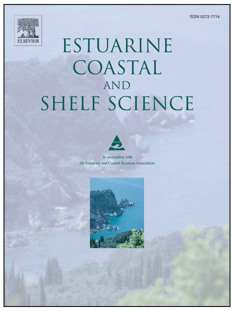


Restoring the reef: Coral restoration yields rapid impacts on certain fish assemblages

Stéphanie Krimou, Xavier Raick, Ethel Mery, Jeremy Carlot, Camille Carpentier, Jérome Sowinski, Lucille Sowinski, Lana Minier, Natacha Roux, Tehani Maueau, Frédéric Bertucci, David Lecchini

PII: S0272-7714(24)00122-7

DOI: https://doi.org/10.1016/j.ecss.2024.108734

Reference: YECSS 108734

To appear in: *Estuarine, Coastal and Shelf Science*

Received Date: 13 December 2023

Revised Date: 6 March 2024

Accepted Date: 23 March 2024

Please cite this article as: Krimou, Sté., Raick, X., Mery, E., Carlot, J., Carpentier, C., Sowinski, Jé., Sowinski, L., Minier, L., Roux, N., Maueau, T., Bertucci, Fréé., Lecchini, D., Restoring the reef: Coral restoration yields rapid impacts on certain fish assemblages, *Estuarine, Coastal and Shelf Science* (2024), doi: https://doi.org/10.1016/j.ecss.2024.108734.

Restoring the reef: coral restoration yields rapid impacts on certain fish assemblages

Stéphanie Krimou[a,b*], Xavier Raick[c*#], Ethel Mery[a,b], Jeremy Carlot[d], Camille Carpentier[a,e], Jérome Sowinski[e], Lucille Sowinski[e], Lana Minier[a,f], Natacha Roux[a], Tehani Maueau[g], Frédéric Bertucci[h,¤], David Lecchini[a,b,¤]

[a] PSL Research University: EPHE-UPVD-CNRS, UAR 3278 CRIOBE BP, Moorea, French Polynesia

[b] Laboratoire d'Excellence "CORAIL", Perpignan, France

[c] Laboratory of Functional and Evolutionary Morphology, FOCUS, University of Liège, Liège, Belgium

[d] Sorbonne Université, CNRS-INSU, Laboratoire d'Océanographie de Villefranche, 181 Chemin du Lazaret, F–06230 Villefranche-sur-Mer, France

[e] Espace Bleu, Bora Bora, French Polynesia

[f] Polynésienne des Eaux, Vaitape, Bora Bora, French Polynesia

[g] Association Ia Vai Ma Noa Bora Bora, 98730 Bora Bora, French Polynesia

[h] UMR MARBEC, University of Montpellier, CNRS, IFREMER, IRD, Sète, France

Corresponding author: xavier.raick@uliege.be; +32 4 366 51 33; allée du 6 août 11 (B6c) 4000 Liège

* Equal contribution as first authors

¤ Equal contribution as last authors

stephaniekrimou4@gmail.com; xavier.raick@uliege.be; ethel.mery13@gmail.com; jeremy.carlot@hotmail.fr; camillecarpentier@yahoo.fr; sowinski.jerome@gmail.com; lucillesowinski@gmail.com; lanaminier@gmail.com; Natacha.Roux@oist.jp; tehanimaueau@netcourrier.com; frederic.bertucci@ird.fr; david.lecchini@ephe.psl.eu

Running tittle: Restoring Reefs: Rapid Fish Assemblage Impact

Authorship contribution statement

SK, CC, JS, TM, and JC conducted the investigation. SK, DL, and XR worked on the methodology. SK and XR wrote the initial draft. SK, EM, LS, LM, NR, FB, DL, and XR reviewed and edited the final manuscript. SK, XR, and DL oversaw project administration. DL and XR conceptualized the study. XR implemented the code in R, validated the analyses, and conducted formal analysis, managed data curation and visualization. XR and DL supervised the project. JC and DL provided resources, and DL managed funding acquisition.

Abstract

Coral reefs harbor one of the highest biodiversity on Earth but increasing disturbances have often led to rapid shifts from coral to algal states, prompting the development of conservation methods, including coral restoration. While most studies have focused on the medium and long-term effects of restoration on fish assemblages, less is known about its short-term effects (i.e., within one month) on associated communities. This study explored the short-term impacts (< 1 month) of coral restoration, including four restoration conditions, on fish abundance, diversity, and assemblages in a marine educational area (a small coastal area managed by a scholl in the frame of an eco-citizen pedagogical program) in Bora Bora, French Polynesia. Sixteen dead reef patches previously covered by macroalgae were grouped into four conditions as follows: four were non-restored (control condition), four were restored to 25% living coral cover (condition 25%), four to 50% living coral cover (condition 50%), and four were restored to 75% living coral cover (condition 75%). The abundance of fish at adult and juvenile stages was assessed, before and after coral restoration, using the fixed-point method for a period of 5 minutes on each of the 16 reef patches. Two successive observation periods were conducted for each patch: one focusing on more visible and mobile fish, and another on more cryptic species. Surveys were conducted one day and three days prior to restoration, and then 24 days and 28 days post-restoration. For adults, the difference in abundance, number of species, and diversity before and after restoration were not significant between the conditions. Similarly, for juveniles, no significant differences were observed when considering the conditions and restoration. Before restoration, the fish assemblages were randomly distributed between the four conditions for both adults and juveniles. After the restoration, the inter-conditions similarity decreased significantly for adults, but not for juveniles. Some species were associated with the more restored patches (*Chaetodon citrinellus*, *Halichoeres trimaculatus*, and *Zanclus cornutus*). Finaly, the restoration seemed to have variable effects depending on the trophic groups. Coral restoration has short-term effects on fish assemblages, indicating the effectiveness of restoration efforts even within a brief period. These rapid changes underscore the remarkable ability of adult fish to adapt to rapidly changing environments.

Keywords: fish communities, French Polynesia, restoration efforts, diversity, abundance, Marine educational area, Bora Bora, Society Islands, algal states, short-term

INTRODUCTION

Although coral reefs cover slightly less than 0.1% of the ocean’s surface, they host one of the most extensive taxonomic biodiversity on Earth (Porter and Tougas, 2001). However, the increasing frequency and intensity of disturbances linked to climate change and local human activities are causing rapid degradation of coral reefs (Hughes et al., 2017; Noisette et al., 2022). In response, various monitoring and conservation methods, such as coral restoration, have been developed (Boström-Einarsson et al., 2020; Clark and Edwards, 1995).

The International Science and Policy Working Group of the Society for Ecological Restoration defines coral restoration as “the process of helping to recover an ecosystem that has been degraded, damaged, or destroyed” (SER, n.d.). Traditional methods of active reef restoration include physical restoration (*e.g.,* reprofiling the sea floor, consolidating the reef structure, and installing artificial structures) and/or biological restoration (*e.g.*, direct coral transplantation, coral gardening, micro-fragmentation, and repopulation with larvae) (Boström-Einarsson et al., 2020; Romon, 2018). In the last decade, new types of restoration have emerged, including the modification of coral phenotypic plasticity (Thériault-Gauthier, 2017), acoustic enrichment (Gordon et al., 2019), the introduction of herbivorous species (Krimou et al., 2023), and microbiome manipulation to mitigate heat stress (Voolstra et al., 2023), which are interconnected (Thériault-Gauthier, 2017). For instance, acoustic enrichment coupled with active coral restoration can enhance fish assemblages (Gordon et al., 2019). However, caution must be exercised to prevent pushing a restoration technique to its extreme, as exemplified by the re-introduction of species, which, if done excessively, may result in invasive species concerns and disrupt the ecological balance. In light of these elements, it appears that coral restoration is widely employed to address declines in coral cover. While it is necessary to monitor the dynamics of fish in restored areas to assess restoration progress (Zakaria et al. 2020, Alvarez-Filip et al. 2015), very few studies have focused on the temporal response of fish communities to coral restoration (Hein et al. 2020).

The term ‘succession’ refers to the changes observed in an ecological community because of a disturbance that opens up a relatively large area. These changes often include a sequence of species and increases in biomass and diversity (Connell and Slatyer, 1977). Ecological succession has mainly been studied in terrestrial ecosystems in studies focusing on a broad range of topics such as primary and secondary plant succession, arthropod succession in mangroves and carcasses, or in link with carbon sequestration (Anderson, 2007; Liu et al., 2023), but studies are generally more recent in the marine realm (Harrison and Whitfield, 2004; Jouval et al., 2020, Toledo et al., 2020, Mathews et al., 2021, Li et al., 2022, Vicente et al., 2022, McDevitt et al., 2023).

Understanding the impact of habitat fragmentation and consumer loss on coral reefs is crucial for comprehending how habitat characteristics moderate the effects of consumer-resource interactions on successional dynamics (Gonzalez et al., 2020). The architectural complexity of the coral reef environment, mainly driven by the abundance of hermatypic corals, plays an influential role in shaping the community structure of reef-associated organisms (Komyakova et al., 2013).

In response to acute disturbances such as coral bleaching, cyclones, or other events, fish assemblages exhibit a wide range of responses (Pratchett et al., 2011; Wilson et al., 2006). This variability includes scenarios where there is no perceived change, declines, or even increases in the abundance of certain fish species (Bellwood et al., 2006; Garpe et al., 2006; Munday et al., 2008). Notably, fish species highly specialized and dependent on corals, such as coral-feeding butterflyfish, are particularly sensitive to coral loss (Pratchett et al., 2008). While numerous studies have explored the crucial role of some fish species in coral reef resilience (Adam et al., 2011; Hughes et al., 2007), there is also a focus on artificial or restored natural reefs in understanding the mechanisms of ecological succession in aquatic ecosystems (Santos et al., 2011; Wang et al., 2021).

The structure and diversity of fish assemblages can serve as valuable indicators to assess the success of restoration projects (Harrison and Whitfield, 2004; Zakaria and Syaifullah, 2020, Sangil et al., 2024). While some restoration projects have directly assessed fish populations, fish are often studied as secondary qualitative observations, and research on the effects of adding live coral cover and complexity on fish is still in its early stages (Seraphim et al., 2020). Few studies exist on how the addition of structural complexity during coral restoration can restore reef ecosystems (Opel et al. 2017). Specifically, the effect of adding coral cover and complexity on fish lacks scientifically validated research (Seraphim et al. 2020).

Moreover, the effect of coral restoration on fish assemblages varies strongly over time, whether for the short term (*i.e.*, within the first month), medium term, or long term (*i.e.*, at least one year). After a week of outplanting, it has been demonstrated that there was an increase in fish abundance, species richness, and a significant shift in fish community composition (Opel et al., 2017). More research is needed to confirm the trends observed in this Caribbean reef. While there is generally a positive effect of coral reef restoration in the medium/long-term, often resulting in increased fish diversity and abundance after months or years (Fadli et al., 2012), responses of fish assemblages to coral restoration have been shown to be very complex, with region-, site-, and size-specific patterns (Hein et al., 2020). For example, while a higher abundance of damselfish at restored sites seems consistent, the increased abundance of herbivorous fish appears to be limited to individual reefs (Ladd et al., 2019).

Patterns of fish abundance and richness during the first months following coral restoration can be complex and variable, with fluctuations occurring during this period. In a study from a non-reef environment, Santos et al. (2011) demonstrated that fish abundance and richness may initially increase following the installation of an artificial reef, but then decline within the first six months. These observations were associated with an increase in biomass, with variations noted depending on the type of material used for the artificial reef. Other studies indicated drops in fish abundances six months after structural addition (Smith 1978, Golani and Dimant 1999). An explanation could be that the initial high abundance reaches a plateau (Bohnsack and Sutherland 1985).'

Our study aims to compare fish abundance, diversity, and assemblages before and after coral restoration in the Marine Educational Area (MEA) of Bora Bora (French Polynesia) to evaluate short-term fish changes occurring within one month. A marine educational area is an eco-citizen pedagogical concept that involves a small coastal area managed by students from a school under the supervision of a scientific mentor and their teacher(s). Therefore, analysis over a short-term period will enable us to understand the early mechanisms of ecological succession in fish and their evolution over time within a month. Our hypothesis is that within a month, changes in abundance and diversity would not be yet significant while we expect to observe initial signs of modifications in fish assemblages.

MATERIALS AND METHODS

Study sites

The study was conducted at a Marine Educational Area (MEA), located on the fringing reef of Bora Bora (French Polynesia, Fig. 1). The MEA is a 40,000 m^2 area located on the west coast of the south part of the main island (16°31'29" S, 151°44'20" W). Sixteen dead reef patches with a size range from 5 to 12 m^2 were identified and grouped into four conditions as follows: four were non-restored (control condition), four were restored to 25% living coral cover (condition 25%), four to 50% living coral cover (condition 50%), and four were restored to 75% living coral cover (condition 75%).

Prior to the restoration efforts, the reef patches had less than 1% living coral cover and were dominated by macroalgae, especially by *Dictyota* spp., *Halimeda* spp., *Padina boryana*, and *Turbinaria ornata*, which covered over 85% of the reef surface. To restore the reef patches, healthy coral colonies (size between 10 x 5 x 5 cm and 15 x 30 x 10 cm), naturally present near the MEA zone, were manually glued (using a mix of SikaLatex, cement, and sand) individually in less than two days. The coral colonies used in this study were relocated prior to the construction of a new infrastructure, which is located 500 meters away from the AME. The proportion of different coral species used on each reef patch was as follows: 70% *Acropora* spp., 18% *Porites rus*, and 12% *Porites lobata* (Fig. 1). This distribution was based on the coral cover found on the fringing reef close to the MEA (Lecchini et al., 2021). Coral colonies were transplanted from a similar and nearby fringing reef to the studied patches. Macroalgae were manually removed before attaching new corals. In addition, throughout the experiment, macroalgae that settled on the coral patches were removed daily (McClanahan et al., 2001, 2000).

Fish survey

The abundance of fish at adult and juvenile stages was assessed, before and after coral restoration, using the fixed-point method for a period of 5 minutes on each of the 16 reef patches (method adapted from Dethier *et al.* 1993). The mean depth was approximately 1 m and the maximal depth was approximately 1.4 m. Each site was surveyed across the entire patch. The potential effect of the size of the patches was not directly accounted for during the survey, but it was considered in the statistics (see Statistical analysis section). Visual estimates were employed because they are deemed to be more accurate, especially for rare species, compared to other methods involving random points (Dethier et al. 1993). Surveys were conducted one day (D−1) and three days (D−3) prior to restoration, and then 24 days (D24) and 28 days (D28) post-restoration. Abundances at D−1 and D−3 characterized the pre-restoration period, and values at D24 and D28 characterized the post-restoration period. Abundance and life stage (adult *vs.* juvenile) were determined for each species, excluding small cryptic species from the families *Blenniidae, Carapidae, Gobiidae,* and *Tripterygiidae* (Siu et al., 2017). The size of the individuals allowed to distinguish between juveniles and adults. In addition, the pigmentation patterns and the behavior were also used to differentiate adults from juveniles (Lecchini and Galzin 2005).

S.K. conducted all the surveys during one hour and a half between 10 AM and 4 PM. Due to the limited tidal range at Bora-Bora, which reaches a maximum of 40 cm during spring tides (Pirazzoli et al. 1985), there is no temporal effect (e.g., day of sampling).

Statistical analysis

All statistical analyses were performed using R software 4.1.1 (R Core Team). The abundance (Ab, *i.e.,* the total number of fish), the number of species (NoSp), and the Shannon diversity index (H') were calculated for each of the four conditions (control, 25%, 50%, and 75% conditions), each patch (A, B, C, and D), each period (before vs. after coral restoration), and replicates (1 vs. 2). Linear mixed-effects models were used, with one for juveniles and another for adults (function *lme*, library *nlme*. To account for site-level differences, the site was treated as a random variable. For each feature (Ab, NoSp, and H'), the interaction of the condition and the period was examined. Homoscedasticity of variances and normality assumptions were checked and met. The similarities in fish assemblages' composition among the four conditions (control, 25%, 50%, and 75%) were tested using analyses of similarities (ANOSIM) based on Bray-Curtis dissimilarity matrices using the package *vegan* (Bray & Curtis 1957). The output is a metric called R with $R \in [-1, 1]$. Null R values indicate random grouping, positive R values indicate greater similarity within groups, and negative R values indicate greater similarity between than within groups (Warton *et al.* 2012).

A permutation-based test was used to test the multivariate homogeneity of group variance (functions *permutest* and *betadisper*, *vegan* package) on distance matrices that were previously standardized (function *decostand*, method = normalize). The homogeneity of variance was confirmed after this standardization (Fisher tests: Df = 3, F = 1.70 and 0.40, P = 0.18 and 0.77). Therefore, permutational multivariate analyses of variance (PerMANOVA) based on distance matrices (function *adonis2*) were used to determine whether the fish assemblage's composition varied with restoration (group 1 = control, group 2 = 25%, group 3 = 50%, and group 4 = 75%) (Anderson 2017). The method of Bray was used to calculate pairwise distances. Canonical Correspondence Analysis (CCA) was used to visualize the fish assemblages and the effect of the restoration. A first CCA was conducted on the data before the restoration, and a second CCA on the data after the restoration. The "restoration" variable was added only on the ordination plot of the second CCA. The same analyses were conducted separately for adult and juvenile fish.

Fish species were then classified into seven trophic groups (Viviani et al., 2019): (*1*) grazers, (*2*) herbivorous scrapers or excavators, (*3*) herbivorous detritivores, (*4*) omnivores, (*5*) planktivores, (*6*) piscivores, and (*7*) benthic invertebrates' feeders. As only one species was herbivorous detritivore, it was excluded from the trophic level analysis. Nevertheless, it was included when considering all species collectively. It was neither abundant nor significant, constituting only 3% of observations. The differences in the three ecological features (Ab, NoSp, and H') before and after the restoration for each condition were calculated (*e.g.,* $\Delta H' = H'_{after} - H'_{before}$). The difference between the mean number of individuals before and after restoration (Δ) was calculated in each trophic group. Kruskal-Wallis tests were used to compare the four conditions (0%, 25%, 50%, and 75%).

RESULTS

During the study, 53 fish species from 19 families were observed. The most abundant families were Labridae (10 species), Pomacentridae (8 species), Scaridae (7 species), Chaetodontidae (6 species), and Acanthuridae (4 species). The total fish abundance before restoration was 16.47 ± 10.30 individuals per patch reef (mean ± SD), which increased to 20.97 ± 10.98 individuals per patch reef (overall mean for the four conditions together) after the restoration (Fig. 2). For adults, the difference in abundance (Ab), number of species (NoSp), and diversity (H') before and after restoration were not significant between the conditions (Ab: $F = 1.81$, $P = 0.16$; NoSp: $F = 1.97$, $P = 0.13$; and H': $F = 1.40$, $P = 0.26$; Table SP5). Similarly, for juveniles, no significant differences were observed when considering the conditions and restoration (Ab: $F = 1.37$, $P = 0.27$; NoSp: $F = 2.36$, $P = 0.085$; and H' = 1.14, $P = 0.35$; Table SP6). For both adults and juveniles, irrespective of the period, no significant differences were observed between the conditions (for Ab, NoSp, and H': all $P > 0.05$, Table SP5 and SP6), indicating homogeneity in the patches within the study area. In contrast, without considering the conditions, significant differences were observed between the two periods for adults (all $P \leq 0.0003$, Table SP5), indicating high variability in the fish species present. For juveniles, fish abundance was equivalent ($P = 0.78$) but not the number of species or diversity (both $P < 0.0001$, Table SP6).

Before restoration (D−1 and D−3), the fish assemblages were randomly distributed between the four conditions (control, 25%, 50%, and 75%) for both adults and juveniles (ANOSIM, $R = 0.057$ and 0.024, $P = 0.15$ and 0.25, respectively). After the restoration, the inter-conditions similarity decreased significantly for adults (ANOSIM, $R = 0.27$, $P = 0.001$), but not for juveniles (ANOSIM, $R = 0.068$, $P = 0.11$). The fish assemblages were equivalent between the four groups (0%, 25%, 50%, and 75%) before the restoration for both adults and juveniles (PerManova, df = 3, $F = 0.16$, $P = 0.15$; df = 3, $F = 1.33$ and $P = 0.20$, respectively), while after the restoration a significant difference was observed for adults (PerManova, df =

3, F = 2.72, P = 0.001), but not for juveniles (PerManova, df = 3, F = 1.16, P = 0.29). Thus, after the restoration, the CCA concentration ellipses of fish assemblages were distributed along the CCA1 axis illustrating the effect of the restoration on the fish assemblages (Fig 3). After the restoration, adults and juveniles were distributed in the CCA plot according to two axes: CCA1 reflected coral restoration while CCA2 reflected variability in some patch reefs restored at 25%. Some species were associated with the more restored patches (*C. citrinellus*, *H. trimaculatus*, and *Z. cornutus*; scores: −0.94, −0.96, and −1.3). When considering 95% confidence interval ellipses, there was no overlap between the 75% and the 0% assemblages.

When considering each trophic group at adult stage separately, the maximal Δ in the mean number of individuals was observed at 50% restoration for all trophic groups (i.e., herbivorous grazers, herbivorous scrapers/excavators, omnivores, and benthic invertebrates' feeders), except piscivores and planktivores (Fig. 4). Maximal values for piscivores were observed at 75% restoration, while for planktivores, they were observed when there was no restoration. However, differences among the four conditions were not statistically significant (Kruskal-Wallis: χ^2 = 0.24 – 4.51; df = 3; P = 0.21 – 0.97). The restoration has variable effects on each of the various trophic groups when compared to one another. For grazers, positive Δ values were obtained, while negative values were observed for planktivores in all restored patches.

DISCUSSION

While restored reefs remain vulnerable to global factors such as climate change, pollution, and diseases, coral restoration can enhance essential ecological functions and services for reefs that have undergone significant degradation and lack resilience for natural recovery (Rinkevich, 2008) or in cases where expedited recovery is desired. For instance, when sites have been degraded to the point of rubble, fast natural recovery without human intervention is generally unlikely (Fox et al., 2003). In the context of restoration projects, the structure and diversity of fish assemblages can serve as valuable indicators for evaluating success (Harrison and Whitfield, 2004). An increase in fish abundance and diversity is commonly observed after a significant period, typically months or years, following the start of the restoration process (Fadli et al., 2012). If artificial reefs are known to be rapidly (i.e., > 1 day) colonized by fish (Bohnsack and Sutherland 1985, Golani and Dimant 1999), the colonization in coral restoration processes is not widely studied (Opel et al. 2017). Our study specifically investigated the short-term effects of coral restoration on fish assemblages in the Bora Bora reef over a period of 24 to 28 days. The results suggest a rapid shift in some adult fish assemblages with coral restoration, without significant changes in richness, diversity, and abundance. In other words, our findings conclude that early restoration effects did not manifest as differences in abundance or diversity but rather in the type of assemblage present. In the Caribbean, it has been shown that restoration leads to a change in community composition, resulting in no overlap between controls and outplants seven months later, very similar to what we observed between our control and 75% restoration condition.

More specifically, the results underscored that the short-term effects of coral restoration were primarily attributed to adult fish at Bora-Bora. This distinction could be due to the fact that newly recruited juvenile fish might not have had sufficient time to establish themselves on the newly restored patches. In longer-term studies, changes in abundance and diversity can be influenced by both the specimens that were already present and those that recruited to the area (Fadli et al., 2012). On the contrary, in short-term studies, the timeframe is too brief to consider new juveniles resulting from recruitment. Newly recruited individuals often exhibit cryptic behavior, making them challenging to identify, and they are typically not counted in visual estimations. Additionally, the requirements of juvenile fish may differ from those of adults, encompassing variations in feeding habitats and nursery preferences (Mumby et al., 2004; Nagelkerken et al., 2002, 2000; Ogden and Quinn, 1984). The findings underscore the importance of considering the life history of fish when planning and evaluating coral reef restoration efforts. Juvenile fish recruits play a critical role in the long-term success of restoration efforts, contributing to the replenishment of populations and the maintenance of functional roles within the ecosystem (Seraphim et al., 2020). Consequently, it is essential to incorporate considerations for the recruitment and survival of juveniles into restoration planning (Seraphim et al., 2020).

One of the unique aspects of our study lies in not altering the species proportion of restored coral, but rather quantifying coral cover using the same species, while considering the area of coral cover. In our case, the species of coral restored were consistent across the experiment (*Acropora* spp., *Porites rus*, and *Porites lobata*) and only their abundance varied (control, 25, 50 vs. 75% coral cover). Restoration efforts can involve creating habitat mosaics, establishing multiple habitat types within a single restoration project (Henningson et al., 2015). On the other hand, artificial reefs may yield different assemblages from those required due to the preference of certain organisms for specific substrates (Burt et al., 2009). Maintaining connected coral colonies is crucial for sustaining prey fish assemblages, as a low coral cover can create wide-open spaces that increase predator densities (Stewart and Jones, 2001). Moreover, high levels of coral cover and species richness generally favor high levels of fish abundance and species richness (Komyakova et al., 2013). Furthermore, architecturally complex coral morphologies, such as branching forms, support a higher number of individuals and fish species than less architecturally complex morphologies, such as mounding forms (Holbrook et al., 2002). This general relationship is likely due to the increase in architectural complexity and, thus, in 3D space, which translates into increased quantities of resources for fish (i.e., food/prey and shelter) (Graham and Nash, 2013). The associations between fish assemblages and habitat parameters were predominantly positive in Hawaii (Fukunaga et al., 2020), confirming earlier research findings: greater architectural complexity of habitats is associated with higher levels of fish abundance and diversity (Graham and Nash, 2013; Holbrook et al., 2002; Komyakova et al., 2013). In contrast, a high percentage of scleractinian coral cover may suggest a less heterogeneous fish fauna. Therefore, a study focused on coral restoration by coral species could enhance our understanding of fish preferences, assemblage dynamics, and ecological succession.

The latest finding in our study concerned differences between trophic groups. In the literature, Fukunaga (et al. 2020) noted that certain herbivorous fish assemblages prefer habitats with high levels of small- and large-scale architectural complexity associated with all types of coral morphologies (similarly to our 50% condition) but not necessarily habitats with high architectural complexity (similarly to our 75% condition). Different successions seem to occur for small herbivorous grazers/corallivores (e.g., butterflyfish and some damselfish) that appear to prefer habitats containing a high level of small-scale architectural complexity associated with branching and/or encrusting corals (Fukunaga et al., 2020). Regarding planktivores, it is known that their abundance could be more strongly correlated with current strength and predator abundance than with topographic complexity or branching coral cover (Thresher, 1983). In our study, the percentage of coral cover did not appear to be correlated with the abundance of planktivores. This highlights the limitations of generalizing habitat-fish interactions without considering trophic variability and underscores the importance of conducting formal assessments with individual species when there are a priori specific species of interest or when data analyses reveal potential species of importance (Fukunaga et al., 2020).

Conclusion

This study unveils the effect of coral restoration on fish assemblages in a short time frame. These rapid changes prove the effectiveness of coral restoration and showcase the incredible adaptability of adult fish to a rapidly changing environment.

Acknowledgements

We would like to thank the staff of ‘Polynésienne des Eaux’, ‘Ia Vai Ma Noa Bora-Bora, the ‘Commune de Bora-Bora’ and the private society Espace Bleu for their help.

DECLARATIONS

Funding

Several funds support this study: Fondation de France (2019-08602), Polynésienne des Eaux, Bloody Mary’s project, ANR-19-CE34-0006-Manini, ANR-19-CE14-0010-SENSO, and ANRT grant (CIFRE 2021/1268), the King Leopold III Fund for Nature Exploration and Conservation (XR), and the University of Liège (XR, “financement mission scientifique”).

Conflicts of interest/Competing interests

The authors declare no competing interest.

Ethics approval

Not applicable

Consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and material

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.7821962.

Code availability

Not applicable

Authors' contributions

Stéphanie Krimou: Investigation, Methodology, Writing – original draft, Writing – review and editing, Project administration. Xavier Raick: Conceptualization, Methodology,

Software, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review and editing, Visualization, Supervision, Project administration. Ethel Mery: Writing – review and editing. Jeremie Carlot: Investigation, Ressources. Camille Carpentier: Investigation. Jérome Sowinski: Investigation. Lucille Sowinski: writing – review and editing. Lana Minier: writing – review and editing. Natacha Roux: writing – review and editing.Tehani Maueau: investigation. Frederic Bertucci: writing – review and editing. David Lecchini: conceptualization, methodology, validation, resources, writing – review and editing, supervision, project administration, and funding acquisition

References

Adam, T.C., Schmitt, R.J., Holbrook, S.J., Brooks, A.J., Edmunds, P.J., Carpenter, R.C., Bernardi, G., 2011. Herbivory, Connectivity, and Ecosystem Resilience: Response of a Coral Reef to a Large-Scale Perturbation. PLoS One 6, e23717. https://doi.org/10.1371/journal.pone.0023717

Alvarez-Filip, L., Paddack, M.J., Collen, B., Robertson, D.R., Côté, I.M., 2015. Simplification of Caribbean Reef-Fish Assemblages over Decades of Coral Reef Degradation. PLoS One 10, e0126004. https://doi.org/10.1371/journal.pone.0126004

Anderson, K.J., 2007. Temporal Patterns in Rates of Community Change during Succession. Am. Nat. 169, 780–793. https://doi.org/10.1086/516653

Bellwood, D.R., Hoey, A.S., Ackerman, J.L., Depczynski, M., 2006. Coral bleaching, reef fish community phase shifts and the resilience of coral reefs. Glob. Chang. Biol. 12, 1587–1594. https://doi.org/10.1111/j.1365-2486.2006.01204.x

Bohnsack, J.A., Sutherland, D.L., 1985. Artificial Reef Research: A Review with Recommendations for Future Priorities. Bull. Mar. Sci. 37, 11–39.

Boström-Einarsson, L., Babcock, R.C., Bayraktarov, E., Ceccarelli, D., Cook, N., Ferse, S.C.A., Hancock, B., Harrison, P., Hein, M., Shaver, E., Smith, A., Suggett, D., Stewart-Sinclair, P.J., Vardi, T., McLeod, I.M., 2020. Coral restoration – A systematic review of current methods, successes, failures and future directions. PLoS One 15, e0226631. https://doi.org/10.1371/journal.pone.0226631

Burt, J., Bartholomew, A., Bauman, A., Saif, A., Sale, P.F., 2009. Coral recruitment and early benthic community development on several materials used in the construction of artificial reefs and breakwaters. J. Exp. Mar. Bio. Ecol. 373, 72–78. https://doi.org/10.1016/j.jembe.2009.03.009

Clark, S., Edwards, A.J., 1995. Coral transplantation as an aid to reef rehabilitation: evaluation of a case study in the Maldive Islands. Coral Reefs 14, 201–213. https://doi.org/10.1007/BF00334342

Connell, J.H., Slatyer, R.O., 1977. Mechanisms of Succession in Natural Communities and Their Role in Community Stability and Organization. Am. Nat. 982, 1119–1144.

Dethier, M., Graham, E., Cohen, S., Tear, L., 1993. Visual versus random-point percent cover estimations: “objective” is not always better. Mar. Ecol. Prog. Ser. 96, 93–100. https://doi.org/10.3354/meps096093

Fadli, N., Campbell, S.J., Ferguson, K., Keyse, J., Rudi, E., Riedel, A., Baird, A.H., 2012. The role of habitat creation in coral reef conservation: a case study from Aceh, Indonesia. Oryx 46, 501–507. https://doi.org/10.1017/S0030605312000142

Fox, H.E., Pet, J.S., Dahuri, R., Caldwell, R.L., 2003. Recovery in rubble fields: long-term impacts of blast fishing. Mar. Pollut. Bull. 46, 1024–1031. https://doi.org/10.1016/S0025-326X(03)00246-7

Fukunaga, A., Kosaki, R.K., Pascoe, K.H., Burns, J.H.R., 2020. Fish Assemblage Structure in the Northwestern Hawaiian Islands Is Associated with the Architectural Complexity of Coral-Reef Habitats. Diversity 12, 430. https://doi.org/10.3390/d12110430

Garpe, K., Yahya, S., Lindahl, U., Öhman, M., 2006. Long-term effects of the 1998 coral bleaching event on reef fish assemblages. Mar. Ecol. Prog. Ser. 315, 237–247. https://doi.org/10.3354/meps315237

Golani, D., Diamant, A., 1999. Fish Colonization of an Artificial Reef in the Gulf of Elat, Northern Red Sea. Environ. Biol. Fishes 54, 275–282. https://doi.org/10.1023/A:1007528210270

Gonzalez, A., Germain, R.M., Srivastava, D.S., Filotas, E., Dee, L.E., Gravel, D., Thompson, P.L., Isbell, F., Wang, S., Kéfi, S., Montoya, J., Zelnik, Y.R., Loreau, M., 2020. Scaling-up biodiversity-ecosystem functioning research. Ecol. Lett. 23, 757–776. https://doi.org/10.1111/ele.13456

Gordon, T.A.C., Radford, A.N., Davidson, I.K., Barnes, K., McCloskey, K., Nedelec, S.L., Meekan, M.G., McCormick, M.I., Simpson, S.D., 2019. Acoustic enrichment can enhance fish community development on degraded coral reef habitat. Nat. Commun. 10, 1–7. https://doi.org/10.1038/s41467-019-13186-2

Graham, N.A.J., Nash, K.L., 2013. The importance of structural complexity in coral reef ecosystems. Coral Reefs 32, 315–326. https://doi.org/10.1007/s00338-012-0984-y

Harrison, T.D., Whitfield, A.K., 2004. A multi-metric fish index to assess the environmental condition of estuaries. J. Fish Biol. 65, 683–710. https://doi.org/10.1111/j.0022-1112.2004.00477.x

Hein, M.Y., Beeden, R., Birtles, R.A., Chase, T.J., Couture, F., Haskin, E., Marshall, N., Ripple, K., Terry, L., Willis, B.L., Willis, R., Gardiner, N.M., 2020. Effects of coral restoration on fish communities: snapshots of long-term, multiregional responses and implications for practice. Restor. Ecol. 28, 1158–1171. https://doi.org/10.1111/rec.13177

Henningson, B., Norton, N., Young, B., 2015. The rock ponds ecosystem restoration project–a true mosaic of coastal habitats for Tampa Bay, in: Burke, M. (Ed.), Bay Area Scientific Information Symposium—Navigating Changing Tides, Addressing New Challenges with Effective Science and Management. St. Petersburg: Tampa Bay Estuary Program, St. Petersburg.

Holbrook, S.J., Brooks, A.J., Schmitt, R.J., 2002. Variation in structural attributes of patch-forming corals and in patterns of abundance of associated fishes. Mar. Freshw. Res. 53, 1045. https://doi.org/10.1071/MF02063

Hughes, T.P., Barnes, M.L., Bellwood, D.R., Cinner, J.E., Cumming, G.S., Jackson, J.B.C., Kleypas, J., van de Leemput, I.A., Lough, J.M., Morrison, T.H., Palumbi, S.R., van Nes, E.H., Scheffer, M., 2017. Coral reefs in the Anthropocene. Nature 546, 82–90. https://doi.org/10.1038/nature22901

Hughes, T.P., Rodrigues, M.J., Bellwood, D.R., Ceccarelli, D., Hoegh-Guldberg, O., McCook, L., Moltschaniwskyj, N., Pratchett, M.S., Steneck, R.S., Willis, B., 2007. Phase Shifts, Herbivory, and the Resilience of Coral Reefs to Climate Change. Curr. Biol. 17, 360–365. https://doi.org/10.1016/j.cub.2006.12.049

Jouval, F., Bigot, L., Bureau, S., Quod, J.-P., Penin, L., Adjeroud, M., 2020. Diversity, structure and demography of coral assemblages on underwater lava flows of different ages at Reunion Island and implications for ecological succession hypotheses. Sci. Rep. 10, 20821. https://doi.org/10.1038/s41598-020-77665-z

Komyakova, V., Munday, P.L., Jones, G.P., 2013. Relative Importance of Coral Cover, Habitat Complexity and Diversity in Determining the Structure of Reef Fish Communities. PLoS One 8, e83178. https://doi.org/10.1371/journal.pone.0083178

Krimou, S., Gairin, E., Gautrand, L., Sowinski, J., Trotier, M., Minier, L., Bischoff, H., Sturny, V., Maueau, T., Waqalevu, V., Bulleri, F., Raick, X., Bertucci, F., Lecchini, D., 2023. Herbivory effects of sea urchin species on a coral reef (Bora-Bora, French Polynesia). J. Exp. Mar. Bio. Ecol. 564, 151900. https://doi.org/10.1016/j.jembe.2023.151900

Lecchini, D. & Galzin, R. 2005 Spatial repartition and ontogenetic shifts in habitat use by coral reef fishes (Moorea, French Polynesia). Marine Biology 147, 47–58 (2005). https://doi.org/10.1007/s00227-004-1543-z

Lecchini, D., Brooker, R.M., Waqalevu, V., Gairin, E., Minier, L., Berthe, C., Besineau, R., Blay, G., Maueau, T., Sturny, V., Bambridge, T., Sang, G.T., Bertucci, F., 2021. Effects of COVID-19 pandemic restrictions on coral reef fishes at eco-tourism sites in Bora-Bora, French Polynesia. Mar. Environ. Res. 170, 105451. https://doi.org/10.1016/j.marenvres.2021.105451

Li, R., Guo, Y., Zhang, A., Zhang, S., Zhang, H., Qin, C., 2022. Variation in the attached community structure and function of artificial habitats during ecological succession: A case study of the artificial reef area in Bailong Pearl Bay, China. Front. Mar. Sci. 9. https://doi.org/10.3389/fmars.2022.950151

Lirman, D., Schopmeyer, S., 2016. Ecological solutions to reef degradation: optimizing coral reef restoration in the Caribbean and Western Atlantic. PeerJ 4, e2597. https://doi.org/10.7717/peerj.2597

Liu, J., Gao, W., Liu, T., Dai, L., Wu, L., Miao, H., Yang, C., 2023. A Bibliometric Analysis of the Impact of Ecological Restoration on Carbon Sequestration in Ecosystems. Forests 14, 1442. https://doi.org/10.3390/f14071442

Mathews, G., Raj, K.D., Laju, R.L., Bharath, M.S., Kumar, P.D., Arasamuthu, A., Gnana Asir, N.G., Kumar, T.K.A., Jayanthi, M., Edward, J.K.P., 2021. First approach to the characterization of the ecological succession on perforated trapezoidal multi-purpose reef modules: Building climate resilience. Ocean Coast. Manag. 210, 105669. https://doi.org/10.1016/j.ocecoaman.2021.105669

McClanahan, T., Bergman, K., Huitric, M., McField, M., Elfwing, T., Nyström, M., Nordemar, I., 2000. Response of fishes to algae reduction on Glovers Reef, Belize. Mar. Ecol. Prog. Ser. 206, 273–282. https://doi.org/10.3354/meps206273

McClanahan, T., McField, M., Huitric, M., Bergman, K., Sala, E., Nyström, M., Nordemar, I., Elfwing, T., Muthiga, N., 2001. Responses of algae, corals and fish to the reduction of macroalgae in fished and unfished patch reefs of Glovers Reef Atoll, Belize. Coral Reefs 19, 367–379. https://doi.org/10.1007/s003380000131

McDevitt-Irwin, J.M., McCauley, D.J., Brumbaugh, D.R., Elmer, F., Ferretti, F., Joyce, F.H., White, T.D., Wible, J.G., Micheli, F., 2023. Consumers decrease variability across space and turnover through time during coral reef succession. Oecologia 202, 431–443. https://doi.org/10.1007/s00442-023-05404-y

Mumby, P.J., Edwards, A.J., Ernesto Arias-González, J., Lindeman, K.C., Blackwell, P.G., Gall, A., Gorczynska, M.I., Harborne, A.R., Pescod, C.L., Renken, H., C. C. Wabnitz, C., Llewellyn, G., 2004. Mangroves enhance the biomass of coral reef fish communities in the Caribbean. Nature 427, 533–536. https://doi.org/10.1038/nature02286

Munday, P.L., Jones, G.P., Pratchett, M.S., Williams, A.J., 2008. Climate change and the future for coral reef fishes. Fish Fish. 9, 261–285. https://doi.org/10.1111/j.1467-2979.2008.00281.x

Nagelkerken, I., Roberts, C., van der Velde, G., Dorenbosch, M., van Riel, M., Cocheret de la Morinière, E., Nienhuis, P., 2002. How important are mangroves and seagrass beds for coral-reef fish? The nursery hypothesis tested on an island scale. Mar. Ecol. Prog. Ser. 244, 299–305. https://doi.org/10.3354/meps244299

Nagelkerken, I., van der Velde, G., Gorissen, M.W., Meijer, G.J., Van't Hof, T., den Hartog, C., 2000. Importance of Mangroves, Seagrass Beds and the Shallow Coral Reef as a Nursery for Important Coral Reef Fishes, Using a Visual Census Technique. Estuar. Coast. Shelf Sci. 51, 31–44. https://doi.org/10.1006/ecss.2000.0617

Noisette, F., Pansch, C., Wall, M., Wahl, M., Hurd, C.L., 2022. Role of hydrodynamics in shaping chemical habitats and modulating the responses of coastal benthic systems to ocean global change. Glob. Chang. Biol. 28, 3812–3829. https://doi.org/10.1111/gcb.16165

Ogden, J.C., Quinn, T.P., 1984. Migration in Coral Reef Fishes: Ecological Significance and Orientation Mechanisms, in: Mechanisms of Migration in Fishes. Springer US, Boston, MA, pp. 293–308. https://doi.org/10.1007/978-1-4613-2763-9_18

Pirazzoli P., Brousse R., Delibrias G., Montaggioni L., Faure G. & Salvat B. (1985). Leeward islands, Maupiti, Tupai, Bora Bora, Huahine, Society archipelago. In: Proceedings of the 5th International Coral Reef Congress, Tahiti, France, 27 May–1 June 1985. Volume 1.

Porter, J.W., Tougas, J.I., 2001. Reef Ecosystems: Threats to their Biodiversity, in: Encyclopedia of Biodiversity. Elsevier, pp. 73–95. https://doi.org/10.1016/B0-12-226865-2/00229-7

Pratchett, M., Munday, P., Wilson, S., Graham, N., Cinner, J., Bellwood, D., Jones, G., Polunin, N., Mcclanahan, T., 2008. Effects Of Climate-Induced Coral Bleaching On Coral-Reef Fishes ,Äî Ecological And Economic Consequences. pp. 251–296. https://doi.org/10.1201/9781420065756.ch6

Pratchett, M.S., Trapon, M., Berumen, M.L., Chong-Seng, K., 2011. Recent disturbances augment community shifts in coral assemblages in Moorea, French Polynesia. Coral Reefs 30, 183–193. https://doi.org/10.1007/s00338-010-0678-2

R, 2021. R: A language and environment for statistical computing, R Core Team: R Fondation for Statistical Computing. Vienna.

Rinkevich, B., 2008. Management of coral reefs: We have gone wrong when neglecting active reef restoration. Mar. Pollut. Bull. 56, 1821–1824. https://doi.org/10.1016/j.marpolbul.2008.08.014

Romon, A., 2018. Le jardinage corallien en tant qu’outil de restauration du récif : éléments d’optimisation et bilan des expériences dans les Caraïbes. Université de Sherbrooke.

Salvat, B., Chancerelle, Y., Schrimm, M., Morancy, R., Porcher, M., Aubanel, A., 2002. Restauration d’une zone corallienne dégradée et implantation d’un jardin corallien à Bora Bora, Polynésie française. Rev. d’Écologie (Terre Vie) supplément.

Sangil, C., Álvarez-Canali, D., Reyes, J., Rodríguez, J., Sansón, M., 2024. Primary ecological succession of marine communities on the Tajogaite lava flows (La Palma, Canary Islands), fishes colonize faster than macroinvertebrates and algae. Front. Mar. Sci. 11. https://doi.org/10.3389/fmars.2024.1337894

Santos, L.N., García-Berthou, E., Agostinho, A.A., Latini, J.D., 2011. Fish colonization of artificial reefs in a large Neotropical reservoir: material type and successional changes. Ecol. Appl. 21, 251–262. https://doi.org/10.1890/09-1283.1

SER, n.d. What is ecological restoration? [WWW Document]. Last accessed 4 Sept. 2023. URL https://www.ser-rrc.org/what-is-ecological-restoration/

Seraphim, M.J., Sloman, K.A., Alexander, M.E., Janetski, N., Jompa, J., Ambo-Rappe, R., Snellgrove, D., Mars, F., Harborne, A.R., 2020. Interactions between coral restoration and fish assemblages: implications for reef management. J. Fish Biol. 97, 633–655. https://doi.org/10.1111/jfb.14440

Siu, G., Bacchet, P., Bernardi, G., Brooks, A.J., Carlot, J., Causse, R., Claudet, J., Clua, É., Delrieu-Trottin, E., Espiau, B., Harmelin-Vivien, M., Keith, P., Lecchini, D., Madi-Moussa, R., Parravicini, V., Planes, S., Ponsonnet, C., Randall, J.E., Sasal, P., Taquet, M., Williams, J.T., Galzin, R., 2017. Shore fishes of French Polynesia. Cybium 41, 245–278.

Smith, C.L., 1978. Coral reef fish communities: a compromise view. Environ. Biol. Fishes 3, 109–128. https://doi.org/10.1007/BF00006312

Stewart, B.D., Jones, G.P., 2001. Associations between the abundance of piscivorous fishes and their prey on coral reefs: implications for prey-fish mortality. Mar. Biol. 138, 383–397. https://doi.org/10.1007/s002270000468

Thériault-Gauthier, M., 2017. L'évolution assistée pour favoriser la résilience et la résistance des récifs coralliens face aux changements climatiques. Université de Sherbrooke.

Thresher, R.E., 1983. Environmental correlates of the distribution of planktivorous fishes in the One Tree Reef Lagoon. Mar. Ecol. Prog. Ser. 10, 137–145.

Toledo, M.-I., Torres, P., Díaz, C., Zamora, V., López, J., Olivares, G., 2020. Ecological succession of benthic organisms on niche-type artificial reefs. Ecol. Process. 9, 38. https://doi.org/10.1186/s13717-020-00242-9

Vicente, J., Timmers, M.A., Webb, M.K., Bahr, K.D., Jury, C.P., Toonen, R.J., 2022. Ecological succession of the sponge cryptofauna in Hawaiian reefs add new insights to detritus production by pioneering species. Sci. Rep. 12, 15093. https://doi.org/10.1038/s41598-022-18856-8

Viviani, J., Moritz, C., Parravicini, V., Lecchini, D., Siu, G., Galzin, R., Viriot, L., 2019. Synchrony patterns reveal different degrees of trophic guild vulnerability after disturbances in a coral reef fish community. Divers. Distrib. ddi.12931. https://doi.org/10.1111/ddi.12931

Voolstra, C.R., Peixoto, R.S., Ferrier-Pagès, C., 2023. Mitigating the ecological collapse of coral reef ecosystems. EMBO Rep. 24. https://doi.org/10.15252/embr.202356826

Wang, J., Soininen, J., Heino, J., 2021. Ecological indicators for aquatic biodiversity, ecosystem functions, human activities and climate change. Ecol. Indic. 132, 108250. https://doi.org/10.1016/j.ecolind.2021.108250

Warton, D.I., Wright, S.T., Wang, Y., 2012. Distance-based multivariate analyses confound location and dispersion effects. Methods Ecol. Evol. 3, 89–101. https://doi.org/10.1111/j.2041-210X.2011.00127.x

Wilson, S.K., Graham, N.A.J., Pratchett, M.N.S., Jones, G.P., Polunin, N.V.C., 2006. Multiple disturbances and the global degradation of coral reefs: are reef fishes at risk or resilient? Glob. Chang. Biol. 12, 2220–2234. https://doi.org/10.1111/j.1365-2486.2006.01252.x

Young, C., Schopmeyer, S., Lirman, D., 2012. A Review of Reef Restoration and Coral Propagation Using the Threatened Genus Acropora in the Caribbean and Western Atlantic. Bull. Mar. Sci. 88, 1075–1098. https://doi.org/10.5343/bms.2011.1143

Zakaria, I.J., Syaifullah, H.A., 2020. Succession of reef fish community at the coral area rehabilitated with coral transplantation and artificial reef in West Sumatra, Indonesia. AACL Bioflux 13, 1934–1945.

FIGURES CAPTIONS

Fig. 1. Location of the study site. (**A**) Bora Bora with the zone of interest highlighted in red, (**B**) Detail of the Marine Educational Area (MEA) outlined with a dashed white line. The imagery used is from Airbus and has been modified from Google Earth. Each study patch is denoted by a yellow circle. (**C** and **D**) Examples of non-restored vs. a restored patch in the MEA, respectively.

Fig. 2 Violin plots illustrating probability distribution with boxplots illustrating the median and the interquartile range to illustrate the differences in (**A**) the number of species(ΔNoSp), (**B**) the diversity (ΔH'), and (**C**) the abundance (ΔAb) before and after the restoration for the four restoration conditions (0%, 25%, 50%, and 75%).

Fig. 3 Canonical correspondence analysis ordination plot displaying the composition of the adult fish assemblages after the restoration based on Bray-Curtis dissimilarities, with 95% confidence intervals represented by ellipses. The colors red, orange, yellow, and green correspond to the four restoration conditions (0%, 25%, 50%, and 75%, respectively). The pink dots correspond to each site replicate and the fish icons to the fish species. A different icon was used for each fish family.

Fig. 4 Δ mean number of individuals (mean ± SE) for the different trophic groups. (**A**) herbivorous grazers, (**B**) herbivorous scrapers or excavators, (**C**) omnivores, (**D**) planktivores, (**E**) piscivores, and (**F**) benthic invertebrates' feeders.

FIGURES

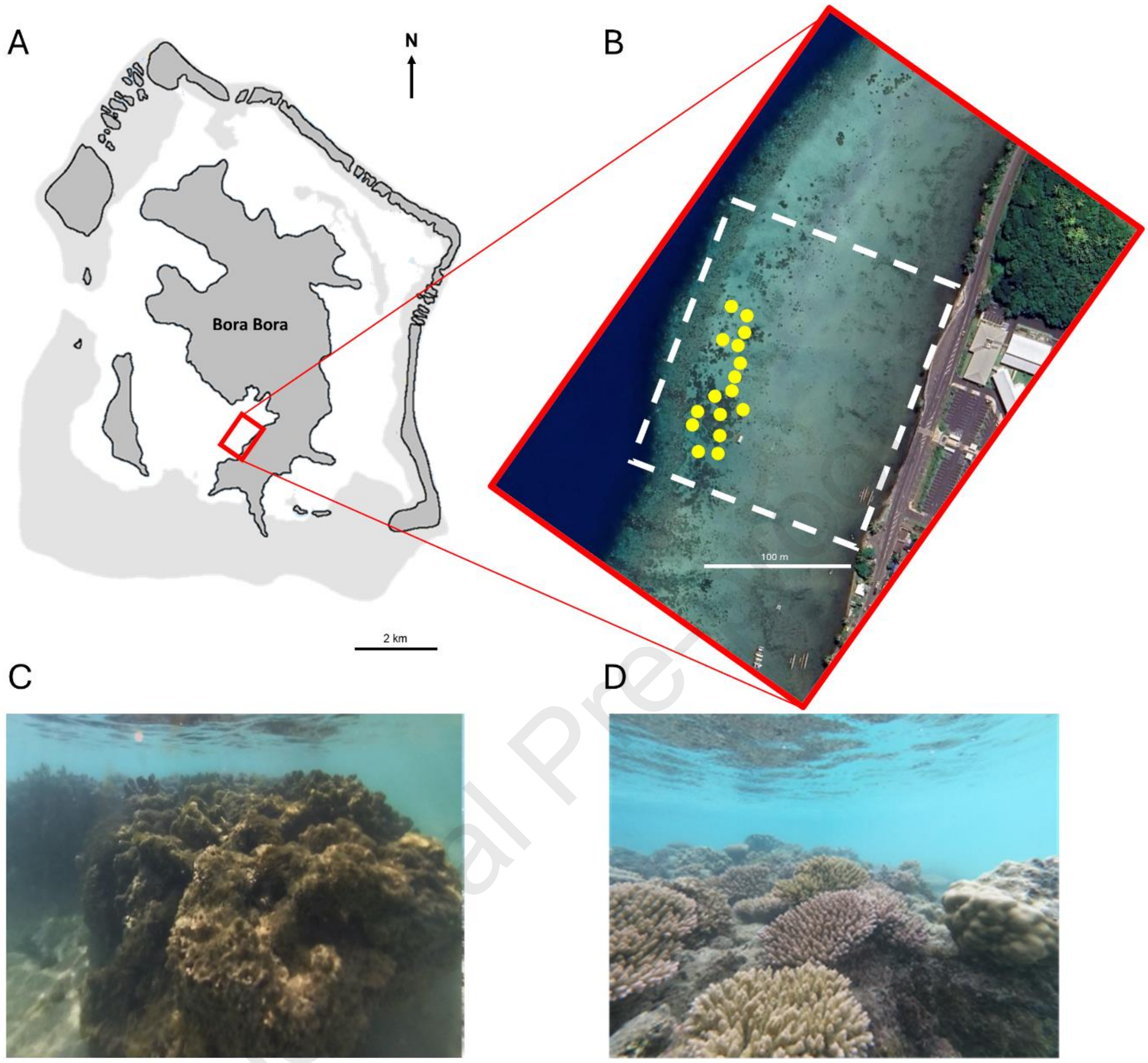


Fig. 1

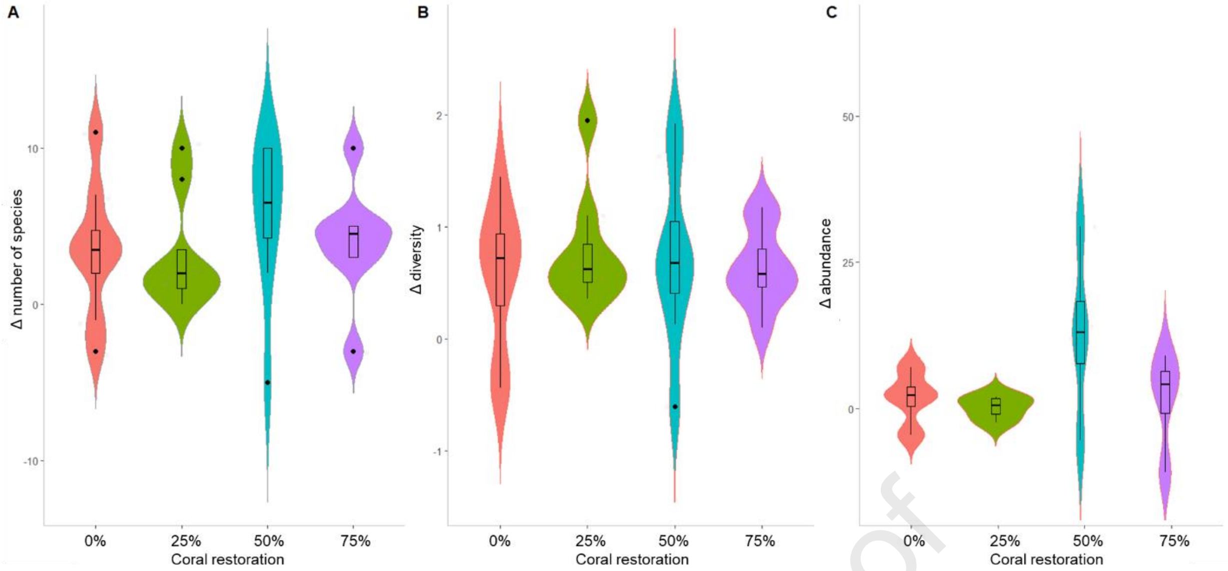

A
Δ number of species
10
0
-10
0%
25%
50%
75%
Coral restoration
B
Δ diversity
2
1
0
-1
0%
25%
50%
75%
Coral restoration
C
Δ abundance
50
25
0
0%
25%
50%
75%
Coral restoration

Fig. 2

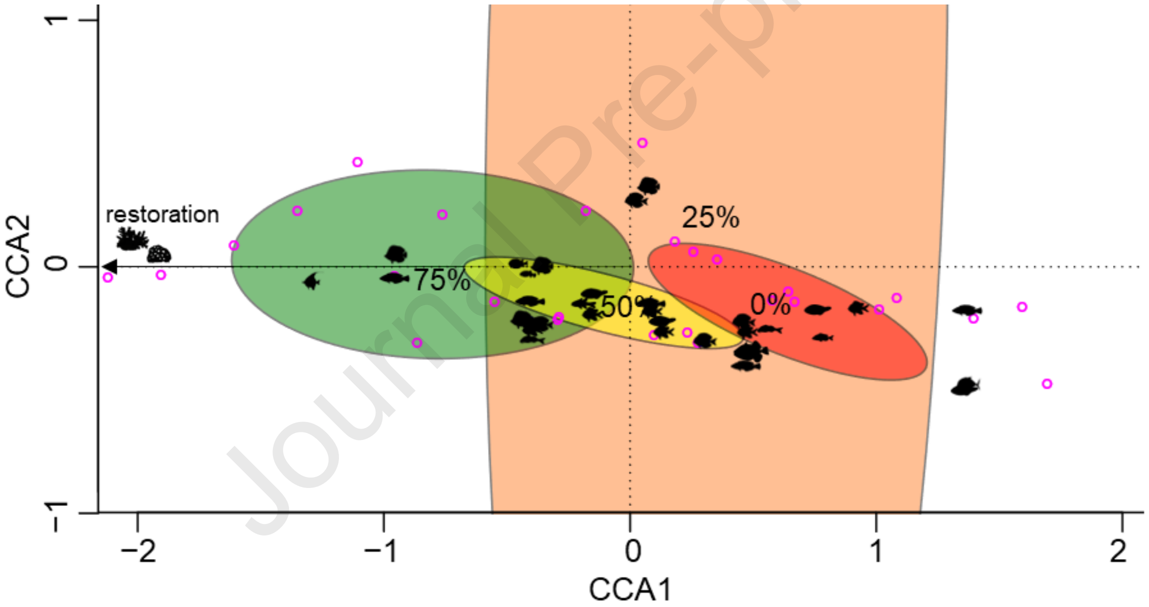
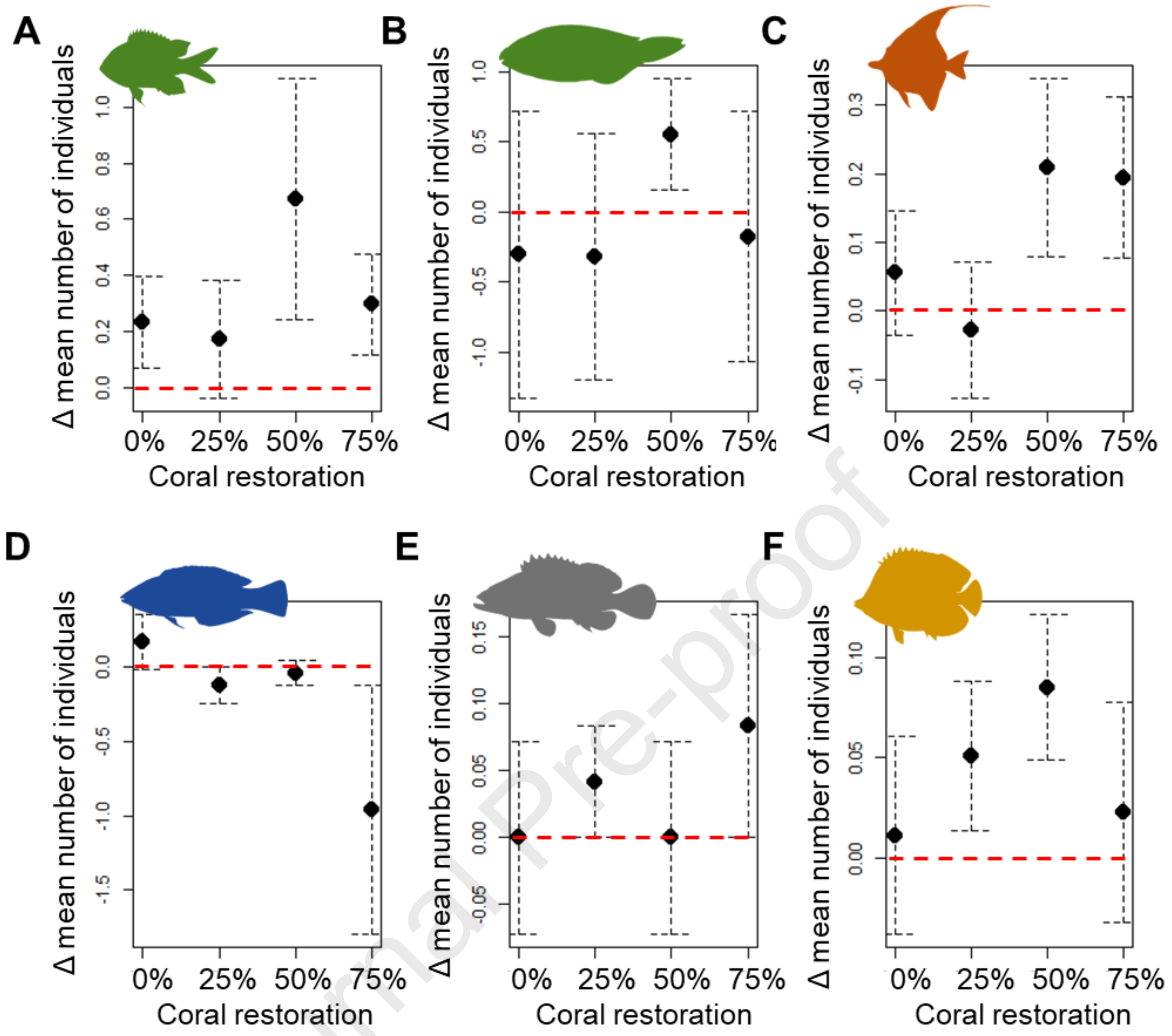

restoration
75%
50%
25%
0%
CCA2
1
0
−1
−2
−1
0
1
2
CCA1

Fig. 3



725

726 **Fig. 4**

727

728

729

730

Highlights

- Short-term impacts (< 1 month) of coral restoration on fish abundance, diversity, and assemblages in a marine educational area in Bora Bora were studied.
- Some species were associated with the more restored patches (*Chaetodon citrinellus*, *Halichoeres trimaculatus*, and *Zanclus cornutus*).
- There was no short-term effect on abundance and diversity but there was a significant modification of adult assemblages.
- It indicates the effectiveness of restoration efforts even within a brief period.
- These rapid changes underscore the remarkable ability of adult fish to adapt to rapidly changing environments.

Conflicts of interest/Competing interests

The authors declare no competing interest.