

Rapid expansion and successful recruitment of the invasive Mediterranean mussel *Mytilus galloprovincialis* in the main mussel farming region of Brazil

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Abstract

The Mediterranean mussel *Mytilus galloprovincialis* is one of the world's most successful marine invaders and represents a growing threat to mussel aquaculture. Throughout 2024, we monitored nine mussel farms across Santa Catarina Island Bay, southern Brazil (27°37'10.66"S; 48°33'8.87"W), using commercial spat-collector and grow-out ropes to assess the species' current distribution and recruitment. *M. galloprovincialis* recruitment occurred year-round across all monitored sites, exhibiting strong spatial heterogeneity. Recruitment rates in spat collectors revealed that *M. galloprovincialis* already recruits as successfully as the native mussel *Perna perna*. Furthermore, despite the site-specific variation during initial recruitment, *M. galloprovincialis* reached significantly higher overall densities on cultivation ropes. Individuals ranging from recently settled juveniles to adults were found on grow-out ropes across all sites, with extreme density events favoring the invasive species, indicating its successful establishment and persistence throughout Brazil's principal mussel-producing region. These findings demonstrate that *M. galloprovincialis* is now widely established in southern Brazil and undergoing sustained recruitment, highlighting the need for continued monitoring and targeted management of this invasive species.

1. Introduction

The Mediterranean mussel, *Mytilus galloprovincialis*, is among the world's most successful marine invaders and is listed among the 100 worst invasive alien species globally (Lowe et al. 2000). Following its introduction outside its native range, this species has established self-sustaining populations in numerous coastal regions and has caused substantial ecological and economic impacts. In mussel aquaculture, *M. galloprovincialis* is recognized as an important biofouling species capable of competing with cultivated mussels for space and resources, reducing production efficiency and increasing operational costs (Padilla et al. 2011; Forrest and Atalah 2017).

The impacts of this invasion have been documented in several regions worldwide. In South Africa, *M. galloprovincialis* rapidly expanded after its introduction and displaced native mussel populations along extensive stretches of coastline (Rius & McQuaid, 2006). In New Zealand, where the species occurs within farms cultivating the green-lipped mussel *Perna canaliculus*, infestations have been associated with substantial economic losses to the aquaculture industry (Forrest and Atalah 2017).

In Brazil, the first confirmed record of *M. galloprovincialis* was reported from mussel farming areas in the state of Santa Catarina in 2016 (Belz et al. 2020). Subsequent surveys documented its presence in Bombinhas, Florianópolis, and Palhoça, indicating that the species was already established in several farming areas along the central coast of Santa Catarina (Lins et al. 2021). More recently, surveys conducted in the South Bay of Florianópolis revealed that *M. galloprovincialis* represented, on average, approximately 40% of the mussels present on cultivation ropes in some farms (Suplicy 2022).

Santa Catarina is the main mussel-producing region in Brazil, accounting for most of the national production of the native brown mussel *Perna perna*. Local farmers have reported that *M. galloprovincialis*

is less desirable commercially because of its weaker byssal attachment, lower meat yield, and smaller market acceptance compared with *P. perna* (Suplicy and Meneghetti 2024). Consequently, the continued expansion of this invasive mussel may represent a significant challenge for the regional aquaculture industry.

Although the occurrence of *M. galloprovincialis* has been documented previously, information on its current distribution, settlement dynamics, and recruitment intensity within the main mussel-producing embayments of southern Brazil remains limited. The present study reports the occurrence and recruitment of *M. galloprovincialis* across mussel farming areas in Santa Catarina Island Bay, providing evidence of its widespread establishment and successful reproduction in the principal mussel aquaculture region of Brazil.

2. Methods

The study was conducted between October 2023 and January 2025 (Table 1) at nine mussel farms distributed throughout Santa Catarina Island Bay, Santa Catarina, southern Brazil (Fig. 1). The Bay (total area = 430 km²) is located between the mainland and Santa Catarina Island and it connects with the Atlantic Ocean through its northern and southern ends. The bay is shallow (average depth = 3.4 m) and microtidal, with water temperature ranging from 15.7°C to 27.3°C (seatemperature.org, accessed August/2026).

Table 1
Sampling periods for spat collectors and commercial cultivation ropes used to monitor *Mytilus galloprovincialis* in Santa Catarina Island Bay.

Spat collectors		
Campaign	Period	Seasons covered
1	15/01/2024 to 30/01/2024	Summer
2	15/02/2024 to 06/03/2024	Summer–Autumn
3	19/02/2024 to 01/04/2024	Summer–Autumn
4	08/04/2024 to 24/04/2024	Autumn
5	13/05/2024 to 03/06/2024	Autumn–Winter
6	10/06/2024 to 27/06/2024	Winter
7	08/07/2024 to 06/08/2024	Winter
8	13/08/2024 to 06/09/2024	Winter–Spring
9	09/09/2024 to 04/10/2024	Spring
10	14/10/2024 to 06/11/2024	Spring
11	26/11/2024 to 29/11/2024	Spring
12	06/01/2025 to 22/01/2025	Summer
Cultivation ropes		
Campaign	Period	Seasons covered
1	20/10/2023 to 06/11/2023	Spring
2	15/02/2024 to 06/03/2024	Summer–Autumn
3	08/07/2024 to 07/08/2024	Winter
4	14/10/2024 to 06/11/2024	Spring

Recruitment was assessed using commercial spat collector ropes, configured as sets of three 30-cm segments positioned at three distinct depths (surface, 0.5 m, and 1 m). Five replicate sets of these collectors were deployed at each farm. They were retrieved for laboratory analysis and replaced every two months, at which time all recruits were identified and counted. To assess species establishment within the farms, mussels attached to commercial cultivation ropes were sampled every three to four months, identified to the species level, and quantified. Three 30-cm segments of cultivation rope were inspected at each site during each monitoring campaign.

Statistical analysis

Mussel density was analyzed separately for spat collectors and cultivation ropes. For comparisons between species, counts from the three depths of each spat collector and from the four size classes of each cultivation-rope sample were summed, respectively. Thus, the sampling unit was each campaign × site × collector combination. Missing observations were excluded and were not treated as zero. Because densities were zero-inflated and strongly right-skewed, species were compared using paired permutation tests applied to log-transformed densities [$\log(x + 1)$], with species labels permuted within each sampling unit. Analyses were conducted both across all sites and separately for each site. The effect size was expressed as the ratio of geometric mean densities, calculated by exponentiating the mean paired difference on the logarithmic scale. Its 95% confidence interval was obtained by bootstrap resampling with the site as the sampling cluster. Depth effects in spat collectors and size-class effects in cultivation ropes were evaluated using repeated-measures permutation tests, with depth or size-class labels permuted within collectors. All tests were two-sided, and statistical significance was set at $\alpha = 0.05$.

3. Results

Spat collectors

The median density of *M. galloprovincialis* in the spat collectors was 1 individual m^{-1} (mean $\pm$ SD = 16.37 ± 49.24 individuals m^{-1} , $n = 485$), while *P. perna* had a median density of 2 individuals m^{-1} (mean $\pm$ SD = 7.46 ± 13.12 individuals m^{-1} , $n = 485$). Densities equal to zero represented 48.2% of the observations for *M. galloprovincialis* and 41.6% for *P. perna*. A pronounced difference between the mean and median was observed, especially for *M. galloprovincialis*, indicating that its overall mean was strongly influenced by a relatively small number of high-density events. There was no overall difference between species (paired permutation test, $\Delta\log = 0.020$, $N = 485$ pairs, $P = 0.798$), with an estimated geometric density ratio between *M. galloprovincialis* and *P. perna* 1.02 (site-bootstrap 95% CI = 0.73–1.45; Fig. 2A,B).

The five highest densities of *M. galloprovincialis*, ranging from 255 to 484 individuals m^{-1} , were recorded on all five replicate cables at 4-PPO during campaign 9 (Fig. 3). The maximum depth-specific density was also recorded during this event, reaching 855 individuals m^{-1} in the surface segment. For *P. perna*, the highest density was 97 individuals m^{-1} at 8-PAL during campaign 8, while the maximum depth-specific density was 246 individuals m^{-1} , also in the surface segment at the same site and campaign.

Site-specific comparisons indicated spatial heterogeneity: *P. perna* had higher densities at 2-SER and 8-PAL, whereas *M. galloprovincialis* had a higher density at 3-BAR. No differences were detected at the other six sites. These opposing site-specific effects were consistent with the absence of an overall difference between species.

Recruitment differed among depths for both species (repeated-measures permutation tests, $P < 0.0001$), with the consistent ordering surface > 0.5 m > 1 m across all nine sites. The decline from the surface to deeper sections was proportionally greater for *P. perna*, particularly between the surface and 1 m (Fig. 4).

Cultivation ropes

M. galloprovincialis had a median density of 210 individuals m^{-1} (mean $\pm$ SD = $828.82 \pm 1,709.09$ individuals m^{-1} , $n = 96$) and *P. perna* a median of 96 individuals m^{-1} (mean $\pm$ SD = 215.06 ± 304.25 individuals m^{-1} , $n = 96$). Different from what was observed for spat collectors, densities equal to zero were uncommon in the cultivation ropes, representing 1.0% of the observations for *M. galloprovincialis* and 2.1% for *P. perna*. On the other hand, extreme densities were more pronounced on cultivation ropes. *M. galloprovincialis* reached a maximum total density of 8,814 individuals m^{-1} , whereas the maximum for *P. perna* was 1,605 individuals m^{-1} . Their respective 95th percentiles were 4,577.3 and 690 individuals m^{-1} . These upper-tail observations contributed to the marked difference between means and medians. *M. galloprovincialis* had a higher overall density than *P. perna* (paired permutation test, $\Delta\log = 0.845$, $N = 96$ pairs, $P < 0.0001$). The geometric density ratio was 2.33 (site-bootstrap 95% CI = 1.21–5.04), indicating that the typical density of *M. galloprovincialis* was approximately 2.3 times that of *P. perna*.

Site-specific comparisons showed higher densities of *M. galloprovincialis* at 2-SER, 3-BAR, and 8-PAL, with no differences at the remaining sites. The three highest densities of *M. galloprovincialis* (8,633.1–8,814 individuals m^{-1}) occurred in the three samples collected at 8-PAL during campaign 1. High densities of *P. perna* (1,275–1,605 individuals m^{-1}) occurred in the same samples. Thus, campaign 1 at 8-PAL represented a high-density event for both species, although the magnitude was substantially greater for the invasive *M. galloprovincialis*.

Density differed among size classes (repeated-measures permutation test, $P < 0.0001$). Both species had comparatively high densities in the smallest and largest classes and lower densities in the intermediate classes. The contrast between the < 10 mm and intermediate classes was proportionally greater for *P. perna*.

Discussion

The simultaneous occurrence of widespread larval settlement and abundant juvenile and adult populations demonstrates that *M. galloprovincialis* is now firmly established throughout Santa Catarina Island Bay. Recruitment was recorded at all monitored farming locations during 2024, indicating active reproduction and effective dispersal across the principal mussel farming region of Brazil. Particularly noteworthy is the fact that, although no overall dominance was detected in spat collectors, the initial recruitment of the invasive species has already reached levels comparable to the native *P. perna* across the bay. Considering that *M. galloprovincialis* was undetected in these farming areas a few years ago (Belz et al. 2020), this numerical equivalence in recent recruitment represents a major ecological shift and a critical milestone in its invasion process.

Contrary to a pattern of uniform dominance, initial recruitment showed strong spatial and vertical structuring. Recruitment exhibited pronounced spatial heterogeneity, with site-specific differences occurring in opposite directions. While the native *P. perna* maintained higher settlement densities at specific sites (e.g., 2-SER and 8-PAL), *M. galloprovincialis* was higher at 3-BAR, resulting in no overall

statistical difference in recruitment intensity between the two species across the bay. Historically in southern Brazil, areas with more successful results for *P. perna* recruitment have been used as nurseries, where shellfish farmers position their spat collectors which are later transferred to growing out areas. The results suggest that 2-SER and 8-PAL may be eligible for this role in the current scenario of *M. galloprovincialis* presence. However future studies or the observation on a longer term will reveal if this spatial pattern is consistent over time.

The observed spatial structuring of the settlement suggests that different environmental conditions favour the two species differently. Although our preliminary attempts to correlate recruitment data with environmental parameters during this one-year study did not yield significant findings (data not presented in this note), previous research in other invaded regions has demonstrated that factors such as wave exposure, heat/desiccation stress, and sand scour play crucial roles in mediating the competitive outcomes between *M. galloprovincialis* and native mussel species (Bownes & McQuaid, 2006; Rius & McQuaid, 2006). Therefore, the relationship between local environmental drivers and recruitment success should be further investigated in future monitoring studies utilizing longer time-series datasets in southern Brazil.

Vertically, both species displayed a consistent decline in spat density with increasing depth, although the strongest surface-to-depth contrast was observed for *P. perna*. This preference for shallower settlement aligns with previous studies indicating that *M. galloprovincialis* recruits heavily in the upper water column and near the surface on artificial substrates (Curiel-Ramírez & Cáceres-Martínez, 2010). While studies in deeper coastal environments have evaluated *Mytilus* settlement over much broader depth ranges (e.g., Curiel-Ramírez & Cáceres-Martínez, 2010), focusing on the upper 1-meter layer is highly relevant for shallow systems like Santa Catarina Island Bay, where the average depth is around 3 meters. The sharp decline in recruitment within just one meter reveals that larvae of both species, but particularly *P. perna*, are highly sensitive to superficial microgradients, such as light intensity, temperature, or salinity variations. From a practical perspective, this compressed vertical stratification means that farmers have a very narrow spatial window to optimize spat collection. Because both species share this strict surface preference, utilizing depth-specific placement of spat collectors to selectively favor the native species over the invasive one is unfeasible.

Despite the observed competitive balance during initial recruitment, the scenario on commercial cultivation ropes is even more concerning from an ecological and economic perspective. On these structures, *M. galloprovincialis* generally reached significantly higher overall densities than *P. perna*. The data indicate that the invasive species produced a much more pronounced upper tail than the native species. These extreme values were concentrated within specific site–campaign combinations and replicated among multiple sampling units, with the highest settlement recorded at point 4-PPO in October 2024.

The discrepancy between spat collectors and grow-out ropes suggests that while larval supply and initial recruitment might be highly variable for both species, *M. galloprovincialis* may benefit from episodic

massive recruitment events, favorable local environmental conditions, better post-settlement survival, or enhanced retention on the cultivation ropes rather than being random analytical outliers. The latter hypothesis of enhanced retention makes theoretical sense based on these density results; however, it contradicts the weaker byssal attachment of *M. galloprovincialis* reported by local marine farmers (Suplicy and Meneghetti, 2024). This paradox warrants further biomechanical and ecological investigation. Furthermore, on cultivation ropes, both species showed higher densities in the smallest and largest size classes and lower densities in the intermediate classes. The similarity of this pattern suggests that common recruitment, growth, retention, or size-dependent loss processes structure both populations, but the invasive species is currently more successful in capitalizing on these dynamics to persist and dominate.

This capacity to establish dense adult populations on cultivation ropes indicates that *M. galloprovincialis* may continue increasing its relative abundance within farming areas. Similar expansion patterns have been reported in other invaded regions globally, where the species became dominant and generated significant ecological and economic impacts (Forrest and Atalah 2017; Lins et al. 2021). Because Santa Catarina accounts for most Brazilian mussel production, the continued spread and competitive advantage of *M. galloprovincialis* on grow-out structures represents an important challenge for the regional aquaculture industry. Ongoing monitoring will be essential to track its expansion and support management strategies aimed at minimizing impacts on native mussel cultivation.

Declarations

Compliance with Ethical Standards

All applicable international, national and/or institutional guidelines for sampling, care and experimental use of organisms for the study have been followed.

Ethical approval was waived for this study as *Perna perna* and *Mytilus galloprovincialis* are bivalve invertebrates excluded from Brazilian (Law No. 11.794/2008; Portaria ICMBio No. 748/2022) and European (Directive 2010/63/EU) animal research regulations. The exploratory, observational study complied with ARRIVE 2.0 guidelines and followed international best practices for shellfish handling.

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Emanuela Rodrigues Meneghetti and Felipe Matarazzo Suplicy. The first draft of the manuscript was written by Felipe Matarazzo Suplicy and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

The datasets generated and analysed during the current study are available in the Seanoe repository: Suplicy Felipe Matarazzo , Meneghetti Emanuela Rodrigues, de Souza Robson Ventura(2026). Recruitment of the invasive Mediterranean mussel *Mytilus galloprovincialis* in the main mussel farming region of Brazil. SEANOE. <https://doi.org/10.17882/118859>

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Figures

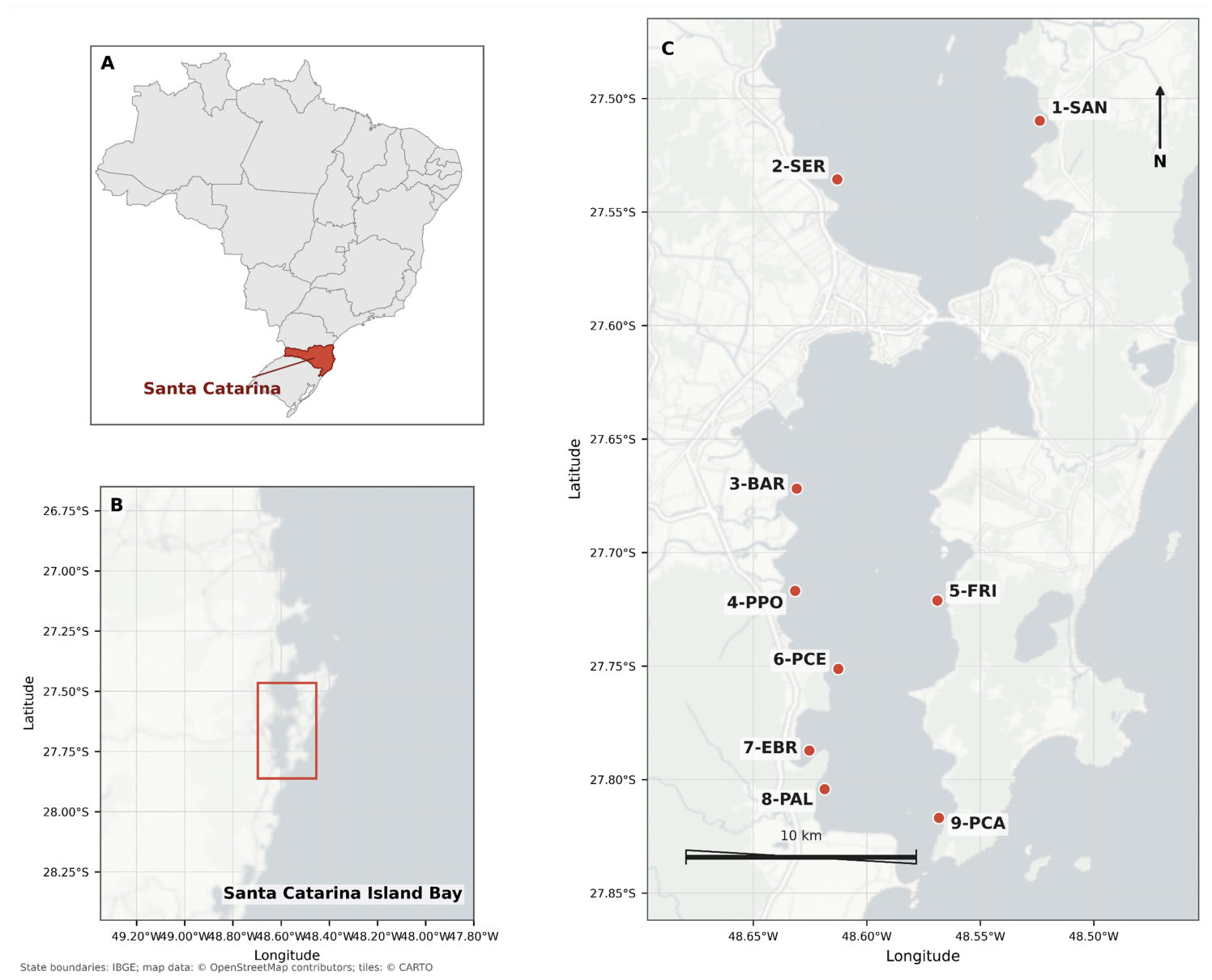


Figure 1

Map of Santa Catarina Island Bay with the location of the nine farms monitored for the presence and recruitment of *Perna perna* and *Mytilus galloprovincialis* spats. Santo Antônio de Lisboa (1-SAN), Serraria (2-SER), Barra do Aririú (3-BAR), Praia do Pontal (4-PPO), Freguesia do Ribeirão (5-FRI), Ponta do Cedro (6-PCE), Enseada do Brito (7-EBR), Pedras Altas (8-PAL), Ponta do Caetano (9-PCA).

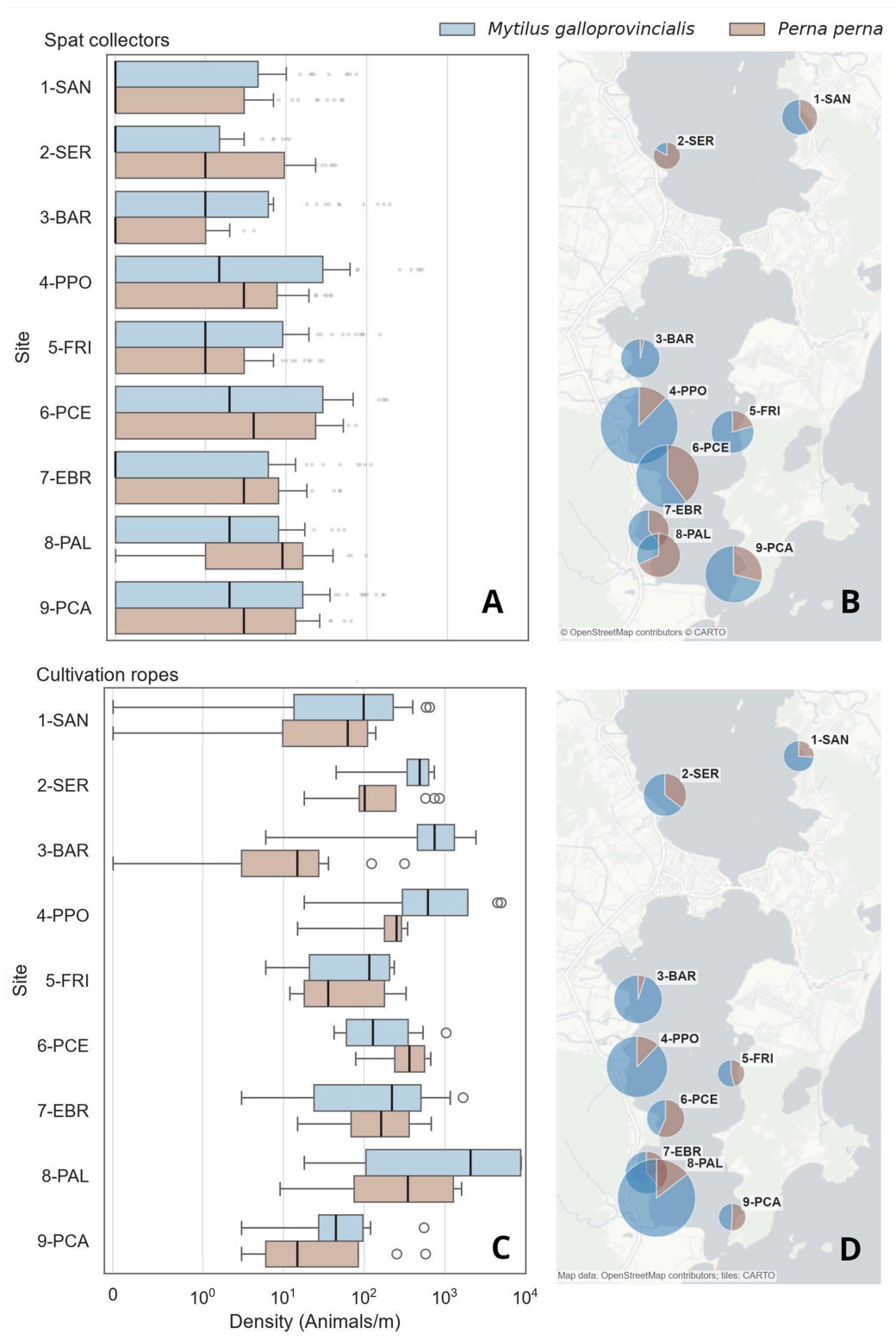


Figure 2

Spatial variation in the densities of the invasive mussel *Mytilus galloprovincialis* and the native mussel *Perna perna* on spat collectors (A, B) and cultivation ropes (C, D) at nine mussel farms in Santa Catarina Island Bay, southern Brazil. Boxplots show densities by sampling site for spat collectors (A) and cultivation ropes (C). Boxes represent the interquartile range, horizontal lines indicate medians, whiskers indicate the range excluding outliers, and points represent outliers. Map pie charts show the total

number of mussels recorded and the relative contribution of each species at each site for spat collectors (B) and cultivation ropes (D). Pie-chart area is proportional to the total number of mussels recorded at each site

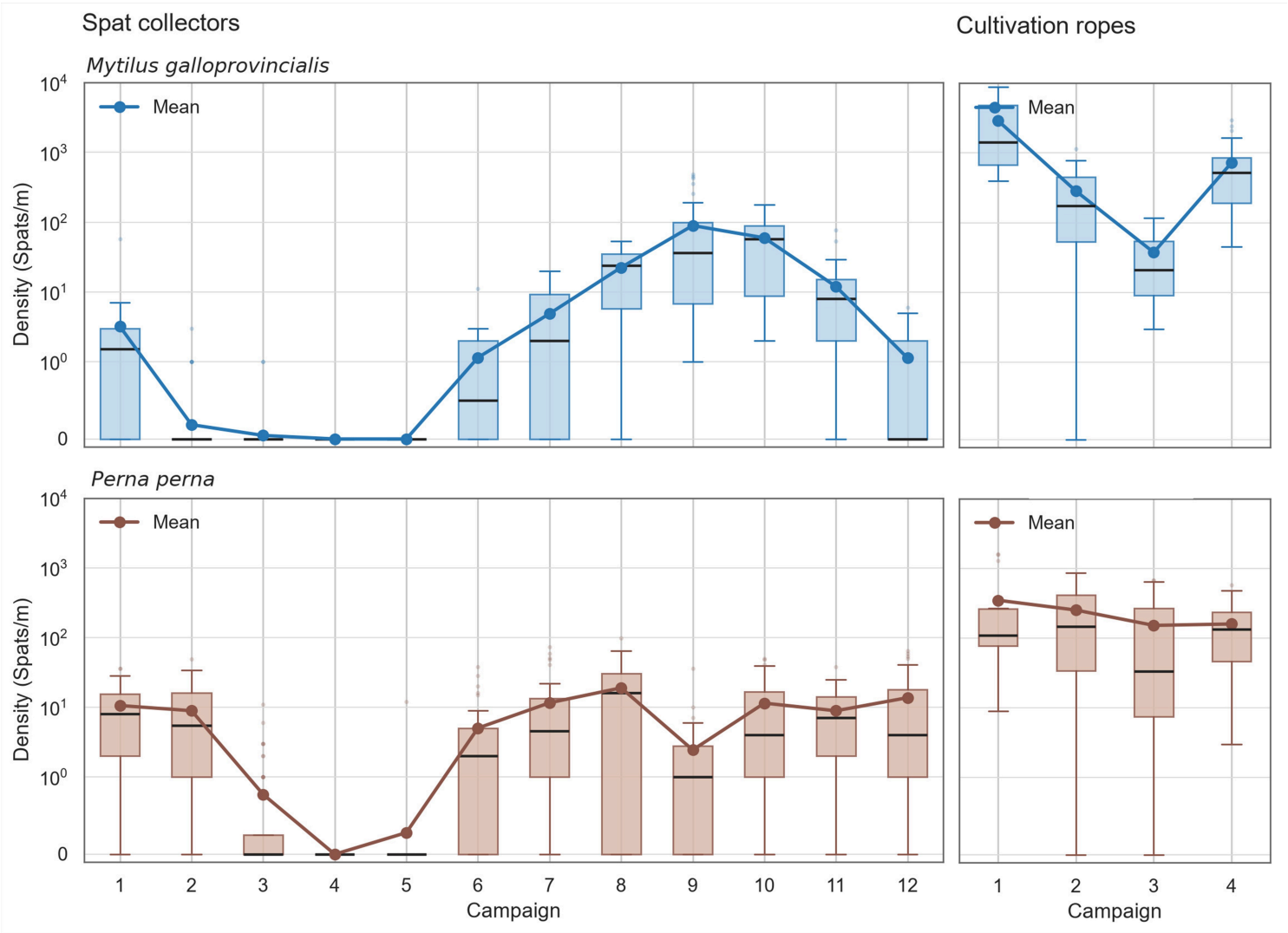


Figure 3

Temporal variation in the densities of the invasive mussel *Mytilus galloprovincialis* and the native mussel *Perna perna* on spat collectors (left panels) and cultivation ropes (right panels) during the monitoring campaigns. Boxes represent the interquartile range, horizontal lines indicate medians, whiskers indicate the range excluding outliers, and points represent outliers. Filled symbols connected by solid lines show the mean density in each campaign.

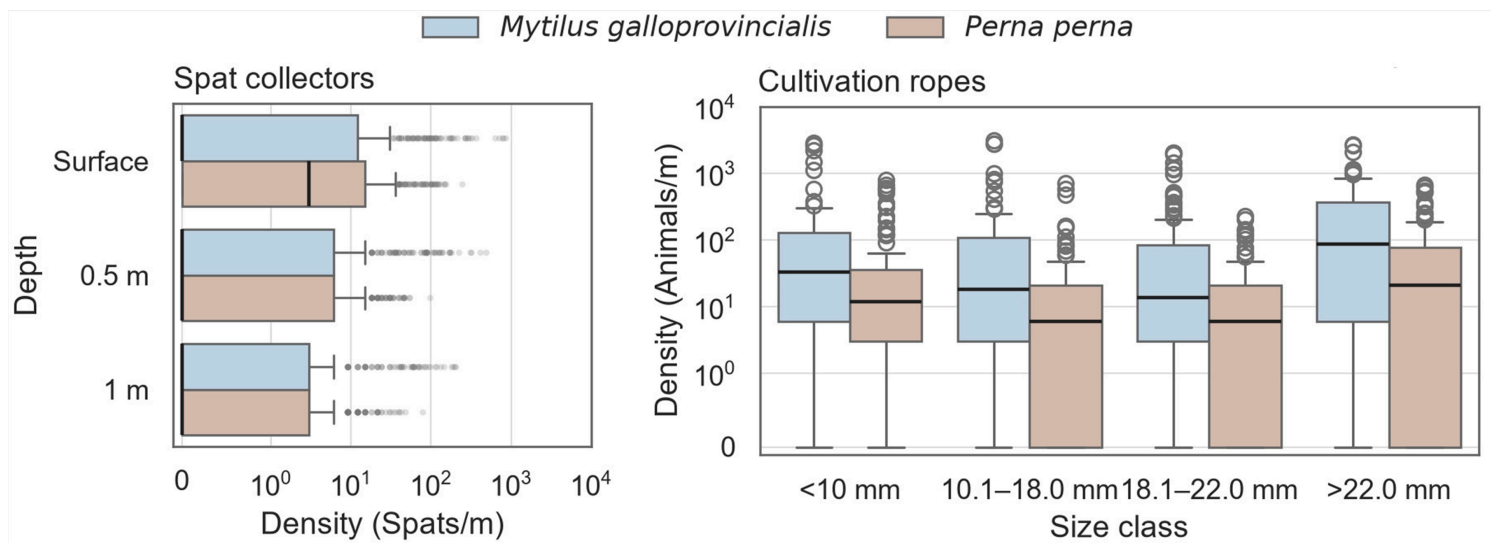


Figure 4

Vertical distribution of mussel recruitment on spat collectors (A) and density by size class on cultivation ropes (B) for the invasive mussel *M. galloprovincialis* and the native mussel *P. perna*. Spat-collector densities are shown for the surface, 0.5-m, and 1-m sections. Mussels from cultivation ropes were classified as <10 mm, 10.1–18.0 mm, 18.1–22.0 mm, or >22.0 mm. Boxes represent the interquartile range, horizontal lines indicate medians, whiskers indicate the range excluding outliers, and points represent outliers.