutus* has expanded its coverage since the early 2000's, although the species was recorded in the area at least 70 years ago. The combination of remote image analysis and a survey of local ecological knowledge, together with the temporal analysis of the physical information (hydrological, topographic and climatic) and of the bibliography on the

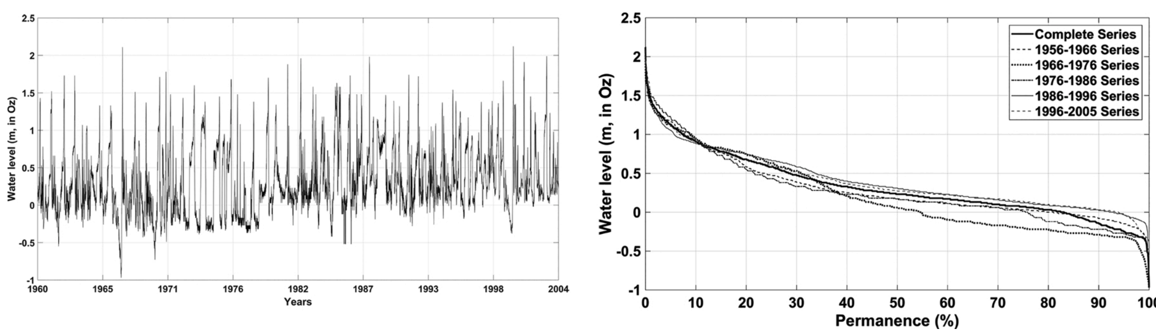

Fig. 5. Water level (a) and permanence curves of the water level series (b) in Laguna de Rocha. The permanence curve of the complete series is indicated in black and the gray dotted lines indicate the permanence curves at intervals of 10 years.

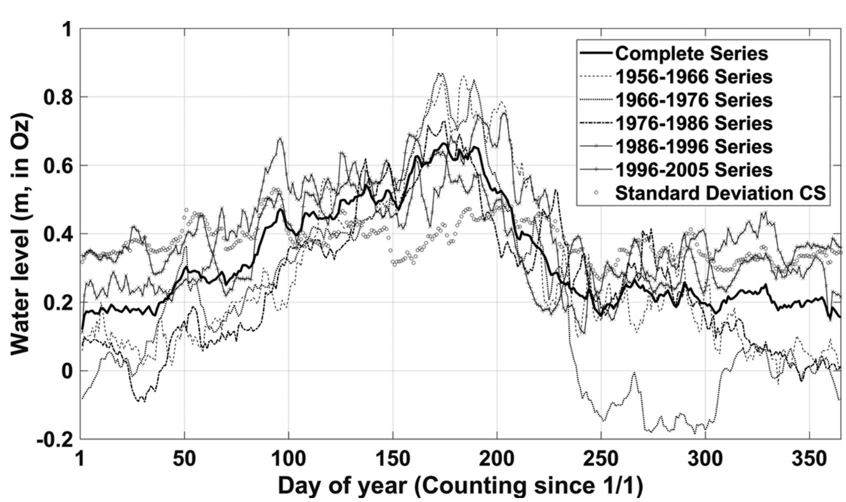

Fig. 6. Mean annual water level of Laguna de Rocha. The black line shows the complete series (1956 to 2005); the dotted lines show the mean annual water level every 10 years. The variability for the complete series of the water level is shown by the value of the standard deviation.

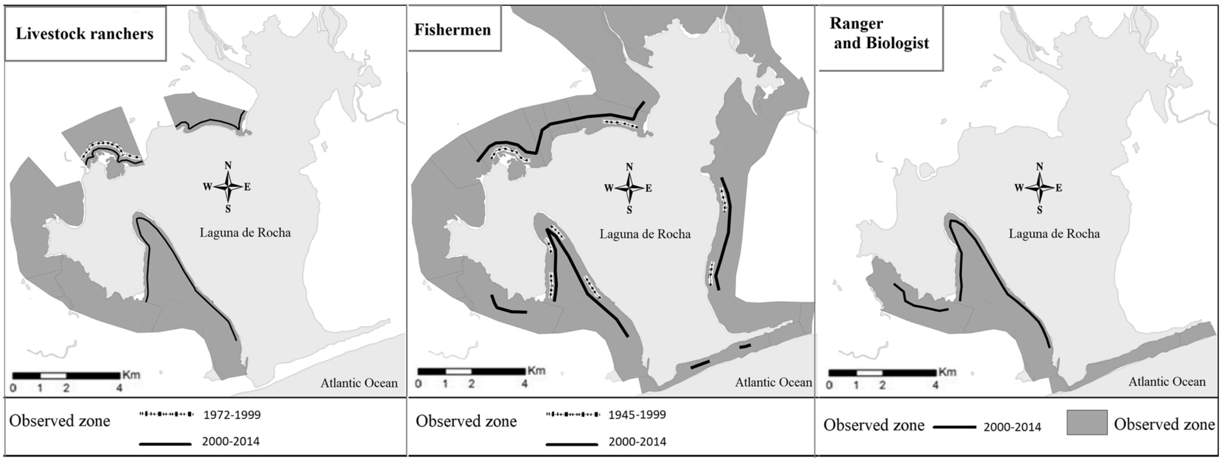

Fig. 7. Map based on local ecological knowledge of the distribution of *J. acutus* in Laguna de Rocha. The maps based on information obtained from livestock ranchers, fishermen, and a ranger and an ornithologist are shown from left to right (a, b and c, respectively). The dark gray areas indicate the zones that are commonly surveyed by the interviewees; the black line and the dotted line indicate the time periods described.

Table 1
Stakeholder's perceptions regarding biology and ecology of *J. acutus*, spreading causes and impacts on production and biodiversity in Laguna de Rocha.

	Livestock ranchers	Fishermen	Ranger	Ornithologist
J. acutus biology and ecology	*J. acutus* tolerates floods (up to ca. 5 cm of water) but does not grow in permanent water. The high seed production is dispersed by floods and deposited together with the plant litter in the backwash line of the lagoon, where it then establishes.	Seed dispersion is related to hydrological regime. Seeds and plants litter are deposited during high floods in the backwash line of the lagoon, where it later germinates. During severe floods, the species colonizes inland zones. In summer, capsules are broken and the seeds are liberated.	The species grows on the flood plain along the sand deposits that surround the lagoon shore and also on the plant litter deposits.	Similar description as the one provided by the ranger. *J. acutus* renewals are spreading over a specific soil type.
Spreading causes	Interruption of the mixed herbivory of cows and sheep increase spreading. Sheep feed on *J. acutus* juveniles helping control its population while is not palatable to cows. Also the arrival of the exotic wild boar is a dispersion cause. This animal removes surface soils, favoring germination of the species.	The temperature increased in recent years, favoring the growth and dispersion of the species.	When the plant is growing it is tender and can be grazed by cattle, while adult plants are avoided. When the field is flooded with brackish water (warmer months), cattle do not graze on the species, and after a few months the plants become unpalatable.	The change in the flooding regime is the main cause of the spreading of the species due to the shortening of the flooding periods caused by the artificial opening of the sand barrier.
Affectation to production activities	Decrease in the grazing surface area available to cattle. Obstruction of the movement of cattle and horses. *J. acutus* is useless because it has no grazing value.	*J. acutus* does not interfere greatly with fishing, but it breaks nets and makes it more difficult to move along the shores and to set up the nets *Odontesthes* sp. feeding behavior may have been affected during some periods of the year, also affecting fisheries.	The species reduces the grazing surface area available to cattle and also interferes with motorbike or horse riding, as well as with the movement of fishermen and cattle.	Similar description as the one provided by the ranger.
Effects on biodiversity	Unsuitable habitat for wildlife.	Mammal may have been favored: foxes (*Cerdocyon thous* and Licalopex gymnocercus), crab-eating raccoons (*Procyon cancrivorus*), exotic wild boars and small wetland rodents (subfamily Sigmodontinae). A decrease in bird and plant diversity may have occurred.	Refuge for endangered wild cats (*Lynchailurus braccatus*), wetland rodents, skunks (*Conepatus chinga*) and the exotic wild boar.	The spreading of this species is changing the structure of the entire plant community, affecting bird diversity mainly by reducing the feeding areas for endangered migratory birds (*Calidris subruficollis* and *Pluvialis dominica*)

biology of the species, made it possible to confirm this previous assumption. In line with other works (Tattoni et al., 2017; Tomasini & Theilade, 2019), these approaches, combined, permitted extending the period of time, the spatial scope analyzed and the human practices involved and allowed us to form hypotheses regarding the causes and mechanisms of the expansion of the species that would not have arisen from classical disciplinary approaches.

Juncus acutus colonized the coastal grassland vegetation as well as sites with bare sandy soils. The most marked changes were noted in 2010. For the period prior to 2010, we were unable to obtain satellite images of the study site that were of sufficient quality. The changes noted are substantial, at least for the singular bare and sandy microenvironments, which show reduced area in the saltmarshes of Uruguay and are home to plant species of restricted distribution (Fagúndez & Lezama, 2005; Alonso Paz & Bassagoda, 2006). It was ruled out that the expansion was due to invasion by the exotic species *Juncus kraussii* (collection of specimens and identification by the botanist C. Fagúndez), which is similar to *J. acutus* and is invading the saltmarshes of Lagoa dos Patos in Brazil (Marangoni & Costa, 2010).

The coverage by *J. acutus* of the two analyzed sites differed. In site 1, the distribution was dispersed (cover classes 3 and 4), while in site 2 the species was located in dense strips parallel to the lagoon (cover classes 1 and 2). The first site has a wide, flat floodplain, while in the second site the floodplain is narrower and has several channels parallel to the coastline of the lagoon. It may be that the microtopography of site 2 is more suitable for the establishment of the species due to its sensitivity to waterlogging conditions (Cagnoni, 1999). According to the fishermen, these areas exhibited the greatest abundance of the species prior to its expansion and have the greatest current coverage. The interviewed stakeholders, especially the fishermen, gave very precise descriptions of the biology and ecology of the species that were consistent with the descriptions in the bibliography and with the results of this study. They accurately identified the spatial distribution of *J. acutus* in the flooding gradient and adequately described its tolerance of different environmental conditions. This confirms the importance of surveying the LEK and the relevance of generating participatory processes for finding solutions to complex problems that may involve them.

5.1. The impact of J. acutus spreading

Plant species are considered weeds when they affect people's interests and also depending on historical or cultural context (Labrada & Parker, 1996; Mortimer, 1990). In Laguna de Rocha, *J. acutus* became a weed for some local stakeholders due to its recent expansion and its negative impact on productive activities. Livestock ranching is currently being affected due to the reduction in the amount of feeding and transit surface area for cattle caused by the high density of the species mats and the strong spines of its leaves (Parsons & Cuthbertson, 2001). However, there have been no surveys of the economic effects of the expansion.

The impacts of the spreading of *J. acutus* on biodiversity in the Laguna de Rocha Protected Landscape are little known and seems to have both negative and positive effects. Among the negative effects the interviewees pointed out the impact on the diversity of plants, while the ornithologist highlighted the reduction in the coastal grassland habitat, which is a critical feeding area for migratory bird species that hold priority for international conservation (Aldabe, Lanctot, Blanco, Rocca, & Inchausti, 2019). One quarter of the population of *Calidris subruficollis* feeds in Laguna de Rocha during its migration (Lanctot et al., 2009). In addition, the interviewees pointed out that the establishment of the wild boar, an invasive exotic species that was declared a plague in Uruguay (Decreto N° 96/004, 2004; González & Lanfranco, 2001), may have been favored by the increase in the refuge generated by *J. acutus* and that the establishment of this animal species could in turn have favored the germination and establishment of *J. acutus* due to the soil disturbances caused by them (Barrios-García & Ballari, 2012). Among the positive effects of *J. acutus* expansion on biodiversity, they also pointed out the population increase of small- and medium-sized mammals, including the threatened wild cat *Lynchailurus braccatus* (González & Lanfranco, 2001).

To determine the relative importance of the negative and positive impacts of *J. acutus* spreading on biodiversity in Laguna de Rocha, studies of botanical species and fauna are needed. Given the large size of the private lands and the surface area occupied by *J. acutus* (less than 100 ha) in the study area, it is possible that there is an overestimation of the impact, possibly due to the size and aspect of the plant. Some studies have focused on the importance of the physical attractiveness of species in determining their social perception and as a decision factor in their preservation (Gunnthorsdottir, 2015) or management. Studies of the social perception of the species may be useful in distinguishing between the real impact of its spreading and the bias associated with its aesthetic characteristics. However, it is of priority to quantify the real economic impact on livestock ranching. Monitoring of the surface area of the species cover must continue before actions to manage the species are implemented.

5.2. Causes of the spreading of J. acutus

The stakeholders, especially fishermen, pointed out that the hydrological regime has changed in recent decades and that this has affected the floodplain and the distribution of *J. acutus*. The oldest fisherman remarked that until the 1960s it was common to observe lows in which the surface area of the lagoon was reduced by almost half. However, this has occurred only sporadically in recent decades, which this fisherman associates with the opening regime of the sand barrier. Before it was opened with backhoes, the channel of connection with the sea was very deep (up to 5 m), allowing the lagoon to be emptied or filled at a higher rate depending on winds and precipitation. In addition, the channel used to remain open for several months, and if it was closed with a low water level, the lagoon could remain low for long periods. According to the interviewees, machine-made artificial opening began sporadically in 1984, and since 2000, coinciding with the beginning of the expansion of the species, almost all of the openings have been mediated by machinery (Conde et al., 2015, 2019).

The analysis of the hydrological and climatological variables coincides with the observations of the interviewees. In recent decades, the lagoon has experienced a more stable hydrological regime with less pronounced droughts and floods that are shorter in duration but has also experienced a higher average water level. As a result, large areas of the flooding plain are less frequently inundated and for shorter periods. Compared to its historical average level, the mean level of the lagoon increased by approximately 0.2 m from the OZ since 1980. On the SW margin of the lagoon, an increase of 0.15 to 0.6 m in the water level can result in flooding between 400 and 1000 m inland (Conde et al., 2015). Moreover, the number of days on which the water level of the lagoon was lower than 0.30 m decreased by 11 %, and this was even more pronounced when levels lower than 0 m from the OZ were considered (the percentage of days on which this occurred decreased from 20 % to 7 %). However, the period of time during which the water level was higher than 0.87 m from the OZ was unchanged (11 %) when compared over all decades. These changes clearly show that the variability of the disturbance regime in the floodplain has decreased since 1980–1990, both spatially and temporally. These results indicate that changes in water level regime seem not to be the simple response to precipitation increase in the last decades.

These changes may also be related to the artificial opening of the lagoon, as pointed out by several of the interviewees. The artificial opening of Laguna de Rocha is promoted by livestock ranchers because it minimizes the flooding of grazing areas and also by fishermen because it allows coastal fish and shrimp larvae to enter the lagoon and prevents the flooding of their houses. Although there is a protocol for the artificial opening (MVOTMA, 2016b) of the lagoon that is based on an interdisciplinary study (Conde et al., 2015, 2019), many aspects of this protocol remain to be evaluated, such as quantifying the real impact on private properties, on households, fisheries and livestock ranching.

Changes in water level could have altered the salinity regime of the lagoon and that of the soil in the floodplain (unfortunately there are no historical data on this variable). *Juncus acutus* is located between 0.87 m and 0.30 m from the OZ, the coastal strip most sensitive to water level changes (Teixeira, Chreties, & Solari, 2013). This could generate more suitable conditions for the species, allowing it to establish in places from which it was previously displaced by droughts or more severe and prolonged floods and by a different saline regime.

The flood regime of marshes or estuaries is one of the main factors that directly or indirectly affect the zoning of vegetation (Penning et al., 2005; Isacch et al., 2006; Canepuccia et al., 2008). Artificial opening of the sand barrier in coastal lagoons can affect the plant community of the littoral wetlands, generating important changes in plant succession and expansion and in invasion by other species (Dos Santos, Amado, Minello, Farjalla, & Esteves, 2006; Lundholm & Larson, 2004; Vromans, 2010).

5.3. Other factors that may explain the spreading of J. acutus

Changes in climatic variables may have also influenced the expansion of *J. acutus*. The average daily temperature of the air increased by 0.7 °C between 1961 and 2013, the minimum temperature was attenuated, and the number of days with frosts in Uruguay decreased (Giménez, Castaño, Olivera, & Baethgen, 2008). This coincides with global changes (IPCC, 2013) and could have favored the germination of the species (Martínez-Sánchez et al., 2006). Precipitation increased by almost 270 mm with respect to the average for the period after 1990, although it showed high variability, coinciding with regional studies that indicate a long-term increase in rainfall (Giménez et al., 2008; IPCC, 2001; Krepper, García, & Jones, 2003). Precipitation can reduce soil salinity, at least temporarily, by superficial removal of salts (Garcia, 1998). This can favor the germination of *J. acutus*, whose seeds remain dormant at high salinities but germinate in the absence of salt (Martínez-Sánchez et al., 2006). Although the changes mentioned so far would have affected all the plant species of the lagoon floodplain, *J. acutus* was possibly one of the most favored species due to its autoecological characteristics. In addition, changes in its distribution may have been quickly noted by local stakeholders due to its size and its impact on productive activities.

Although it seems clear that the hydrological regime of the lagoon and the climate may have favored the propagation of *J. acutus*, changes in productive management may have been equally relevant for the expansion of the species. According to the livestock ranchers, the grazing pressure may have changed between 1990 and 2006 due to the interruption of the mixed grazing of cattle and sheep (cattle now predominate). This is a national tendency due to market changes (Arévalo Cortéz, 2011) and was also observed in the study area. Sheep prefer shorter vegetation than do cattle (Calvo, 2008) and are thus an efficient controller of *J. acutus* outbreaks, whereas cattle have greater selectivity. Grazing can substantially change the composition and dominance of species in saltmarshes (Jensen 1985), favoring the less palatable ones. Studies are needed to enhance our understanding of the effect of livestock management on *J. acutus*.

Another substantial change in management was the suspension of field burns. In Laguna de Rocha, livestock ranchers used fire burning to control *J. acutus* systematically for some years, but burning was suspended when the protected area was planned. There is no agreement among the interviewees on the effect of burning on *J. acutus* control. Some of the stakeholders think that suspension of the burning would have benefited the expansion of the species, while the fishermen remarked that it had the opposite effect, noting that burning also facilitates the release of seeds and that the area disturbed by burning (site 2) is currently the area of the lagoon with the highest density of *J. acutus*. Burning is an effective measure in the short term (Dixon, 2006; Isacch et al., 2004) but is apparently ineffective on its own. According to the interviewees, most plants of this species do not die after burning and sustain a rapid recovery since they are perennial and rhizomatous, recovering the height of adult plants approximately two years after the burning (Isacch et al., 2006). Moreover, the disturbance caused by burning facilitates the germination of *J. acutus* (Brown & Bettink, 2006; Dixon, 2006). Although fire burning can generate an increase in plant diversity in grasslands (Collins et al., 1995) and promote short vegetation that benefits certain bird species, it can also increase the risk of disappearance of rare species and result in outbreaks of other pioneer plants with weed potential (Isacch et al., 2004). Since fire burning has dramatic impacts on vertebrate fauna and its controlling effect is questionable, it appears not to be a recommended action for Laguna de Rocha.

5.4. Is it necessary to manage J. acutus?

The results of this study show that the expansion of *J. acutus* has occurred in the strip of the floodplain that was most affected by the effect of the artificial opening of the sand barrier of Laguna de Rocha and its cascading effects on the hydrology, as well as to changes in livestock management and in the climate in the last decades. There is evidence of both negative and positive impacts of the expansion of this native species on biodiversity. From a classic ecological point of view, given this evidence, it is questionable whether management actions to control *J. acutus* expansion should be undertaken and, if it is, who should take charge of them. A better understanding of the causes of the species' expansion may help predict the potential future spreading of *J. acutus* if current conditions continue, as well as help distinguish whether or not we are facing a problem that requires intervention. However, from a social-ecological system point of view, in an area in which there is an imbricated interrelationship between the productive use and the ecological integrity and in which there are still sustainable uses that are compatible with the protected area targets, making decisions about the management of a troublesome species is a more complex issue that deserve stakeholders involvement. Changing the concept of *J. acutus* from a weed to a provider of ecosystem services and of habitat for fauna could be an alternative that might reduce the tension between production and conservation.

Stakeholders identified possible management actions, highlighting the importance of evaluating their cost, effectiveness and potential impact on biodiversity prior to implementation. Chemical control of *J. acutus* is effective but costly, and the resulting abundant biomass can impede the growth of other plants and generate a fire risk (Brown & Bettink, 2006; Dixon, 2006; Paul & Young, 2006). Chemical control should be used as the last option due to its impact on biodiversity (do Carmo Langiano & Martinez, 2008; Lushchak, Kubrak, Storey, Storey, & Lushchak, 2009; Vera et al., 2010). Burning with fire does not seem to be effective for this species and would have an unwanted impact on biodiversity. The use of machinery to cut the plant, combined with increased grazing pressure in some periods of the year, may be the most practical and effective method for ranchers (Parsons & Cuthbertson, 2001; Paul & Young, 2006), and if it is performed systematically it may contribute to progressively decreasing the species cover. However, the cost of this method is high, and disturbance of the flooded soil caused by heavy machinery could change the natural drainage by creating new grooves and depressions. In all cases, it is recommended that an integrated management system be developed (Hobbs & Humphries, 1995; Higgins, Richardson, & Cowling, 2000) that includes protocols for each action and is closely supervised by personnel within the protected area.

The management of the sand barrier to allow longer and larger floods is undoubtedly the most complex action in terms of analyzing or predicting its effects, but it could be the most effective, the least expensive and the most far-reaching since it affects the floodplain of the entire lagoon. Recovering the natural functioning of the sand barrier is a measure that is based on knowledge of how the ecosystem functions and has the potential to benefit the entire system as a whole by reversing the effects of artificial management on other aspects of the ecosystem (see Conde et al. (2015) and Rodríguez-Gallego et al. (2015) for a description of the impacts of artificial opening). This control method could probably be the best solution in the medium term and could be conducted progressively, as transformative experiments at a small scale. This may promote cross-learning, organized in nested adaptive cycles associated to adjustments of the sand bar opening protocol, oriented to drive the system to a more resilient, biodiverse and sustainable state (*sensu* Folke et al., 2010, Gunderson & Hooling, 2002). However, because the social-ecological system in this area includes the artificial management of the hydrology that has controlled the flood regime for many years, building in flooding zones has been allowed. Therefore, implementation of this measure will require careful study of the real impact of the floods on existing houses as well as additional urban measures to avoid such effects. Today, it is still a viable solution due to the small number of houses and infrastructure that would potentially be affected.

6. Conclusions

The results of this work indicate that *J. acutus* has expanded in the floodplain of Laguna de Rocha. The expansion can be explained by a multiplicity of causes that may have acted synergistically wherein a series of changes in the management of the sand barrier, livestock management and climate interacted to favor the species. These changes coincide with the expansion period of *J. acutus*, which appears to have begun in ca. 1998−2000. Local ecological knowledge was highly useful in gaining an understanding of some local processes and obtaining information on periods for which data were not otherwise available. It is necessary to understand systemically the causes of *J. acutus* expansion and the needs of the productive uses in a framework of social-ecological systems to avoid costly solutions that are only short-term palliatives and that could trigger other unforeseen environmental impacts. Economic analyses of the impact of the expansion of *J. acutus* and the lagoon's flood regime on livestock activity and on the biodiversity of the area are required prior to implementing management measures.

Declaration of Competing Interest

The authors report no declarations of interest.

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