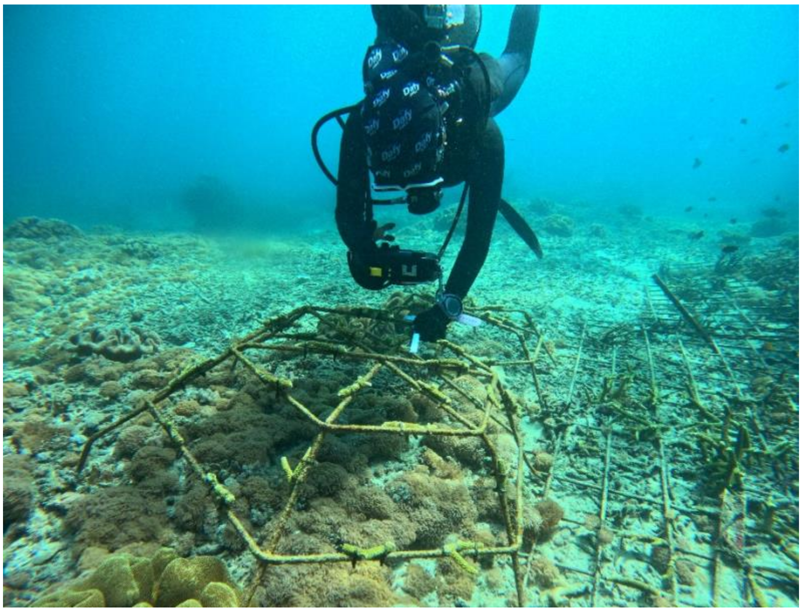
LEBRUN Emma

INTERNSHIP REPORT

LivingSeas Foundation

Influence of Depth (5 m and 10 m) on the Growth of *Acropora spp.* Assessed Using a Photographic Monitoring Method at the LivingSeas Coral Restoration Site in Padangbai



04/05/2026 – 12/07/2026

Internship manager : Leon Boey

Abstract :

This ten-week internship at the Livingseas Foundation aimed to analyze the growth dynamics of *Acropora* corals at depths of 5 m and 10 m. The protocol utilized a five-week photographic monitoring program using the Olympus Tough TG-4, with data subsequently processed through ImageJ software; a caliper was placed in each frame to serve as a reference scale for converting visual pixels into real-world measurements. While specimen mortality at 10 mcaused by butterflyfish predation and mechanical stress from fixations limited direct comparison, the integration of a five-month pilot study by the Livingseas Foundation comparing 5 m and 15 m depths validated the research findings. The results converge to identify the 5 m zone as the optimal environment for restoration, demonstrating a significantly higher growth gain of 4 cm at 5 m compared to only 2,226cm at 15 m over the same period.

Glossary and list of acronyms:

Acropora : Hard coral genus (order Scleractiniaires) characterized by a branched morphology. It is among the fastest-growing corals and plays a major role in the construction of tropical reefs, although it is particularly vulnerable to heat stress and bleaching.

Bioerosion : Biological erosion process by which living organisms such as fish, sea urchins, and sponges fragment or dissolve the calcareous substrate of coral reefs.

Box and whiskers plot : Statistical graphical representation used to visualize the distribution of a dataset. It shows the median, first and third quartiles (forming the box), as well as the minimum and maximum values (whiskers), providing a quick overview of data dispersion and symmetry.

Butterfly fish (*Chaetodon spp.*) : Tropical fish of the family Chaetodontidae, recognizable by its flattened shape, bright colors, and striped or spotted patterns. Some species are corallivorous, meaning they feed directly on coral polyps, which can pose a significant threat to newly transplanted corals.

Cnidarian : Phylum of the animal kingdom grouping aquatic organisms with radial symmetry such as corals, jellyfish, and sea anemones.

Coral transplantation : A coral restoration technique consisting of attaching fragments of corals taken from healthy colonies to artificial or natural structures to promote the regeneration of a degraded reef.

CSR: Corporate Social Responsibility

Dynamite fishing : A destructive and illegal fishing technique involving the use of explosives in the water to stun or kill fish en masse. It causes considerable and often irreversible damage to coral reefs and the surrounding seabed.

Fish fauna : All species of fish present in a given aquatic environment.

Heat stress : A physiological disturbance triggered in corals when the water temperature exceeds their tolerance threshold, generally by 1–2 °C above the usual seasonal average. It causes the expulsion of zooxanthellae and can lead to coral bleaching and death if the stress persists.

Ichthyofauna : Scientific term referring to all fish species inhabiting a defined aquatic ecosystem. Synonymous with fish fauna, it is commonly used in marine ecology to characterize fish communities associated with coral reefs.

Linear regression : A statistical method used to model the relationship between a dependent variable (in this case, coral size) and an independent variable (time) by fitting a line to observed data. The slope of this line represents the average growth rate per unit of time.

Mechanical stress : A physical constraint exerted on the tissues of a living organism by repeated or prolonged external forces. In the context of this study, it refers to the friction caused by zip ties on coral fragments under the influence of marine currents.

NIH: National Institutes of Health

Octodom : A dome-shaped artificial reef structure designed to provide three-dimensional habitat for marine organisms while supporting coral transplantation and growth at multiple elevations. Its elevated architecture increases the available surface area for coral attachment and creates sheltered spaces that enhance habitat complexity and biodiversity.

PAR: Photosynthetically Active Radiation. It is the measure of the amount of light available in the wavelength range (400–700 nm) that can be used by photosynthetic organisms, including coral zooxanthellae, to perform photosynthesis.

Photosynthesis : A biological process by which chlorophyll-containing organisms such as zooxanthellae convert light energy into chemical energy, using carbon dioxide and water to produce sugars and oxygen.

Polyp : The elementary biological unit constituting coral. It is a small cylindrical animal belonging to the phylum Cnidaria, with a mouth surrounded by tentacles and capable of secreting an external calcareous skeleton.

Reef Star : A star-shaped artificial metal reef structure consisting of three intersecting metal bars forming a six-pointed star, enclosed by a circular metal ring that holds the structure together and provides stability. It is used as a support for coral transplantation and can accommodate up to 18 coral fragments on a single tier, promoting coral growth and the restoration of degraded coral reefs.

Reef structures : Formations created by the accumulation of calcareous skeletons of corals and other marine organisms. They constitute the physical architecture of coral reefs and provide habitat for a great diversity of marine species.

Super Star : A star-shaped artificial metal reef structure consisting of three intersecting metal bars forming a six-pointed star, enclosed by two circular metal rings that reinforce the structure and provide additional stability. It is used as a support for coral transplantation and can accommodate up to 24 coral fragments on two tiers, promoting coral growth and the restoration of degraded coral reefs.

Sylvia A. Earle : American oceanographer, marine biologist, and explorer, internationally recognized for her pioneering work in ocean research and conservation. A former Chief Scientist of NOAA, she is known for her record-breaking dives and commitment to marine protection.

Turbidity : A measure of the transparency of an aquatic environment, related to the concentration of suspended particles (sediments, phytoplankton, and organic matter) in the water. High turbidity reduces light penetration, limiting the photosynthetic activity of zooxanthellae and potentially affecting coral growth.

Zooxanthellae : Unicellular symbiotic microalgae living within coral tissues. They provide corals with most of their energy through photosynthesis in exchange for protection and nutrients.

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Introduction

Coral reefs, true pillars of marine biodiversity hosting nearly 30% of ocean species, are now facing an unprecedented crisis. On a global scale, experts predict that 70% to 90% of these ecosystems will disappear by 2050 under the pressure of climate change, pollution, and human activities. In Indonesia, and more specifically at Padang Bai (Bali), reefs have been severely degraded over the last few decades by dynamite fishing practices, turning once flourishing areas into underwater deserts.

It is in this context of environmental emergency that the Livingseas Foundation intervenes. Founded by Leon Boey, this marine conservation organization is dedicated to restoring coastal ecosystems by sustainably involving local communities. Its action is based on a holistic and pragmatic approach, aiming to produce a "visible, tangible and measurable" impact. These efforts have yielded concrete results: 445,293 coral fragments planted, 9,005 reef structures deployed and more than 8,772 m2 of revitalized seabed.

As part of my second year of Biological Engineering, a course entitled "Environmental Sciences and Ecotechnologies" at the University Institute of Technology in Perpignan, I joined the scientific team of the foundation for a ten-week internship, from May 4 to July 12, 2026. Placed under the supervision of Katrina McPherson, head of research, my work became part of the *Research & Restoration* (R&R) program.

This internship focuses on monitoring coral growth after transplantation. The study focuses on the species *Acropora nobilis*, selected for its rapid growth and characteristic green coloration, witnesses of good metabolic health. The main objective of this project is to assess the influence of a determining abiotic factor, depth, on the development of colonies. By comparing the progression of specimens implanted at 5 meters and 10 meters depth within the "Area III" of Padang Bai, this study aims to identify optimal conditions for maximizing the success of future restoration initiatives of the foundation.

1. The Livingseas Foundation

1.1. General presentation: Projects and missions

The Livingseas Foundation is a marine conservation organization based in Padang Bai, Bali, Indonesia. It was founded by Leon Boey, who began his commitment in 2005 with Livingseas Asia before transforming a diving center activity into a foundation dedicated to the reconstruction of marine ecosystems (Livingseas Foundation, 2025).

To carry out its missions, the foundation relies on strategic collaborations with program partners such as the TUI Care Foundation, Handprint and Carbon Ethics. These partnerships make it possible to finance and structure scholarship programs (Fellowships). It also benefits from major financial support, notably from a European foundation that made a €60,000 donation in December 2024, allowing the installation of 127 new coral nurseries and the planting of 127,000 fragments in just 4.5 months. In addition, the foundation is developing a corporate engagement component by offering Corporate Social Responsibility (CSR) partnerships designed to increase brand visibility while supporting ocean preservation (Livingseas Foundation, 2025).

Faced with the climate emergency that threatens to wipe out 70-90% of coral reefs by 2050, the Livingseas Foundation is taking concrete action to reverse this trend by transforming degraded areas into thriving ecosystems. Building on the vision of oceanographer Sylvia A. Earle that ignorance is the greatest threat to the ocean, the organization focuses its action around the physical restoration of reefs and the sustainable involvement of local communities. These efforts are reflected in tangible results such as the deployment of 9,005 structures and the planting of 445,293 coral fragments on 8,772 m2 of seabed. At the same time, the foundation places education at the heart of its strategy through scholarship programs to train local youth so that they become actors in their own conservation. Finally, its pillar dedicated to waste management has already trained 112 young people and removed 43,150 pieces of single-use plastic from the environment, illustrating its philosophy that together we form an ocean of change (Livingseas Foundation, 2025).

1.2. The research group

The Livingseas Foundation's science cluster ensures technical supervision and ecological integrity of all restoration initiatives. This unit of expertise, led by Katrina in her capacity as head of research, relies on the educational coordination of Reiss, who also holds the position of junior researcher, as well as on the operational support of Alex, research assistant. Together, these three scientists supervise the trainees of the Research & Restoration (R&R) program, an immersive training dedicated to the study and reconstruction of reefs in which my internship is directly integrated. The activity of this team revolves around a rigorous environmental monitoring to ensure that each project produces a "visible, tangible and measurable" impact.

1.3. The research topic

This internship focuses on marine biology, and more specifically on the study of coral growth within the Livingseas research team.

Currently, coral reefs are seriously threatened by global warming, pollution, overfishing and human activities. Consequently, coral restoration has become a major priority of marine research and conservation. The reefs off Padangbai have been severely damaged in recent decades, mainly due to an outdated and destructive fishing practice: dynamite fishing. Faced with this situation, the Livingseas Foundation intervenes to reverse this trend.

In this context, the foundation, specialized in coral restoration, offers an ideal framework for conducting this study. Working exclusively with these organisms, it has in-depth expertise to analyze their development after transplantation, identify the factors influencing their survival and determine the favorable conditions for the regeneration of reefs. In addition, the foundation favors the use of corals of the *Acropora* genus for its restoration projects. This choice is a major advantage for the study of their development because these corals have rapid growth, which allows to observe visible and tangible results in a short time.

2. Coral growth mechanism

2.1. The growth mechanism of coral

Coral is not a plant, but an animal (Figure 1): a colony of tiny polyps belonging to the cnidarian family. Each of them secretes calcium carbonate, forming a rigid external skeleton. It is the accumulation of these skeletons, over generations, that gives rise to the coral reefs we know.

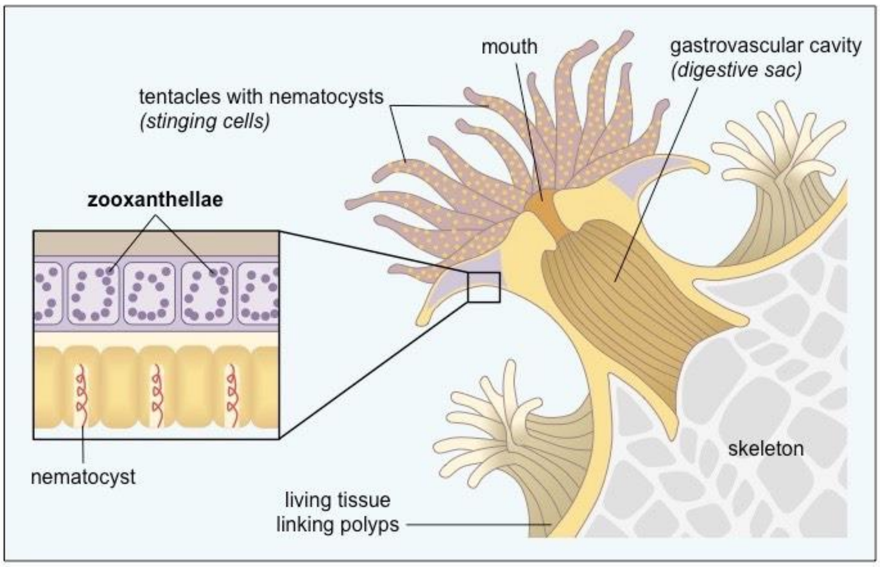


Figure 1: Detailed diagram of the anatomy of a coral polyp and its calcareous structure

But this construction would not be possible without zooxanthellae. These microscopic algae settle in the tissues of the coral and, thanks to photosynthesis, provide it with most of the energy necessary for its growth. In return, the polyp provides them with shelter and nutrients. This mutual exchange is the true engine of coral development. Concretely, this growth is played at the cellular level.

The polyp draws calcium and carbonate ions from seawater, which it combines to form limestone crystals at the base of its body. This mineral deposition takes place day after day, in successive layers, somewhat like the rings of a tree. The speed of this calcification directly depends on the energy provided by zooxanthellae: the more active photosynthesis, the more resources the polyp has to build its skeleton quickly.

This growth, however, is not uniform. Some species, with branchy and thin shapes, can gain several centimeters per year, taking advantage of a light architecture that promotes rapid expansion. Others, with massive and compact structures, grow much more slowly, sometimes only a few millimeters, but in exchange form skeletons that are particularly resistant to waves and storms.

The *Acropora* genus perfectly illustrates this first category. Recognizable by its thin and branched branches, it is among the fastest growing corals, sometimes reaching 10 to 20 centimeters per year depending on the conditions of the environment. This speed is explained by a light and porous skeletal structure, which requires less calcareous material to expand, as well as a high sensitivity to light, which optimizes the photosynthetic activity of its zooxanthellae. This rapid growth makes it an essential player in the rapid formation of reefs, but also one of the species most vulnerable to heat stress and coral bleaching (Rafe Boulon*, et al*, 2005).

2.2. Factors affecting growth

2.2.1. Depth

The main factor influencing coral growth is depth, as it determines the degree of light exposure. The latter is essential for the development of zooxanthellae, symbiotic microalgae that provide corals with a major share of the energy they need through photosynthesis. Therefore, it appears relevant to study the influence of depth on coral development by comparing individuals located at different depths. This comparative analysis will assess possible variations in growth rates and analyse how corals respond to distinct light conditions.

2.2.2. Temperature

Water temperature represents a fundamental biological parameter for the growth of reefs, Builder corals reaching their full development in tropical waters maintained between 25 and 27 °C. This optimal temperature range promotes the precipitation of calcium carbonate, essential to the rigorous formation of their calcareous skeleton. However, this equilibrium is highly fragile since a thermal rise of only 1 to 2 °C can trigger critical heat stress, forcing the host to expel its zooxanthellae. These microalgae are responsible for 75% to 90% of the energy supply of coral, their loss leads to discoloration and a severe nutrient deficiency. This process of bleaching, identified in sources as a direct consequence of ocean warming linked to the climate crisis, weakens reef structures and can lead to the permanent death of colonies.

2.2.3. Fish populations

The balance of marine environments is based on a fundamental interdependence between fish fauna and reef structures. The sustainability of a reef results indeed from a delicate balance between its calcareous expansion and erosion mechanisms, two processes in which fish occupy a central function.

True sanctuaries, reefs are home to between 25% and 30% of the world's ocean biodiversity, providing species with shelter from predators, an abundant food source and nursery areas essential for population renewal. However, this interaction can sometimes become detrimental: excessive consumption of corals, whether it targets living tissues or weakens the skeleton through bioerosion, is likely to disrupt coral growth. This phenomenon can significantly slow the development of colonies, or even cause their disappearance, thus hindering the natural ability of the reef to expand and regenerate.

3. Materials and methods

3.1. Selection of study sites and transplanted species

3.1.1. Selection of study sites

The research protocol was implemented in "Area III", one of three rehabilitation spaces supervised by the organization within its restoration site (Annex I) at Padang Bai, Bali (−8.527381°S; 115.513568°E). This perimeter extends about 120 meters wide and covers an area of depth between 5 and 16 meters (Livingseas Foundation, 2025).

Figure 2: Underwater photograph of the two restoration structures at 5 meters deep, located near the coral nurseries

Figure 3: Underwater photograph of the Octodom sector located at 10 meters

The survey devices were installed on the TUI Care Foundation area (Annex II) at two different depths: 5 meters and 10 meters. The 5-meter structures are located in the immediate vicinity of the coral nurseries (Figure 2), and the 10-meter structures are positioned next to the "Octodom" infrastructure and "Reef Stars" structures established for eight months (Figure 3).

The corals will be transplanted onto two types of structures : Super star, large structure (Figure 4) and Reef Star, one smaller (Figure 5).

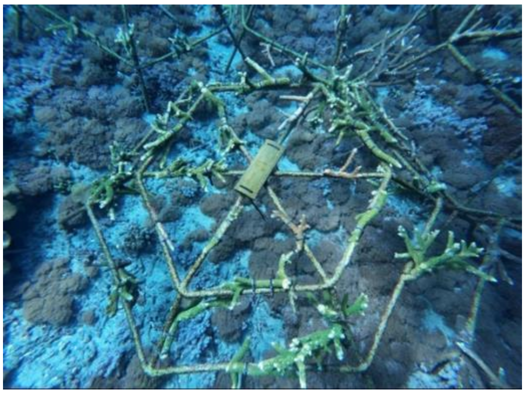


Figure 4 : Underwater picture of a Super star (large structure)

Figure 5 : Underwater picture of a Reef star (small structure)

3.1.2. Choice of the transplanted species of *Acropora*

Among the different species of *Acropora*, the species *Acropora nobilis* was selected for planting. The genus *Acropora* constitutes one of the most important groups of hard corals within tropical reefs. Thanks to their rapid growth and symbiotic relationship with microalgae called zooxanthellae, these corals play a key role in the biodiversity of tropical oceans.

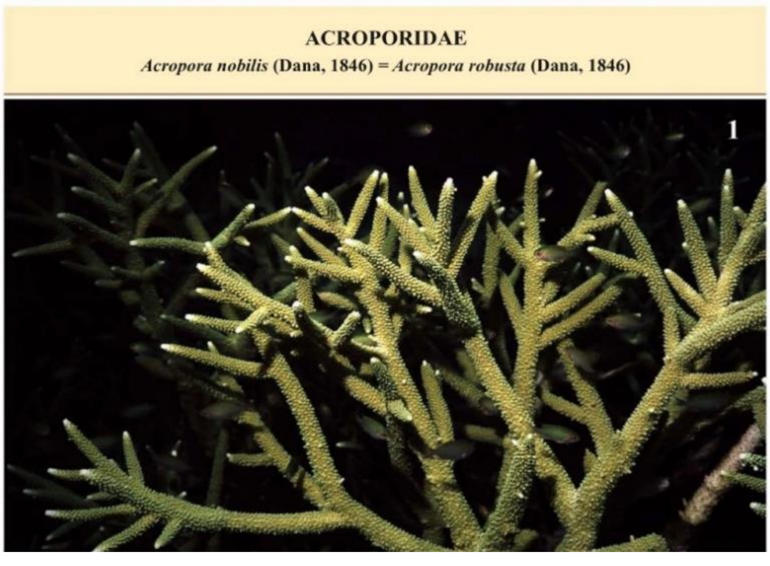


Figure 6: Underwater photograph of a *Acropora nobilis coral*

Acropora nobilis (Figure 6) is characterized by broad, thick branches and a green colouration. This shade is the result of high exposure to light, which promotes the development of coral pigments and its zooxanthellae.

3.2. Coral Growth: Processes and Influencing Factors

3.2.1. Equipment: Olympus TG4 and vernier caliper

The protocol for monitoring coral growth is based on the combined use of a physical measuring instrument and a high-precision optical system, adapted to the constraints of the underwater environment.

The caliper is not used to perform direct manual surveys in the field, an operation that would be complex and imprecise underwater. Its function is to serve as a systematic reference scale by being placed in the field of each photograph. This method makes it possible, during the computer post-processing phase, to calibrate the measurements by converting the pixels of the image into real millimetres, thus guaranteeing precise quantification of the development of the branches of *Acropora nobilis*.

Scientific monitoring of coral growth is based on the use of the Olympus Tough TG-4 (Appendix III). This camera combines an ultra-bright f/2.0 lens for dark depths and a Microscope mode allowing focusing at 1 cm from the subject, complemented by Focus Stacking functions for optimal macro sharpness. Compared to a GoPro-type camera, which could have produced lower quality images under these conditions, this camera is better suited for the study project.

3.2.2. Photo analysis : Image J

The ImageJ software has been mobilized to ensure the scientific and morphometric analysis of underwater photographs collected in the field. This free and royalty-free tool, developed by the National Institutes of Health (NIH), is a global reference in biological research for measurement and automated image processing. As part of this protocol, the software makes it possible to use the vernier caliper present in the images as a systematic visual reference scale. Using the calibration function, ImageJ converts image pixels into real millimeters, which allows to quantify with extreme precision the linear growth of *Acropora nobilis* branches over time. The success of this digital analysis directly depends on the quality of the shots taken with the Olympus TG-4: the sharpness obtained thanks to the microscope mode and the preservation of details by the RAW format guarantee reliable measurements, essential for validating the foundation restoration results.

3.2.3. Methods : Photographic monitoring of coral structure

A photographic follow-up study was conducted over a period of five weeks to assess the progress of transplanted corals. Weekly observations were made on four structures: a small and a large structure located at depths of 5 m and 10 m. Each week, a dive was carried out to photograph the selected corals. The shots were taken using the underwater camera provided by Livingseas. A caliper was placed next to the photographed coral, at the same level and in the same plane, to serve as a reference scale for subsequent measurements.

The photographs were systematically taken vertically, directly above the corals (Figure 7). This position has minimized errors related to perspective and image distortions, ensuring greater accuracy in future measurements. The standardization of photographs over the various weeks of monitoring was also ensured. On each of the four structures, six coral colonies were selected (Figure 8). On each structure, only the six corals located at the top were sampled. Monitoring a large number of individuals allows to minimize the loss of data in case of mortality, detachment or damage suffered by certain corals during the study. This strategy made it possible to maintain a sufficient sample size for analysis, even in the face of unforeseen field conditions.

Figure 7: Diver taking a photo of a coral on a Reef Star located 10 meters away

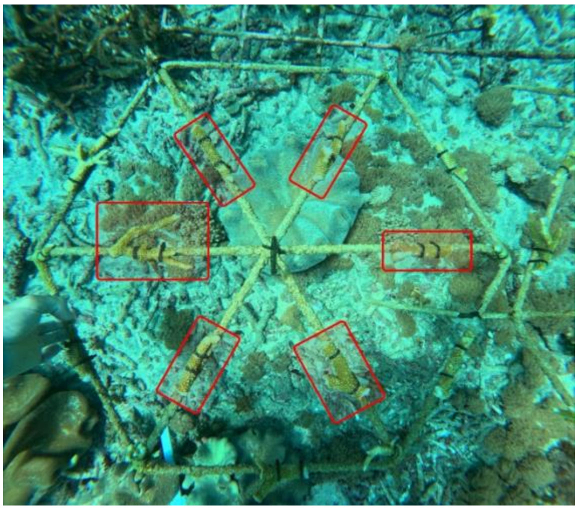


Figure 8: Underwater photograph of the position of the six corals taken for the study

The collected photographs were then analyzed using ImageJ software. The caliper visible in each image allowed to calibrate the measurements and convert the dimensions from pixels to centimeters. The data obtained were then used to monitor and compare the growth of corals on different structures and at different depths.

Once all the values had been obtained, they were represented using various types of graphs generated with the R software, a programming language and statistical computing environment widely used for data processing, statistical analysis, and data visualization. These graphical representations facilitated the interpretation of the results and helped highlight the observed trends.

4. Results

4.1. Coral growth at 5 meters

	Coral 1	Coral 2	Coral 3	Coral 4	Coral 5	Coral 6	Average
0 day	10,536	8,105	8,251	8,047	9,226	8,941	8,851
7 days	10,802	8,261	8,312	8,059	9,399	9,056	8,982
14 days	11,057	8,301	8,409	8,147	9,575	9,289	9,13
21 days	11,252	8,376	8,525	8,239	9,641	9,344	9,23
28 days	11,459	8,493	8,697	8,493	9,701	9,482	9,387
35 days	11,503	9,063	8,878	9,057	9,756	9,544	9,634

Table 1: Results of coral size (in centimeters) of small structure at 5 meters depth

	Coral 1	Coral 2	Coral 3	Coral 4	Coral 5	Coral 6	Average
0 day	9,316	9,067	11,134	8,249	9,279	10,567	9,602
7 days	9,478	9,187	11,564	8,405	9,308	10,601	9,757
14 days	9,555	9,277	11,801	8,642	9,499	10,744	9,919
21 days	9,701	9,371	11,955	8,89	9,629	10,852	10,066
28 days	9,853	9,593	12,056	8,902	10,541	11,269	10,369
35 days	9,981	9,749	12,215	8,918	11,679	11,97	10,752

Table 2: Results of coral size (in centimeters) of the large structure at 5 meters depth

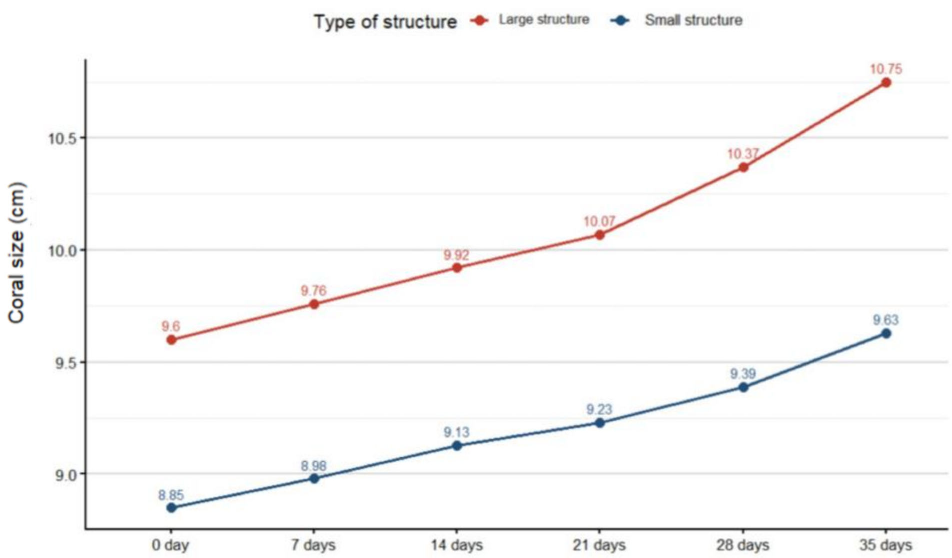


Figure 9: Evolution of the growth of corals (average) of the *Acropora genus* at 5 meters on a small structure and a large structure

The mean values were calculated individually for each weeks (0 day (first day of planting), 7 days,...)

The curve of corals placed on a small structure at a depth of 5 m shows an increasing and gradual trajectory over all 35 days of monitoring. (Annex IV) The slope is initially moderate between D0 and D14, with an average height increasing from 9.60 cm to 9.92 cm, before gradually increasing from D14. Between D14 and D35, the curve adopts an increasingly pronounced slope, with weekly gains increasing from 0.15 cm to 0.30 cm then to 0.38 cm, reflecting a net acceleration in growth at the end of the period. The average height reaches 10.75 cm at D35, for a total gain of 1.15 cm over the entire period.

The curve of corals placed on a large structure at 5 m depth shows a linear and regular trajectory over all 35 days of monitoring (Annex V). The slope remains stable and constant from D0 to D35, with no observable acceleration or deceleration, with homogeneous weekly gains of around 0.13 cm per week on average. The average height thus increases from 8.85 cm at day 0 to 9.63 cm at day 35, for a total gain of 0.78 cm over the follow-up period (Figure 9).

A linear regression was performed to estimate the coefficient of coral growth as a function of time, expressed in days (0, 7, 14, 21, 28 and 35 days).

$$a = \frac{n\sum xy - \sum x \sum y}{n\sum x^2 - (\sum x)^2}$$

y = average height (in cm)
x = time (in day)
a = slope of the line (cm/day)
n = number of observations (5 weeks, n=5)
∑ = summation

By applying the linear regression formula, based on the values of each of the lines, the coefficient for the small structure obtained is 0.042 cm/day and 0,061 cm/day for the large structure.

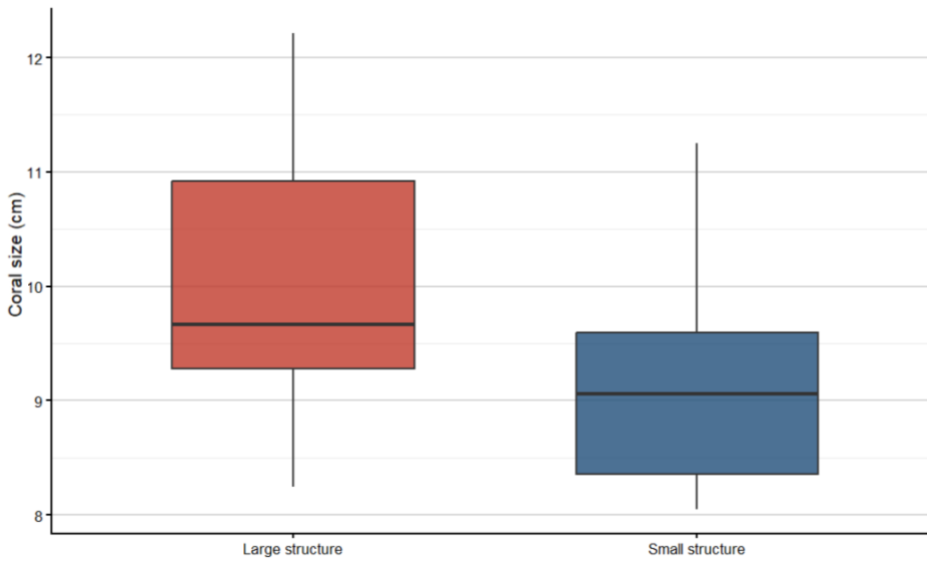


Figure 10: Distribution of coral size at 5 meters depth according to the type of structure (box and whiskers plot)

5 meters (large) : median = 9,65cm / first quartile = 9,30cm / third quartile = 10,90cm/ interquartile = 1,60cm / whiskers = 8,30cm at 12,20cm

5 meters (small) : median = 9,06cm / first quartile = 8,34cm / third quartile = 9,58cm/ interquartile = 1,24cm / whiskers = 8,05cm at 11,46cm

The box plots (Figure 10) show that the median indicates a slightly higher central value for the large structure compared to the small structure. The interquartile range is wider for the large structure, indicating a greater dispersion of values around the median, whereas it is narrower for the small structure, showing more clustered values. The whiskers indicate that the overall range of values is greater for the large structure, with higher extreme values, while the small structure shows a more limited overall range.

4.2. Coral growth at 10 meters

Monitoring of the submerged structures at a depth of ten meters was initially scheduled to last five weeks. However, by the third week of monitoring, the corals attached to the structures no longer showed any signs of growth. This observation was confirmed during the fourth week, raising suspicions that the colony had died. Given this advanced state of degradation, it was no longer possible to continue monitoring growth under the conditions initially planned.

5. Interpretation of results and discussion

5.1. Evolution of coral growth at 5 meters

The results show a difference in coral growth between the small and large structure at a depth of 5 m. The governing coefficients from linear regressions indicate a growth of 0.042 cm/day on small structures compared to 0.061 cm/day on large structures, suggesting that the large structure promotes slightly faster calcification over the period studied. In terms of temporal dynamics, the linear and regular trajectory observed for corals on large structures reflects stable and sustained growth throughout the monitoring. On the other hand, the gradual acceleration of the slope of the curve of small-structure corals from J14 (2 weeks) onwards suggests that they enter an exponential growth phase during the second part of monitoring. which could indicate that calcification processes intensify over time on this type of structure. The difference between the two governing coefficients remains moderate, suggesting that the effect of structure type is present but limited compared to other potential factors of variation.

The greater data dispersion observed for the large structure, reflected by a wider interquartile gap and a more pronounced positive asymmetry, indicates greater size heterogeneity within this group. This higher inter-individual variability could be explained by a heterogeneity of available microhabitats on the structure, with some colonies benefiting from more favorable conditions than others depending on their position. The higher median observed for the large structure reflects overall larger sizes in this group over the entire period, which corroborates the results from the governing coefficients. The tighter and less asymmetric distribution of small-bodied corals suggests more homogeneous growth conditions among individuals, with each colony subject to similar environmental conditions. Thus, the type of structure influences the growth rate at 5 m, with slightly higher growth on the large structure, although other environmental factors may also modulate these dynamics.

5.2. Coral killing at 10 meters

Several factors, acting in combination, may explain the death of corals located at the depth of 10 meters (Figure 11).

First, mechanical stress may have been caused by the method used to fix the coral fragments. Because corals are attached to the structures using plastic zip ties, these can gradually loosen over time. Under the effect of the current, this play between the collar and the fragment causes repeated friction on the coral tissues, causing superficial lesions and thus constituting a significant source of stress for the individuals concerned.

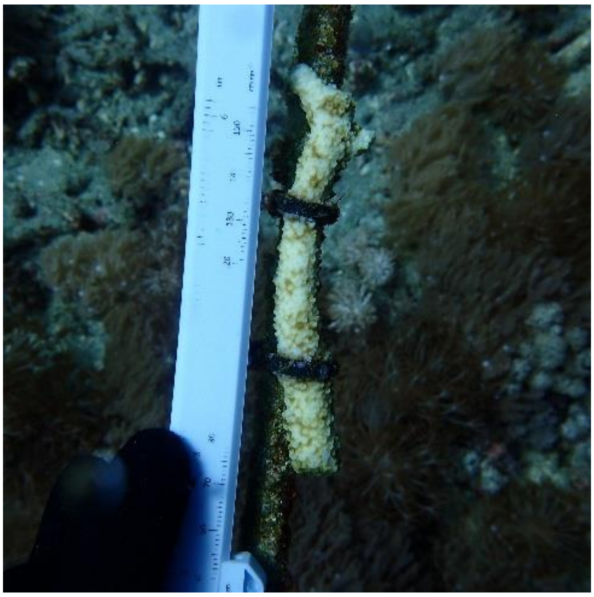


Figure 11 : Underwater photograph of a dead coral located at 10 meters deep

Regarding the water temperature, this parameter does not seem to have been a triggering factor in this case. The surveys carried out throughout the study showed thermal stability, with temperatures between 27 and 28 °C, values that are within the tolerance limits of the species monitored.

The main cause of colony degradation appears to be biological and results from pressure exerted by local ichthyofauna, in particular by butterflyfish (Chaetodon sp.), known to feed on coral polyps (Figure 12). The structures located at a depth of 10 meters were installed in the immediate vicinity of the Octodom, an artificial structure set up about eight months earlier, around which several Reef Star and Super stars had also been deployed during the same period. This area, already benefiting from eight months of colonization, now has a significant coral cover and is a favorable habitat that has attracted a high density of fish.

Figure 12: Underwater photograph of a butterflyfish (*Chaetodon sp.*) eating a *Acropora* type coral

The introduction of two new structures in this already restored environment has probably attracted the attention of butterflyfish to these new substrates. Indeed, recently transplanted corals, more vulnerable and less protected than already established colonies, represent a particularly accessible food resource for this species. A similar phenomenon had already been observed within LivingSeas, during an episode in which all the corals of a nursery intended for transplantation (Annex VI) were consumed by butterfly fish.

This situation illustrates the unpredictable and random nature of this type of biological pressure, which cannot be anticipated with certainty at the time of installation of the structures.

5.3. Limitations of the current protocol and prospects for improvement

This study presents several methodological limitations to be taken into account in the interpretation of the results.

The five-week monitoring duration remains relatively short to fully characterize the growth dynamics of *Acropora* corals. An extended follow-up over several months would allow for more robust and representative results of seasonal variations.

Sample size is also a constraint. Only six corals were monitored per structure, which limits the statistical power of analysis. The total absence of data at 10 meters, due to the early death of the colonies, deprives the study of a cross-depth comparison, which was central to its initial objective.

The method of fixation by plastic zip ties proved to be a source of mechanical stress for the coral fragments. The repeated friction under the effect of the current probably weakened the tissues at 10 meters. The use of epoxy sealant or more flexible fastening systems would be preferred for the next cycles.

Biological pressures exerted by butterflyfish (*Chaetodon* sp.) severely compromised the 10-metre follow-up. The location of structures near an area already colonized and densely populated by fish was not optimal. In the future, it would be preferable to choose less exposed areas or to set up temporary physical protection during the first weeks.

Finally, the photographic method associated with ImageJ depends on the quality of underwater shots. Variations in turbidity or shooting angle between sessions can introduce measurement biases. A stricter standardisation of the protocol (fixed distance, constant lighting) would be a significant improvement.

In the future, resuming monitoring at 10 meters with a revised protocol and a larger sample would make it possible to achieve the initial objective of cross-depth comparison and better document the influence of depth on the growth of *Acropora nobilis* in Zone III.

6. Livingseas Study: Corallian growth comparison *genus Acropora* between 5m/15m,

6.1. Description of the study

Katrina McPherson and her team conducted a 5-month study (October 2025/February 2026). This pilot study focused on the growth of *Acropora* corals in Indonesia at two distinct depths: 5 meters and 15 meters in order to compare their growth speed. Six corals were followed in total and photographed at regular intervals in order to observe their evolution over time. The first photos, taken in October using GoPro cameras, were then replaced with different material for the following sessions.

This study, however, has several limitations that need to be considered. On the one hand, the sample size is very small, only six corals, which does not allow to obtain statistically robust results. On the other hand, photos taken in October with GoPro cameras are not representative for good measurements, because this type of camera, designed for wide-angle shooting, introduces a distortion that distorts distances and makes precision measurements unreliable. Finally, the overall quality of the data can be variable, as the study was initially set up and managed by a research assistant. Despite these limitations, this pilot study remains sufficient to obtain a first order of magnitude on the growth of corals according to depth, and constitutes a solid basis for designing a broader and more rigorous study.

6.2 Results

6.2.1. Average growth over time

	October	November	December	January	February
1	11,432	12,559	13,621	14,587	15,234
2	13,345	14,29	15,234	16,432	17,104
3	13,89	14,935	15,965	16,783	17,887
4	12,341	13,255	14,543	15,123	16,321
5	13,102	14,028	15,137	16,276	17,432
6	11,476	12,563	13,654	14,364	15,607
Average	12,598	13,605	14,692	15,594	16,598

Table 3: Results of the size of corals (in centimeters) located at 5 meters

	October	November	December	January	February
1	8,001	8,594	9,103	10,123	10,678
2	11,309	12,376	12,965	13,432	13,909
3	8,271	8,903	9,432	9,89	10,432
4	12,987	13,499	13,998	14,138	14,678
5	12,498	13,144	13,774	14,243	14,725
6	11,003	11,577	11,99	12,499	13,003
Average	10,678	11,349	11,877	12,387	12,904

Table 4: Results of the size of corals (in centimeters) located at 15 meters

Over the period from October to February, corals of the *Acropora genus* show a significantly different cumulative growth depending on the depth. The two groups start monitoring with almost identical initial sizes in October, but the growth curves diverge rapidly and gradually throughout the observation period.

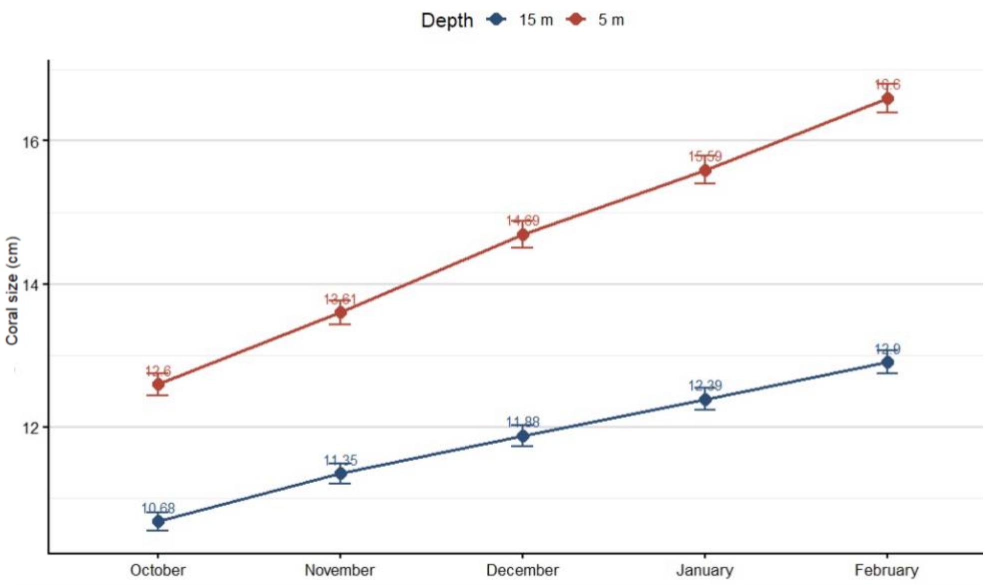


Figure 13: Evolution of the growth of corals (average) of the *Acropora genus* at 5 meters and 15 meters

The mean values were calculated individually for each month (October, November,...)

At a depth of 5 m (Annex VII), average growth was strong and steady, rising from 12,598 cm in October to 16,598 cm in February, for a total gain of 4 cm over five months. The curve presents a quasi-linear trajectory with a sustained and constant slope, without any observable slowdown over the period. At a depth of 15 m (Annex VIII), average growth also follows an increasing trend but with a much less pronounced slope, rising from 10,678 cm in October to 12,904 cm in February, for a total gain of 2,226 cm over the same period.

The gap between the two curves increases continuously over the months. This progressive and monotonous divergence of the two trajectories indicates that the difference in growth between the two depths does not result from a one-time event but settles and increases steadily over the entire monitoring period. The error bars, visible on each measurement point, remain relatively narrow for both groups, which indicates good homogeneity of measurements within each group at each reading date (Figure 13).

6.2.2. Overall distribution of growth

The box of whiskers representing the overall distribution of coral growth over the entire period confirms and completes the observations from the time curves. At 15 m depth, the median is about 12.5 cm, with a first quartile at about 11 cm and a third quartile at about 15 cm, giving an interquartile deviation of about 4 cm. The whiskers extend about 7,5 cm to 19.5 cm, reflecting the total amplitude of the values observed in this group.

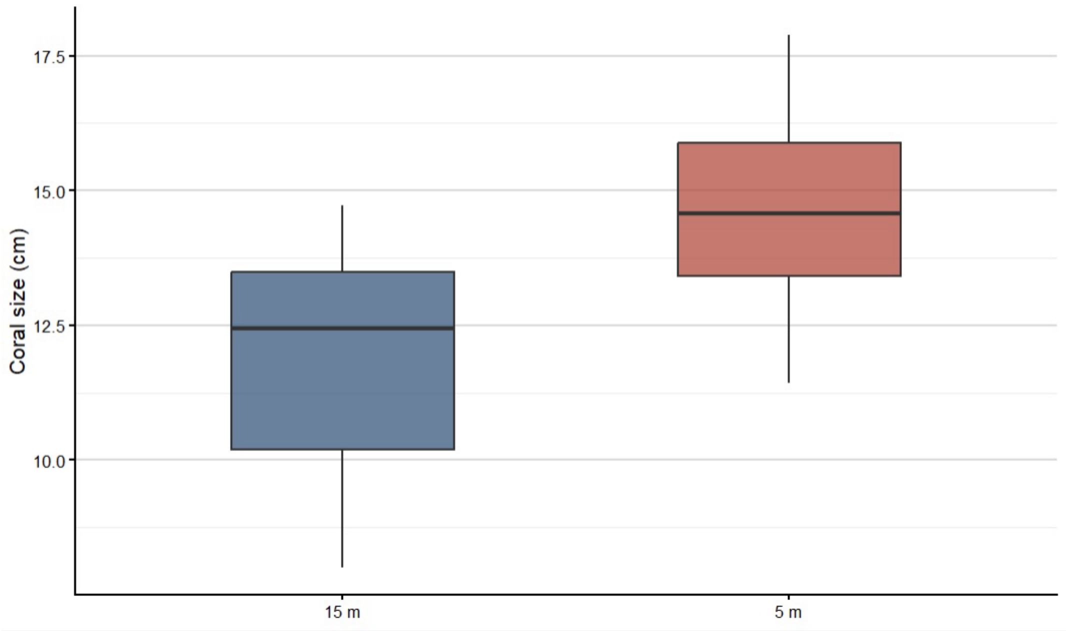


Figure 14 : Distribution of coral size at 5 meters and 15 meters deep (box and whiskers plot)

5 meters : median = 14,57cm / first quartile = 13,35cm / third quartile = 16,28cm/ interquartile = 2,93cm / whiskers = 11,43cm at 17,89cm

15 meters : median = 12,44cm / first quartile = 10,12cm / third quartile = 13,77cm/ interquartile = 3,65cm / whiskers = 8,00cm at 14,73cm

At a depth of 5 meters, the distribution parameters are generally higher than those observed at 15 meters. The median at 5 meters is higher than that at 15 meters. The first quartile is approximately 13.35, and the interquartile ranges indicate a difference in the dispersion of central values between the two depths.

The span of the box plot whiskers shows that the values measured at 5 meters are generally higher and reach greater maximums, whereas those observed at 15 meters show lower values and a more limited overall range.

The position of the median within each box provides information on the shape of the distributions. At 15 meters, the median is relatively centered within the interquartile range, suggesting a fairly balanced distribution. At 5 meters, the median is slightly offset within the box, indicating slight distribution asymmetry with a tendency toward higher values. In both cases, no outliers are observed, as all values remain within the limits defined by the whiskers (Figure 14).

6.2.3. Coefficient guidelines

A linear regression was performed to estimate the coefficient of coral growth as a function of time, expressed in days (0, 1, 2, 3 and 4).

$$a = \frac{n\sum xy - \sum x \sum y}{n\sum x^2 - (\sum x)^2}$$

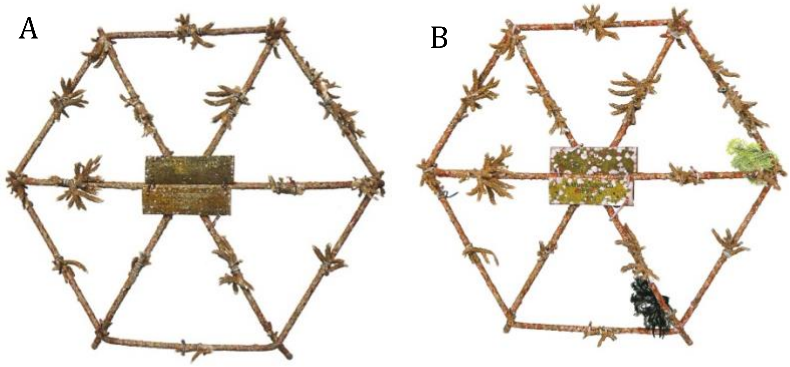
y = average height (in cm)
x = time (in month)
a = slope of the line (cm/month)
n = number of observations (5 month, n=5)
$\sum$ = summation

By applying the linear regression formula, based on the values of each of the lines, the coefficient for the structure in 5 meters obtained is 1,01 cm/month and 0,56 cm/month for the structure in 15 meters.

6.3 Interpretation and discussion

6.3.1. Effect of depth on coral growth dynamics

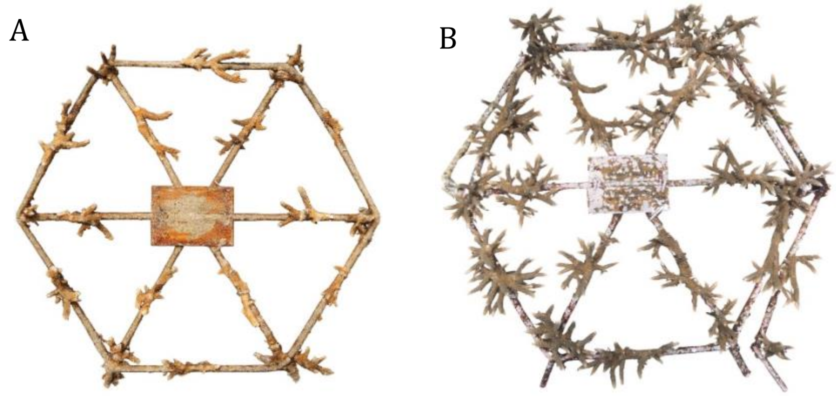
The results obtained show a clear difference in coral growth between the two depths studied, 5 m and 15 m, (Figures 15 and 16), highlighted by both the evolution of sizes over time and the coefficients derived from linear regressions;



<u>Figure 15</u>: Structure at 15 meters depth

A: photo taken in October

B: photo taken in February



<u>Figure 16</u>: Structure at 5 meters depth

A: photo taken in October

B: photo taken in February

Over the entire observation period, both groups show continuous growth. However, the rate of growth differs greatly depending on depth. This difference is quantified by the governing coefficients of the regression lines. At 15 m depth, the coefficient is 0,56 cm/month, which reflects a slow but steady growth over the period studied. At 5 m depth, the coefficient reaches 1,01 cm/month, indicating a much faster growth. This significant difference indicates that the growth dynamics are strongly dependent on depth, with a much more marked acceleration at 5 m.

This trend is also consistent with the observations of time series, where the gap between the two depths gradually increases over time. This shows that the difference in growth is not limited to a point change, but corresponds to a continuous divergence of growth trajectories.

This difference is consistent with the initial hypothesis that coral growth decreases with increasing depth. It is compatible with the fact that environmental conditions change with depth, especially regarding light, a factor involved in the growth of corals of the *Acropora genus*. Thus, the governing coefficients allow to quantitatively summarize this difference: they indicate a significantly faster growth at 5 m than at 15 m over the studied period.

6.3.2. Discussion based on scientific publications

The results obtained in this study show a higher growth of *Acropora* corals at 5 m depth (1,01cm/month) than at 15 m (0,56cm/month), which highlights a strong influence of depth on growth rate.

In the scientific literature, this type of relationship between depth and coral growth is documented, but the observed trends are not always identical depending on the species and environmental conditions.

A classic study conducted on *Acropora formosa* showed that growth rates can vary with depth, with differences in linear growth between 5m, 10m and 15m, but without strictly monotonic relationship depending on the type of growth measured. In some cases, deep-seated corals may exhibit comparable or even greater growth in branch extension, while more superficial areas promote other forms of overall growth (J.K. Oliver, B.E. Chalker, W.C. Dunlap, 1983).

Moreover, several studies indicate that coral growth is strongly related to light availability and zooxanthellar density, with a gradual decrease in biological performance when the depth increases beyond certain limits. However, this relationship can be modulated by other environmental factors such as temperature, hydrodynamics or nutrient availability (Montaser Aly Mahmoud Al-Hammady, 2013).

Experimental studies on different *Acropora species* also show that growth is generally higher at shallow depths (5–10 m), but the differences can vary greatly between sites and species, sometimes with non-linear or environment-specific responses (Suciyono, *et al* 2020).

General conclusion

This internship at the Livingseas Foundation in Padang Bai, Bali, had as main objective to follow and analyze the growth of corals of the genus *Acropora nobilis* transplanted at two distinct depths: 5 meters and 10 meters.

The results obtained at 5 meters show a positive and continuous growth over all 35 days of monitoring, with key coefficients of 0.042 cm/day on small structure and 0.061 cm/day on large structure. These data show favorable conditions for coral development at this depth, with sufficient brightness to support the photosynthetic activity of zooxanthellae. The slight difference observed between the two types of structures also suggests that the size and configuration of the support can modulate growth dynamics.

However, the 10-meter monitoring could not be completed because the colonies were death by predation as early as the fourth week, primarily attributed to predation by butterflyfish (*Chaetodon sp.*) and mechanical stress caused by fixation systems. Although this situation prevented any inter-depth comparison in the context of this study, it made it possible to identify concrete areas for improvement for the rest of the protocol.

Putting these results into perspective with the complementary study conducted by the Livingseas team between 5 m and 15 m confirms the importance of depth as a structuring factor in coral growth, particularly in relation to light availability. These data provide a useful basis for directing future foundation restoration projects to optimal areas and depths.

As coral restoration techniques improve, fundamental questions remain, particularly regarding the influence of abiotic depth parameters, hydrodynamics, availability of light on the survival and growth of transplanted fragments in the long term. Future studies integrating multi-depth monitoring over several seasonal cycles, coupled with continuous environmental measurements (temperature, PAR, turbidity), would make it possible to better define the optimal bathymetric windows for the transplantation of *Acropora nobilis* in the waters of Padang Bai, and to refine predictive models of reef regeneration in a tropical Indo-Pacific context.

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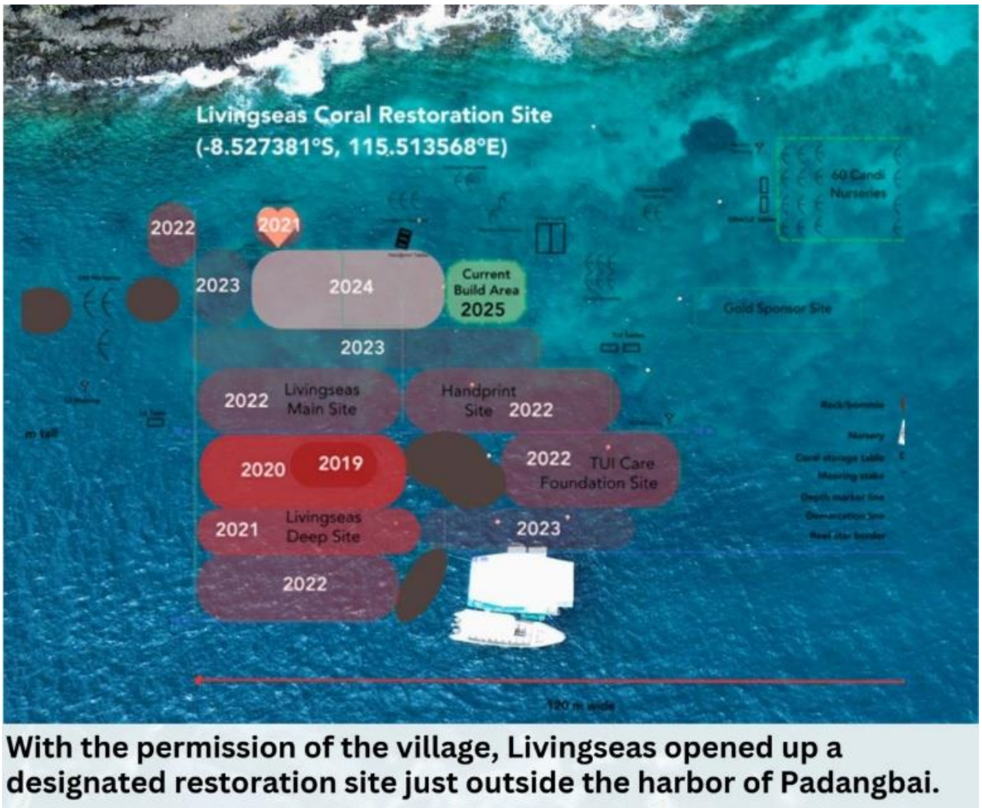
Suciyono, *et al* (2020), Characteristics of *Acropora* divaricata and *Acropora nobilis* on different transplantation depths based on growth rate and zooxanthellae density

Table of annexes:

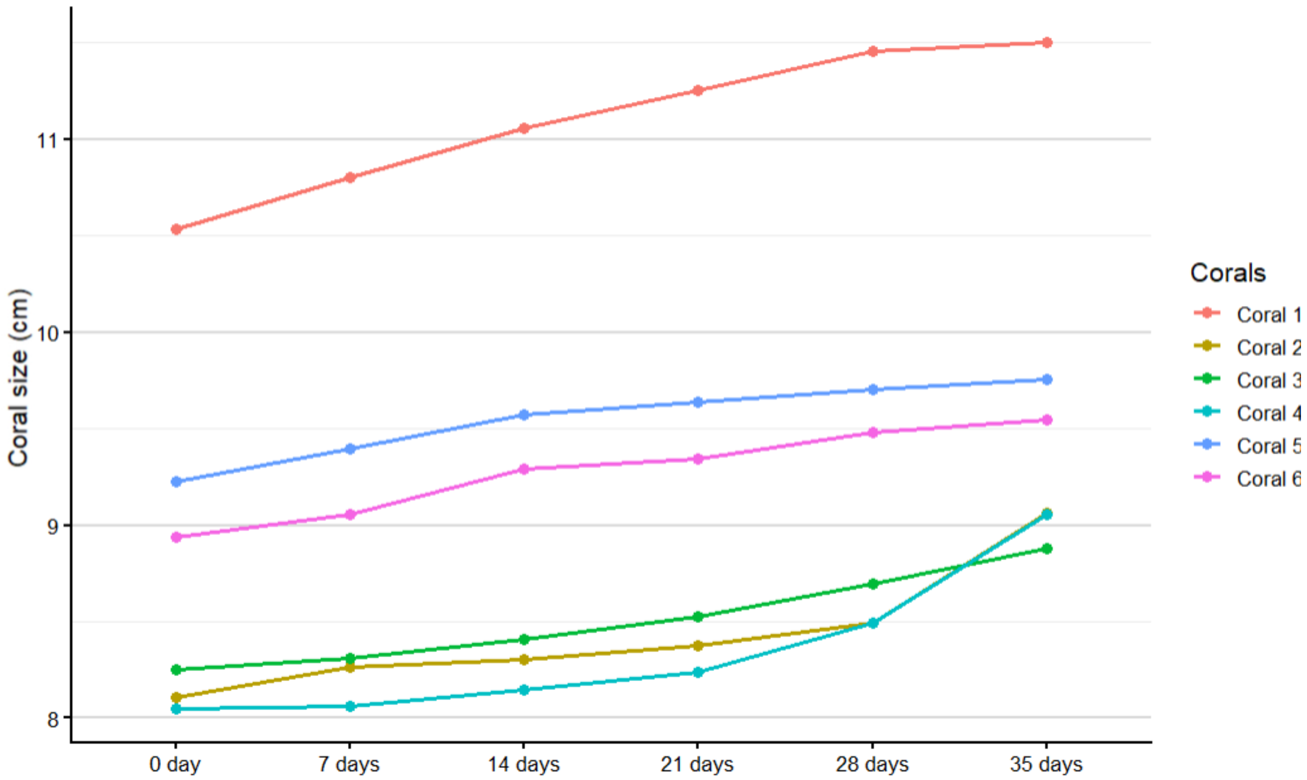
Annex I: Aerial photo of the three Livinseas restoration sites

Annex II: Aerial photo of site III with its different sectors

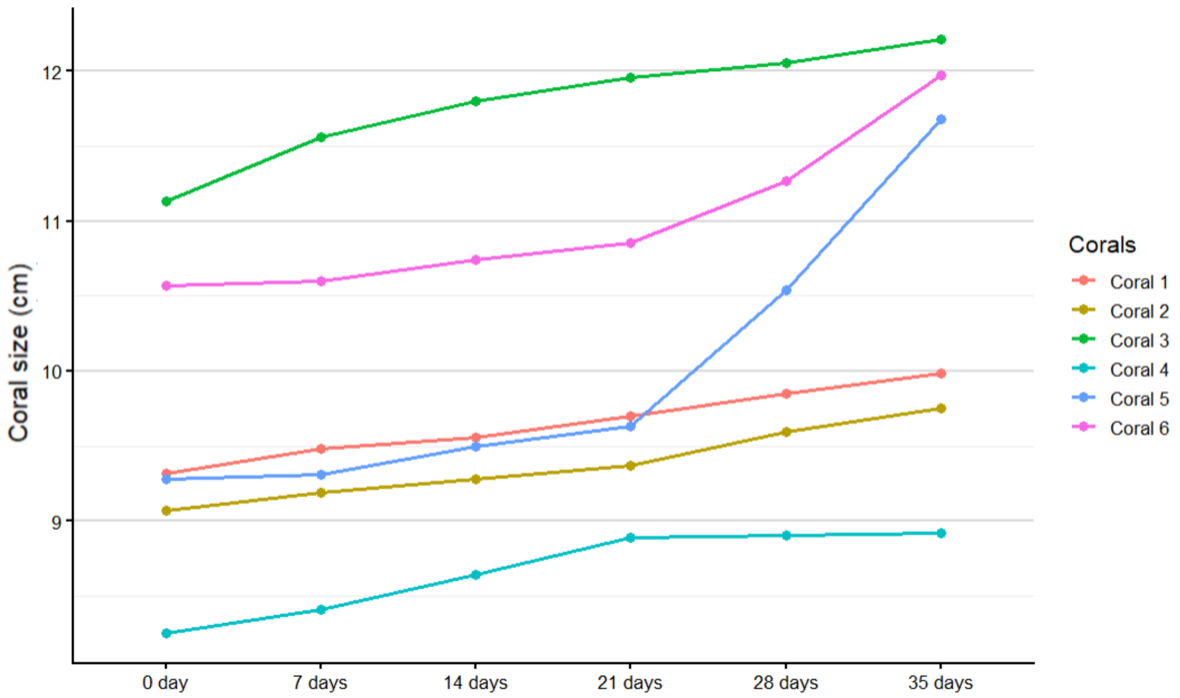


<u>Annex III:</u> Olympus tough TG4 Dive Camera

<u>Annex IV:</u> Evolution of the size of the six corals located on the small structure at 5 meters

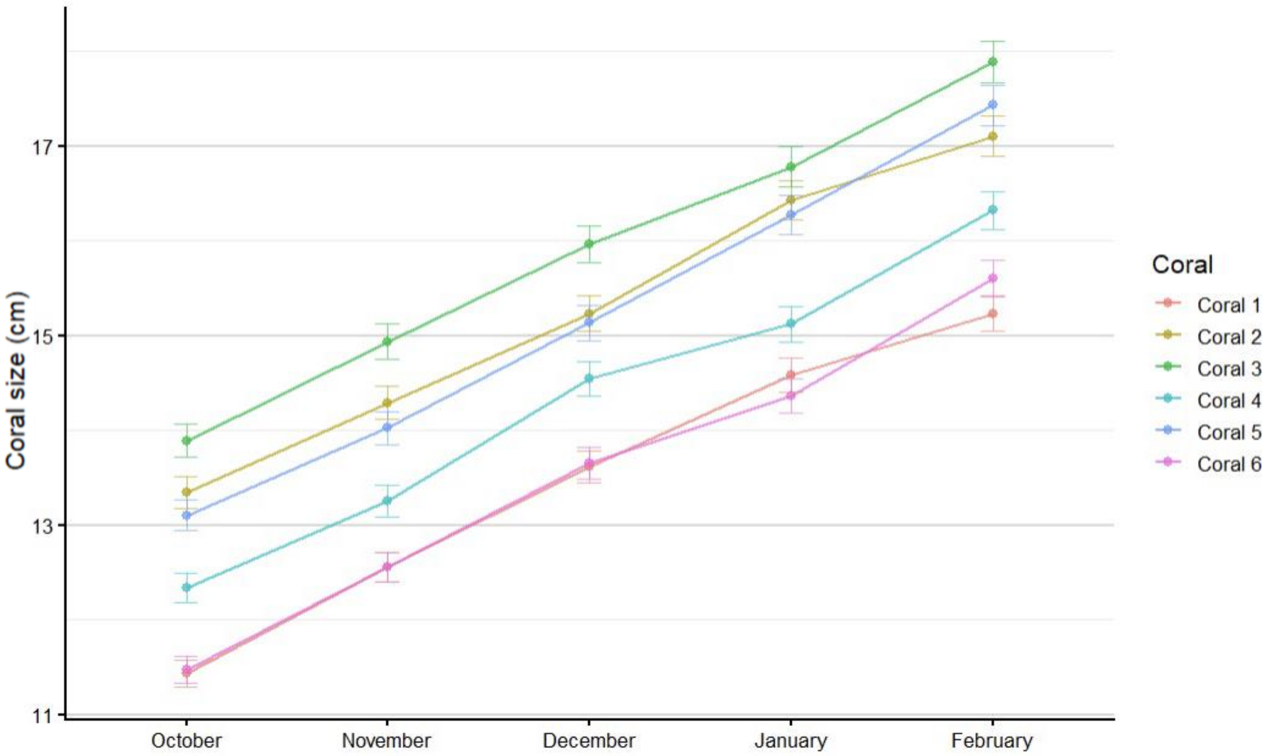


Annex V: Evolution of the size of the six corals located on the large structure at 5 meters



Annex VI: Underwater photograph of a nursery on 2 December 2025

Annex VII: Evolution of the size of the six corals located at 5 meters



Annex VIII: Evolution of the size of the six corals located at 15 meters