

Efficiency of self-recovery in coral living tissue of donor colonies of *Orbicella faveolata* used for coral intervention in the Mexican Caribbean

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ABSTRACT. The effects of climate change and local impacts, such as disease, hurricanes, and nutrient input, have led to the rapid degradation of reef ecosystems. The implementation of active restoration methods has expanded globally to mitigate the loss of these important habitats. However, many intervention strategies are still under development, and their impact is unknown. The aim of this study was to evaluate the efficiency of self-recovery of live *Orbicella faveolata* tissue used as donor microfragments from May 2021 to May 2023 in the Puerto Morelos Reef National Park. Digital images were analyzed to measure the recovery of bare area (~1,250 mm²), transverse diameter (mm), longitudinal diameter (mm), and number of new polyps in donor colonies. After 2 years the results showed that the area of bare tissue had an average recovery of 1,065 ± 237 mm² of living tissue with 97% of tissue recovered. The transverse and longitudinal diameters showed average monthly growth of 0.88 mm and 0.98 mm, respectively, with a recovery of 93–96% and an increase of approximately 18 new polyps by the end of the study period. The removal of live tissue microfragments does not negatively affect healthy donor colonies, which are capable of recovery within a relatively short time frame (24 months). This information reveals the potential of using microtransplants to accelerate live tissue recovery in colonies affected by various stressors. Despite their feasibility in coral species rehabilitation projects, it is necessary to continue investigating the long-term effects related to susceptibility to erosion and disease to establish more appropriate strategies that support the conservation of coral colonies and reef habitats, as well as the provision of ecosystem services.

Key words: coral recovery, live tissue, restoration, *Orbicella faveolata*, Mexican Caribbean.

INTRODUCTION

Coral reefs represent one of the most biodiverse and productive ecosystems on the planet, providing ecosystem services such as the provision of fishery resources, coastal protection, carbon sequestration, sediment retention for beach formation, and tourist attraction (Moberg and Folke 1999, Shepard et al. 2009). Despite their ecological and socio-economic importance, these ecosystems have experienced accelerated degradation due to anthropogenic factors such as overfishing, eutrophication, and pollution (Hughes et al. 2003). Furthermore, over the last 2 decades, the effects of climate change, including rising temperatures, ocean acidification, and pollution, have led to the reduction of more than 60% of coral cover worldwide (Hughes et al. 2017, Boström

et al. 2020). In the Caribbean, live coral cover has drastically decreased from ~50% in 1980 to ~10% in 2024 (Gardner et al. 2003, Perera-Valderrama et al. 2017, Reimer et al. 2024).

The construction and maintenance of coral reefs depend on the accumulation of calcium carbonate (CaCO₃) by hermatypic corals, which contribute structural complexity to the ecosystem (Spalding et al. 2001, González-Barrios et al. 2018, Tortolero-Langarica et al. 2023). Specifically, a reduction in the abundance of reef-building species such as *Acropora* spp. and *Orbicella* spp. has been documented (Álvarez-Filip et al. 2011). Although a relative recovery of coral reefs has been recorded at some Caribbean sites, this has been dominated by low-relief species with low building capacity (González-Barrios et al. 2018, Gouezo 2019). Nevertheless, the increase in frequency, intensity, and severity

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of current disturbances has notably limited natural recovery (Cheal 2017, Hughes et al. 2018).

In the face of the accelerated loss of coral cover, active restoration strategies have been implemented worldwide to mitigate reef deterioration and promote their recovery (Rinkevich 2019). Among these strategies, coral transplantation has been established as one of the most widely used and most successful in the medium and long term (Boström-Einarsson et al. 2020). In this context, microfragmentation has emerged as an alternative method for coral restoration, based on the extraction of small fragments (<3 cm²) of live tissue from a small portion of donor colonies (Page et al. 2018; Tortolero-Langarica et al. 2020, 2023). Observations indicate that the removal of a small fraction of tissue (<10% of the total) does not compromise the viability of the donor colony and promotes a relatively rapid recovery in some coral species (Padilla-Souza et al. 2023). However, regenerative capacity is primarily influenced by the health status of the donor colony, which is more efficient in healthy colonies (Rodríguez-Martínez et al. 2016). Nonetheless, some physiological processes, such as growth and reproduction, could be affected due to the redistribution of energy resources towards regeneration and repair (Carricart-Ganivet 2007).

Microfragmentation has shown promising results in coral reef restoration, but it is still in its early stages of development. Uncertainties exist regarding its effect on the health, growth, and recovery of donor colonies, which highlights the need for long-term research to evaluate its efficacy and relationship to environmental conditions. In this context, the objective of this study was to evaluate the efficiency of self-recovery of live tissue in colonies of the reef-building coral *Orbicella faveolata* used as donors and their growth response over 2 years.

MATERIALS AND METHODS

Growth parameters

The study was carried out from May 2021 to May 2023 in the Puerto Morelos Reefs National Park in the northern Mexican Caribbean (21°00'00" to 20°48'33"N, 86°53'14.94" to 86°46'38.94"W). Five adult colonies with the same morphology and size (~100 cm height), and a healthy appearance (no evidence of disease, erosion, bleaching, or competition) were selected at a depth of 5–8 m. For each colony, 3 to 6 small circular fragments (for a tissue transplant project) with radiuses of ~20–30 mm and depths of 20 mm were extracted using a submersible hydraulic electric drill (Nemo Power Tools, Tucson, USA) with a 30-mm diameter diamond-tipped cylindrical drill tip, producing bare areas of tissue (~1,250 mm²) with ~30-mm depths. Each month for 24 months, we monitored and evaluated the recovery of the bare tissue areas that resulted from harvesting donor tissue in terms of surface growth (area), radial growth (longitudinal and transverse diameters), and the number of new polyps formed. To achieve this, we used digital photography (Hero 10; GoPro, San Mateo, USA) in linear format and 25 MP resolution using a plastic Vernier caliper

(precision: 0.5 mm) as a reference scale. Images derived from monthly samplings were processed using the freely available software ImageJ v. 1.53t (Schneider et al. 2012). To determine the recovered surface growth, the outline of the bare cavity of live coral tissue (mm²) was measured. To obtain the values for both diameters, the maximum length (mm) was measured using 2 perpendicular lines (longitudinal and transverse) taken at the same reference angle for each month. To obtain the number of new polyps, the increase (number) of calyces with living tissue from the initial bare area was recorded from an aerial perspective.

Environmental variables

The environmental variables sea surface temperature (SST, °C) and photosynthetically active radiation (PAR, μmol quanta·d⁻¹) were used in this study to describe the influence of external factors on the self-recovery of living tissue of the massive coral *O. faveolata*. Hourly data for both parameters were obtained from the Sistema Académico de Monitoreo Meteorológico y Oceanográfico (SAMMO) of the *Unidad Académica de Sistemas Arrecifales, Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México* (SAMMO 2025) for the study months (May 2021 to May 2023), which were averaged to obtain a monthly value and associate it to coral growth.

Statistical analyses

Descriptive values were calculated for each variable (mean, range, maximum, and minimum). The assumptions of normality (Kolmogorov–Smirnov, $P < 0.05$) and homoscedasticity (Bartlett, $P < 0.05$) were also tested. Because the data did not have a normal distribution and variances were not homogeneous, we performed two-way analyses of variance (ANOVA) with repeated measures using generalized linear models (GLM) to evaluate differences at the colony level, in time (monthly), and in their respective interactions. Simple linear regression models (coefficient of determination, r^2) were also used to identify the relationship between growth characteristics and environmental factors (temperature and PAR). All statistical analyses were performed using Sigma Plot v. 11.0 (Systat Software, Inc., San Jose, USA), using a 95% confidence interval ($\alpha = 0.05$).

RESULTS

Surface growth

After a 24-month period, the bare areas showed an average recovery of $1,065 \pm 237$ mm² in live tissue area when all colonies were grouped together, with a monthly average of 29.50 ± 19.40 (range: 11.50–150.18 mm²) (Table 1) and a total recovery of 97% (Fig. 1). The results showed significant differences over time ($F_{22} = 10.212$, $P < 0.001$) (Fig. 2), but

no differences were found at the colony level ($F_4 = 1.788$, $P = 0.196$) or in the interaction ($F_{88} = 0.978$, $P = 0.538$) (Table S1). A posteriori results showed differences between the months of the period June–August (lower growth) and those of the period November–February (higher growth), with the same interannual trend during both years of study (Fig. 2).

Transverse and longitudinal diameters

For transverse diameters, the average accumulated growth was 20.97 mm with an average monthly rate of 0.88 ± 0.60 mm (range: 0.35 ± 2.47) (Table 1 and 2) and a 96% recovery at the end of the study (Fig. 1). The results showed differences between colonies ($F_4 = 3.369$, $P = 0.046$) and between months ($F_{22} = 11.981$, $P < 0.001$), but not in the interaction of colonies \times months ($F_{88} = 0.994$, $P = 0.502$). For longitudinal diameters, the accumulated growth was 22.77 mm with a monthly average of 0.98 ± 0.40 mm (range: 0.32 ± 3.15) and a recovery percentage of 94% (Table 2). Similarly, the results revealed no differences between colonies ($F_4 = 3.132$, $P = 0.056$), but they showed differences between months ($F_{22} = 16.274$, $P < 0.001$) and the interaction of colonies \times months ($F_{88} = 1.576$, $P = 0.003$) (Table S1). In both cases, the differences

were associated with the months of November and December of both years, which had the highest monthly values (Fig. 2).

Polyp formation

The damaged (donated) area showed a cumulative number of new polyps of 18 after 24 months of monitoring, with an increase of 0.77 ± 0.91 polyps monthly (Tables 1 and 2). The increase in the number of polyps between colonies showed significant differences, and variations were also present in time and in the interaction between colonies \times months (Table S1), mainly in the warmer months (August to October) (Fig. 3) when the highest values occurred.

Environmental variables

Monthly temperature averaged 28.62 °C (range: 25.95–30.56 °C) (Table 1). The highest temperatures were observed from July to September (~ 30.32 °C) and the lowest from January to February (~ 26.21 °C). Light averaged 52,286 $\mu\text{mol quanta} \cdot \text{d}^{-1}$, ranging from 42,145 $\mu\text{mol quanta} \cdot \text{d}^{-1}$ (November) to 60,112 $\mu\text{mol quanta} \cdot \text{d}^{-1}$ (August) (Table 1). The highest light intensity was observed during the month of August, coinciding with the highest temperature values. Linear regression analysis only showed a negative correlation with the PAR factor and all growth parameters ($P < 0.005$) (Fig. 4).

DISCUSSION

This study demonstrates rapid recovery from microfragmentation injuries in a relatively short period (24 months) in healthy *O. faveolata* colonies. This result is similar to previous reports on tissue regeneration in coring wounds in species from the Mexican Caribbean region (Rodríguez-Martínez et al. 2016), which highlight that recovery can be high (>80%) when the donor colony is in optimal health conditions (i.e., without bleaching damage, disease, or competition for space). Nevertheless, this regenerative capacity can vary due to extrinsic factors, such as environmental microconditions, interspecific interactions, and injury severity (Meesters et al. 1996, Martínez et al. 2016).

Given the environmental regime that influenced Puerto Morelos Reefs National Park during the study period, the growth and recovery rates of live tissue in donor colonies responded primarily to intra-annual variations in light irradiance and temperature. These factors could determine the energy supplied by symbionts to the coral and, consequently, the recovery capacity (Allemand et al. 2011). The results of this study showed a relative variability (10–40%) in live tissue recovery, with improved injury repair observed when SST and PAR had average values of 28–29 °C and 48,078 $\mu\text{mol quanta} \cdot \text{d}^{-1}$, respectively. The temporal variability pattern has also been documented in massive corals from other Pacific regions, where their recovery capacity is usually greater under optimal light (400–700 nm) and temperature (26–29 °C) conditions,

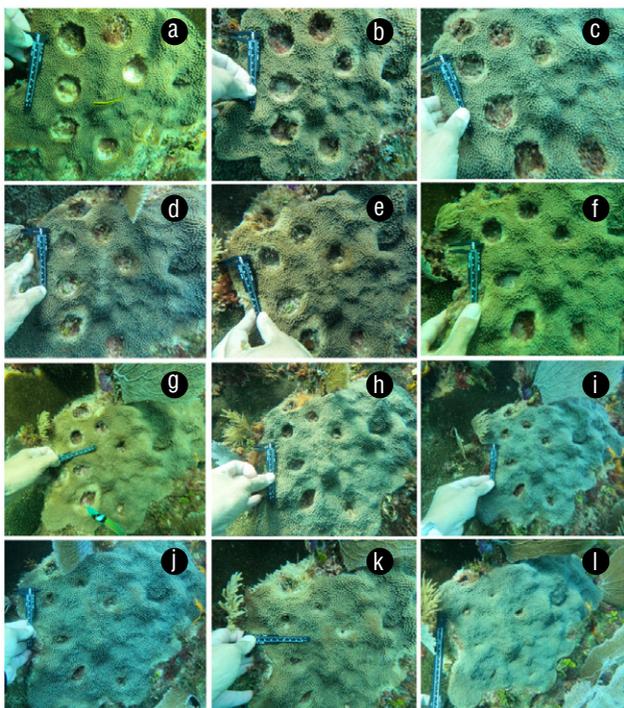


Figure 1. Coral tissue recovery experiment over a 2-year period. Bare area one month after *Orbicella faveolata* fragments were removed (June 2021) (a). Progress in recovery of damaged tissue in August 2021 (b), October 2021 (c), December 2021 (d), February 2022 (e), April 2022 (f), June 2022 (g), August 2022 (h), October 2022 (i), December 2022 (j), and February 2023 (k), and the recovered area at the end of the study (May 2023) (l).

Table 1. Monthly averages of the growth parameters (\pm SD), real area ($\text{mm}^2 \cdot \text{month}^{-1}$), diameters ($\text{mm} \cdot \text{month}^{-1}$), and number of polyps ($\text{N} \cdot \text{month}^{-1}$) in fragments of *Orbicella faveolata*. Descriptions of environmental factors, such as sea surface temperature (SST) and photosynthetically active radiation (PAR), for the Puerto Morelos Reef National Park.

Month	Real area ($\text{mm}^2 \cdot \text{month}^{-1}$)	Transverse diameter ($\text{mm} \cdot \text{month}^{-1}$)	Longitudinal diameter ($\text{mm} \cdot \text{month}^{-1}$)	Polyps ($\text{N} \cdot \text{month}^{-1}$)	SST ($^{\circ}\text{C}$)	PAR (μmol $\text{quanta} \cdot \text{d}^{-1}$)
June 2021	48.9 \pm 32.8	0.48 \pm 0.46	0.62 \pm 0.44	0.39 \pm 0.70	29.61 \pm 1.09	52,539 \pm 39,084
July 2021	43.2 \pm 38.6	0.35 \pm 0.30	0.52 \pm 0.47	0.61 \pm 0.78	30.54 \pm 1.02	51,542 \pm 42,297
August 2021	58.7 \pm 57.9	0.54 \pm 0.39	0.77 \pm 0.32	1.94 \pm 1.47	30.56 \pm 1.10	60,112 \pm 40,072
September 2021	40.0 \pm 41.6	0.72 \pm 0.64	0.55 \pm 0.67	0.22 \pm 0.55	30.09 \pm 0.97	54,275 \pm 38,510
October 2021	44.7 \pm 53.9	0.88 \pm 0.88	0.87 \pm 0.71	0.17 \pm 0.38	29.94 \pm 0.88	54,513 \pm 34,755
November 2021	146.7 \pm 74.3	1.77 \pm 0.88	1.96 \pm 1.19	0.78 \pm 0.81	27.21 \pm 0.87	42,145 \pm 28,672
December 2021	151.8 \pm 58.6	2.47 \pm 1.13	2.32 \pm 1.29	0.44 \pm 0.51	27.02 \pm 1.02	44,825 \pm 28,663
January 2022	37.3 \pm 62.6	0.64 \pm 0.59	0.61 \pm 0.74	2.61 \pm 2.44	25.95 \pm 1.15	42,612 \pm 30,077
February 2022	22.3 \pm 31.6	0.48 \pm 0.53	0.32 \pm 0.33	0.83 \pm 0.92	26.48 \pm 1.10	52,144 \pm 34,325
March 2022	18.4 \pm 16.0	0.35 \pm 0.30	0.36 \pm 0.54	0.78 \pm 1.17	27.18 \pm 1.11	61,573 \pm 37,202
April 2022	31.9 \pm 29.5	0.42 \pm 0.39	0.43 \pm 0.41	0.67 \pm 0.84	28.01 \pm 1.19	63,577 \pm 40,322
May 2022	20.5 \pm 12.7	0.43 \pm 0.24	0.35 \pm 0.27	0.33 \pm 0.55	29.14 \pm 0.94	61,381 \pm 37,809
June 2022	29.9 \pm 24.8	0.91 \pm 0.73	0.88 \pm 0.63	0.61 \pm 0.50	29.71 \pm 1.35	57,781 \pm 38,243
July 2022	22.8 \pm 20.4	0.37 \pm 0.42	0.35 \pm 0.38	0.06 \pm 0.24	30.72 \pm 0.91	60,327 \pm 38,043
August 2022	11.5 \pm 8.9	0.82 \pm 0.62	0.49 \pm 0.51	0.78 \pm 2.10	30.98 \pm 0.94	58,666 \pm 38,903
September 2022	28.7 \pm 25.5	0.47 \pm 0.34	0.50 \pm 0.47	0.67 \pm 0.97	30.41 \pm 1.03	52,459 \pm 38,394
October 2022	42.8 \pm 40.9	1.03 \pm 0.71	1.03 \pm 0.58	1.28 \pm 1.56	28.80 \pm 1.06	53,917 \pm 33,296
November 2022	78.6 \pm 64.1	1.86 \pm 0.75	2.72 \pm 1.48	1.67 \pm 1.37	28.59 \pm 0.69	49,863 \pm 29,993
December 2022	55.7 \pm 32.5	2.29 \pm 1.06	3.15 \pm 0.91	1.39 \pm 1.14	27.25 \pm 0.86	43,210 \pm 29,090
January 2023	36.0 \pm 22.3	1.00 \pm 0.78	1.68 \pm 1.42	0.39 \pm 0.50	26.5 \pm 0.98	54,809 \pm 51,616
February 2023	22.5 \pm 9.5	0.70 \pm 0.44	0.73 \pm 0.36	0.33 \pm 0.49	26.85 \pm 0.79	75,159 \pm 44,280
March 2023	20.1 \pm 12.0	0.64 \pm 0.37	0.54 \pm 0.40	0.17 \pm 0.39	27.18 \pm 1.06	67,717 \pm 51,804
April 2023	20.7 \pm 10.5	0.72 \pm 0.51	0.77 \pm 0.72	0.67 \pm 0.49	28.42 \pm 0.84	68,402 \pm 36,762

favoring physiological processes such as growth, calcification, and repair of damaged tissue (Lough and Barnes 2000, Tortolero-Langarica et al. 2020). Contrary to expectations, the warmer months (August to October) showed the lowest values for injury regeneration parameters, which was related to the highest irradiance (Fig. 3) and temperature values (Van Woesik 1998). High radiation and elevated temperatures could have influenced the reduced rate of calcification and recovery from lesions, possibly due to a decreased photosynthetic

efficiency of algae (i.e., from the Symbiodinacea family) due to light stress (Allemand et al. 2011, Gutiérrez-Estrada et al. 2025). Alternatively, differences in regeneration rates may be attributable to variables such as wound size and intrinsic characteristics, including the genotypes of both the coral host and its symbiont. Studies have shown that recovery rates tend to be relatively low in large lesions ($\leq 1,310 \text{ mm}^2$; Van Woesik 1998) and in colonies with disease or partial mortality (Rodríguez-Martínez et al. 2016). Therefore, it is essential to

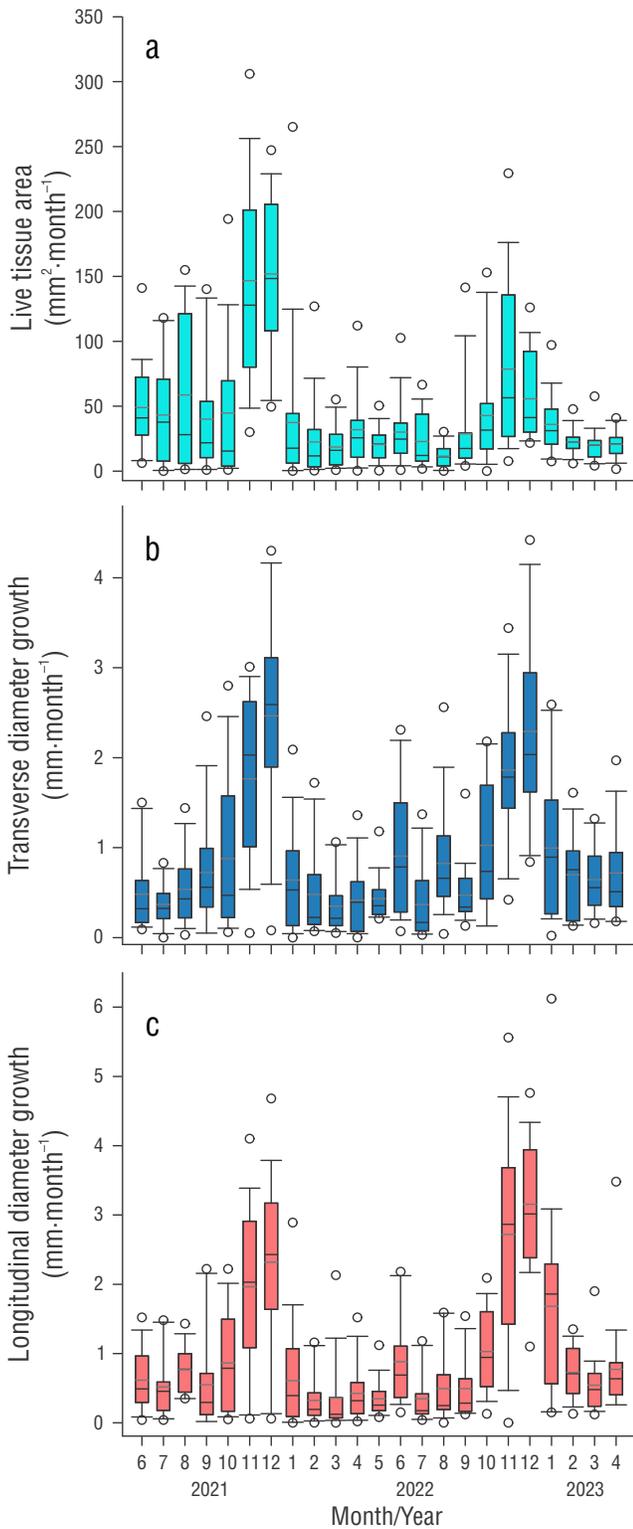


Figure 2. Box plot of monthly growth of live tissue in the coral *Orbicella faveolata* over a 2-year period. Growth rate in area (mm²·month⁻¹) (a), transverse diameter (mm·month⁻¹) (b), and longitudinal diameter (mm·month⁻¹) (c).

consider these intrinsic factors when using or extracting living tissue (Allemand et al. 2011, Padilla-Souza et al. 2023).

In addition, in the present study, a high percentage of live tissue recovery (>90%) and regeneration of new polyps were observed, which could favor pigmentation replacement and an improved photosynthetic efficiency (Sabine et al. 2015). Recovery from lesions has been shown to be primarily mediated by key physiological processes, such as polyp reproduction and cloning, which may exhibit seasonal patterns (Selman et

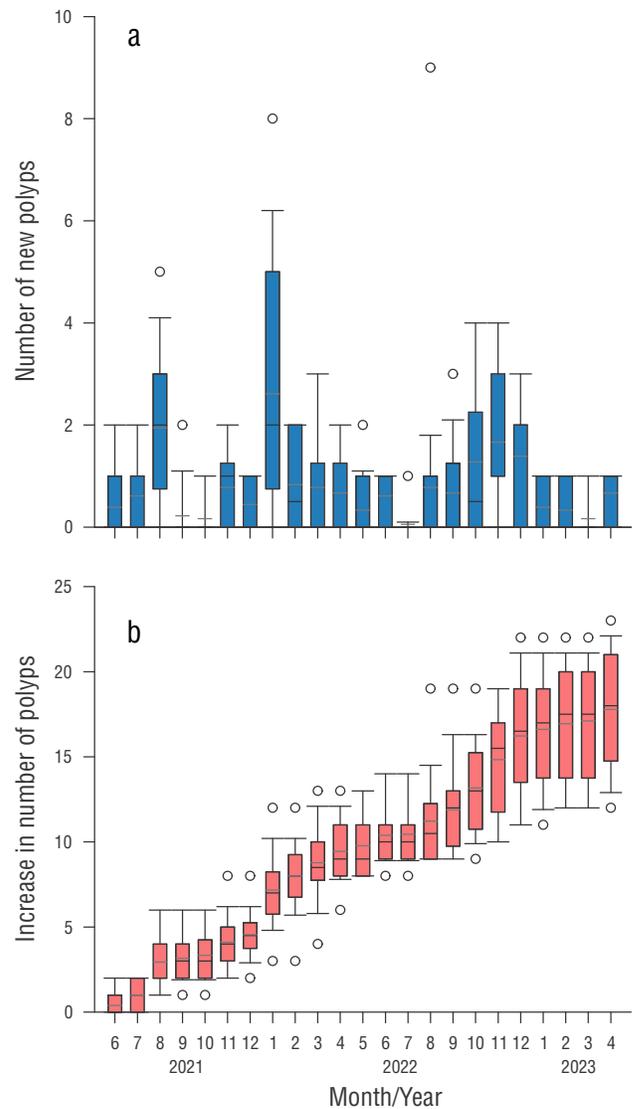


Figure 3. Box plot of new polyp formation over the study period. Number of polyps incorporated each month (a) and cumulative number of new polyps after a 2-year period (b).

al. 2012). Likewise, a lower tissue regenerative capacity has been observed before or after spawning events, because the energy requirement for gametogenesis is greater during the reproductive period (Kramarsky-Winter and Loya 2000). The observed reproductive pattern, which occurred between December and early February, suggests that coral gamete maturation coincides with the warm season. This distribution of energy between reproduction and tissue regeneration could explain the reduction in the regenerative capacity recorded in this study (Stearns 1989, Selman et al. 2012). Thus, it is essential to consider these effects when planning sampling to optimize the success of tissue

regeneration, particularly in interventions involving microfragment transplantation.

CONCLUSIONS

The results suggest that the use of live tissue in massive corals can be an effective strategy for active interventions without compromising the health of donor colonies on the reef. However, several factors must be considered before this can be implemented. Among them, the health status of the colony and extrinsic factors, such as the timing of tissue extraction in relation to optimal

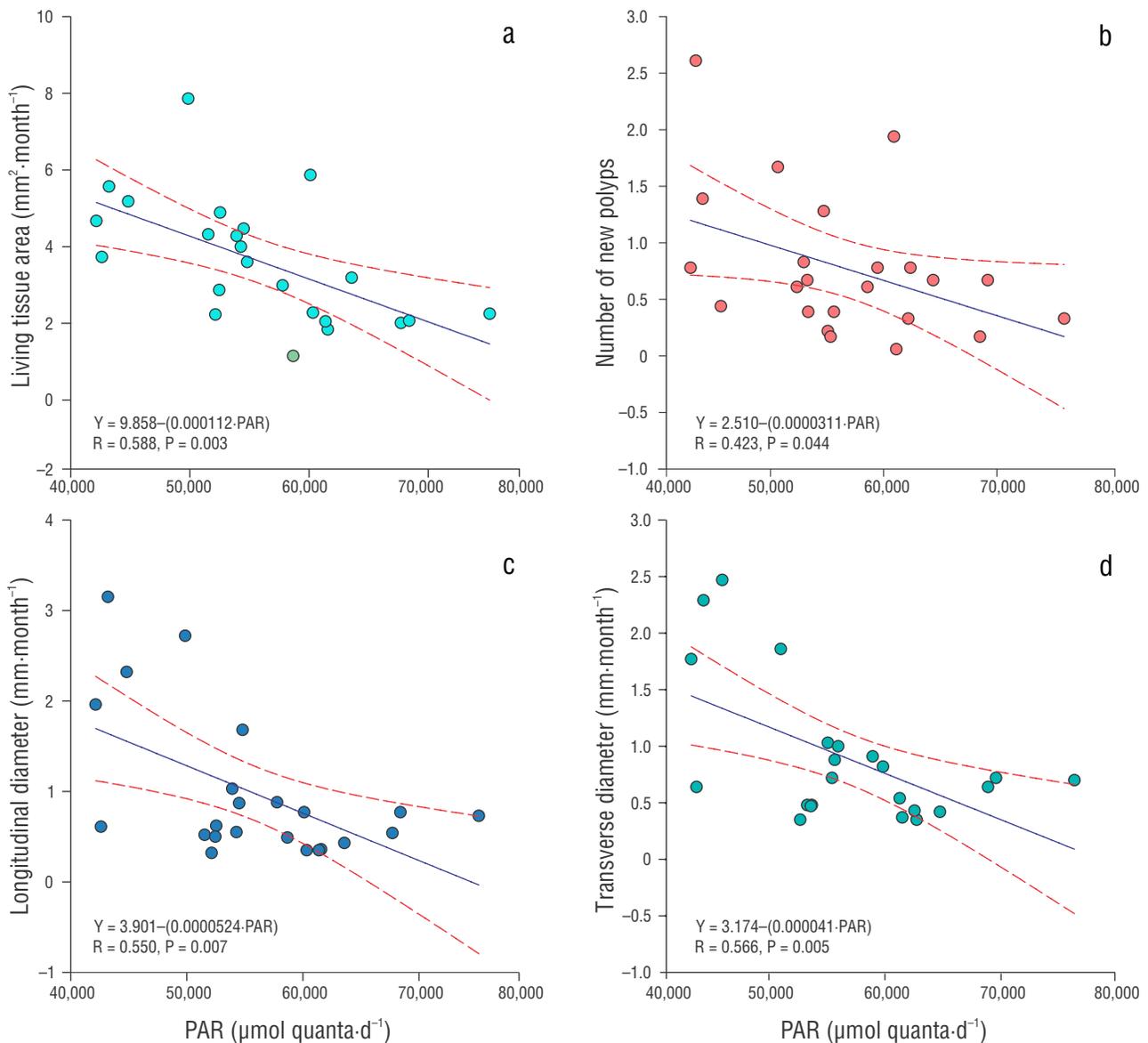


Figure 4. Scatter plot of monthly *Orbicella faveolata* parameters and photosynthetically active radiation (PAR) over 2 years (2021–2023). Area of recovered tissue vs. PAR (a), number of new polyps vs. PAR (b), transverse diameter vs. PAR (c), and longitudinal diameter vs. PAR (d). A regression line and equation for the latter relationship are shown.

Table 2. Accumulated growth (\pm SD) and recovery (%) for the area (mm^2) and transverse and longitudinal diameters (mm) in bare tissue areas of *Orbicella faveolata*.

Month	Accumulated area (mm^2)	Accumulated area (%)	Transverse diameter (mm)	Transverse diameter (%)	Longitudinal diameter (mm)	Longitudinal diameter (%)
June 2021	48.9 \pm 32.8	4.45%	0.48 \pm 0.46	2.19%	0.62 \pm 0.44	3.08%
July 2021	92.1 \pm 60.1	8.38%	0.85 \pm 0.51	3.86%	0.68 \pm 0.42	3.39%
August 2021	150.8 \pm 92.1	13.72%	1.39 \pm 0.53	6.30%	1.28 \pm 0.64	6.42%
September 2021	190.9 \pm 107.4	17.36%	2.11 \pm 0.78	9.59%	1.53 \pm 0.57	7.64%
October 2021	235.7 \pm 148.6	21.43%	2.99 \pm 1.16	13.59%	2.01 \pm 1.08	10.03%
November 2021	382.4 \pm 197.5	34.77%	4.76 \pm 1.94	21.62%	2.92 \pm 1.47	14.58%
December 2021	534.2 \pm 212.8	48.56%	7.22 \pm 2.90	32.82%	4.75 \pm 2.72	22.86%
January 2022	571.6 \pm 224.7	51.96%	7.86 \pm 3.05	35.73%	5.30 \pm 2.29	26.52%
February 2022	594.0 \pm 228.6	54.00%	8.34 \pm 3.19	37.90%	5.24 \pm 3.05	26.19%
March 2022	612.4 \pm 225.6	55.68%	8.69 \pm 3.30	39.49%	5.66 \pm 2.20	28.31%
April 2022	644.3 \pm 217.2	58.58%	9.10 \pm 3.34	41.38%	5.99 \pm 2.99	28.45%
May 2022	664.9 \pm 215.5	60.45%	9.54 \pm 3.48	43.35%	6.13 \pm 2.31	30.65%
June 2022	694.9 \pm 205.7	63.17%	10.44 \pm 3.68	47.47%	6.28 \pm 3.34	31.41%
July 2022	717.7 \pm 200.8	65.25%	10.81 \pm 3.79	49.14%	6.98 \pm 3.42	34.90%
August 2022	729.2 \pm 199.2	66.30%	11.63 \pm 3.53	52.88%	7.44 \pm 3.54	37.19%
September 2022	758.0 \pm 180.6	68.91%	12.11 \pm 3.54	55.03%	7.87 \pm 3.56	39.36%
October 2022	800.8 \pm 181.4	72.80%	13.13 \pm 3.73	59.69%	8.63 \pm 3.77	43.13%
November 2022	879.4 \pm 206.7	79.95%	15.00 \pm 4.08	68.17%	9.83 \pm 4.32	49.14%
December 2022	935.1 \pm 198.4	85.01%	17.29 \pm 4.40	78.59%	12.98 \pm 4.43	64.92%
January 2023	971.1 \pm 210.0	88.29%	18.28 \pm 4.30	83.11%	14.67 \pm 3.93	73.33%
February 2023	993.7 \pm 209.7	90.34%	18.98 \pm 4.31	86.28%	15.31 \pm 3.91	76.97%
March 2023	1,029.7 \pm 222.8	93.61%	19.98 \pm 4.32	90.81%	17.08 \pm 3.92	85.38%
April 2023	1,065.7 \pm 23.72	96.89%	20.97 \pm 4.59	95.33%	18.76 \pm 4.41	93.79%

environmental conditions (e.g., SST and PAR), are crucial for maximizing growth and the capacity for damage repair. It is recommended to avoid periods in which the influence of thermal anomalies or disease outbreaks could compromise the resilience of *O. faveolata* populations. The use of live tissue for transplantation is still in its initial development phase; thus, further exploration of its limitations is necessary for large-scale implementation. This will provide key information to improve management strategies for reefs in the Mexican Caribbean.

English translation by Claudia Michel-Villalobos.

DECLARATIONS

Supplementary Material

The supplementary material for this work can be downloaded from: <https://www.cienciasmarinas.com.mx/index.php/cmarias/article/view/3511/420421209>.

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Conflict of interest

The authors declare they have no conflict of interest.

Author contributions

Conceptualization: JJATL and JPCG; Data curation: AMGC; Formal analysis: JJATL and AMGC; Funding acquisition: JPCG and JJATL; Methodology: GGE, JJATL; Software: AMGC and JJATL; Supervision: JJATL and JPCG; Validation: GGE, JJATL, and JPCG; Visualization: AMGC and JJATL; Writing—original draft: AMGC and JJATL; Writing—review and editing: AMGC, JJATL, GGE, and JPCG.

Data availability

Data for this study are available within the manuscript.

Ethical approvals and permits for studies involving animals

Fieldwork was conducted with the collecting permit (log number 23/LW-0103/04/21) granted by the Mexican authorities of the Puerto Morelos Reefs National Park (SEMARNAT/CONANP).

Use of AI tools

The authors did not employ any AI tools in this work.

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