The Effects of Aquarium Size, Temperature, and Dissolved Ion Concentrations on Growth Rates of Stony Corals and Colonial Anemones

Analyzing Captive Coral Growth Using Aquarists On-line Aquarium Journal Submissions

Tag words: coral; Acropora; Montipora; Seriatopora; birdsnest; Euphyllia; frogspawn; Zoanthus; zoanthid; zoa; Palythoa; paly; reef; marine; aquaculture; cnidarian; calcium; kalk; alkalinity; alk; carbonate; magnesium; mag; aquarium; frag; fragging; sps; lps

Authors: Marko Drazenovic and Julie M. Fagan, Ph.D.

Summary: Corals have become increasingly popular display animals in marine aquaria. It is generally thought that larger tank size and elevated ion levels increase growth rates of these slow-growing, sensitive organisms. We analyzed a variety of parameters that would affect growth rates using observations reported by coral hobbyists from online published parameters and pictures with dates from primarily NanoReef.com, as well several other similar hobbyist forum websites such as ReefCentral.com. We found that alkalinity and magnesium concentrations did have visible effects on increased growth rate but linear regression analysis of growth vs. various parameters did not show calcium, pH, temperature, and tank size as having significant effects on coral growth rates in several species.

Video: https://youtu.be/ae7VbnRPjhc

Introduction to Achieving Healthy Growth in Captive Corals in Home Aquaria

Coral reefs are under threat in the wild with reef health and coverage both in decline. As global coverage of monitored reef habitat has decreased by up to 27% from their original size (1). As coral reef formations depend on coral survival and health, research is being conducted to help understand coral biology and ecology - with the goal of minimizing or potentially reversing the loss of unique habitat.

With advancements of technology and biological understanding, it is now possible to keep corals in a captive aquarium, and due to the exotic beauty of keeping a slice of the reef, the reef keeping hobby has grown - causing a demand for corals in the pet trade industry. Fortunately, corals are able to be reproduced asexually through fragmentative propagation. A portion of a colony, once cut off, will grow and from a new colony is conditions are suitable for it to grow. Since captive grown fragments are much more adaptable to aquarium condition than wild colonies, the demand for wild corals is relatively low for most corals; and corals a propagated in home aquaria as they grow (and threaten to outgrow the aquarium), as well is in professional aquaculture facilities, such as those run by ORA and Pacific East Aquaculture. This allows for popular corals to be maintained totally separate from the ocean after their collection, in literally thousands of aquariums - nearly every aquarium that keeps Acroporids has a specimen of

Acropora microclados, many of them the Jason Fox Pink Lemonade, all such corals are genetically identical clones, offering that one coral virtual immortality. Thus the hobby has the potential to serve as a biological library of corals, shielding at least a handful from the effects of climate change and habitat loss by keeping them in bubbles of man-made habitat. Additionally, hobbyist help pioneer various fragmentation techniques; current fragging methods used in coral conservation facilities meant for explantation onto the reef to combat die offs.

Increasing growth rate optimizes profit for the production of any animal. This occurs as the calories from maintenance remain constant, and are more and more offset as calories bound in new tissue and burned for anabolism take up a larger and larger percentage of total caloric use. This means less lighting, less cooling for the lighting, and less food. Also as corals grow faster, biotic aragonite precipitation becomes a larger percentage of precipitation, meaning less waste of calcium and alkalinity supplements. The reef keeping aquarium hobby is a relatively expensive one, and by increasing the profits from coral growth would improve the hobby experience and offset more of the cost of supplements, food, and equipment upgrades.

Temperature

Temperature is important to all living organisms. Temperature is a large factor in determining the rates of diffusion for materials in cells, outside cells, and into and out of cells. This controls reaction rates, metabolism, and the function of the entire cell. The biochemical machinery must be fine-tuned to any particular temperature, and outside a temperature range, it will fail. Temperature in coral reefs typically ranges from 23 Celsius to 29 Celsius, or 73 Fahrenheit to 84 Fahrenheit (2), so it is to be assumed that outside that range tropical corals will fail to thrive. Excursions may be tolerated, but eventually the coral will die if kept above 30 Celsius, or below 18 Celsius (3).

Aquaria typically keep corals in the center of their range at about 25 Celsius to 26 Celsius. This provides an amount of buffer room from either extreme - if the temperature starts to rise or fall, it will take time for it to reach a lethal temperature, and the aquarist will hopefully notice the issue and remedy it before then. Different corals, even different individual corals of the same species collected in different regions will display different temperature optimums (4), so it would be very difficult to find an optimum for an aquarium contain multiple corals. It should be kept stable, and kept within the acceptable range, but fine tuning it does not seem to likely produce any noticeable overall effect on the corals being maintained in typical aquaria.

Acidity/Basicity

The acidity, or basicity, of water is the concentration of the hydrogen or hydronium ion (H^+ or H_3O^+), versus the concentration of the hydroxide ion (OH^-). In water, hydrogen ions and hydronium ions are equivalent. Solutions with more hydrogen ions are acidic, and solutions with more hydroxide ions are basic. The sum of their molar concentrations always adds up to 10^{-14} molar. The most common measure for aquariums, or any living system, is the pH scale which is defined as: $pH = -\log[H^+]$, with the hydrogen ion concentration in molar. Meaning the higher the pH, the less hydrogen ions, and the more basic the solution. Seawater is always a mildly basic solution generally with a pH between 8 and 8.4 (5). Increased pH results in decreased solubility of aragonite, and will speed up abiotic precipitation, but in theory could also aid the biotic precipitation as well since corals actively pump protons away from their calcification zones (6) - increasing the overall pH of the environment could decrease the energy expenditure in lowering hydrogen ion concentrations at the calcification site. As the pH decreases, aragonite will begin to dissolve into the water (which is the basis of a calcium reactor), but coral skeleton aragonite would dissolve as well - growth will slow as pH decreases (7), partially as the coral has to fight the chemical erosion that would be otherwise occurring.

Calcium

Calcium in seawater and in biological systems exists virtually entirely as a cation with a +2 charge, either in a crystal lattice, associated with a protein, or in solution. All three exist in equilibrium. The importance of calcium to corals is twofold. Calcium is a vital element to living systems, and is used in the routine functions of animal cells. Corals additionally use calcium as a component of their skeletal framework and mechanical support system - built out of aragonite, a calcium carbonate crystal. In stony corals this is apparent, much of the corals apparent volume is solid "bone", but many soft corals utilize microcrystals in their structure and also deplete calcium as they grow, albeit not as quickly (8). Maintenance of sufficient calcium for their uptake is a key aspect in ensuring growth.

Calcium in seawater around coral reefs is generally in concentrations of 420ppm, and it is commonly advised that reef aquaria use this as a target for their calcium levels (5). While a good number of aquaria maintain elevated calcium concentrations in an attempt to increase growth rates of stony corals, the current literature does not support this. Studies on Stylophora showed no increase in calcification rate at increased calcium levels (9). Studies examining coral health through photosynthetic rates on Pocillopora (whose husbandry is comparable to Stylophora), Pavona, and Caulastrea showed a decline in health when calcium levels were depressed below 375ppm, but increase after that threshold showed no benefit to the corals (10), It is believed that the calcium channels in the coral tissues saturate at those concentrations[5], and that there is no incentive to increase the concentration of channels as calcium does not appear to be the limiting reactant in aragonite formation - biopercipitation of aragonite is limited primarily by carbonates concentrations, as demonstrated in Porites (11). Adding calcium can be done through addition of calcium salts, commonly including $CaCl_2$, $Ca(OH)_2$, and $CaSO_4$. A calcium carbonate reactor can be used as well, but this boosts alkalinity and magnesium as well. If supplementing to increase a parameter and not just compensate for calcium usage, it is best increase the concentration slowly as rapid changes are detrimental to many systems - a proverb exists in the aquarium hobby stating that "nothing good happens fast in an ecosystem."

Magnesium

Magnesium is similar to calcium, in that it also exists in a +2 ionic state. Magnesium is another element determined to be vital to living processes. When discussing the care of a photosynthetic organism, it is worth mentioning that magnesium is utilized in chlorophyll, which is required for chloroplast function (some bacterial photosynthesis does not involve chlorophyll). While some magnesium is deposited into the coral's skeleton, the sink on magnesium by coral skeletal growth is minimal as calcium is used in much greater quantities (12), while magnesium is much more abundant (5). The essential nature of magnesium levels in the aquarium come from its importance in the inorganic chemistry occurring in the water. The high levels of magnesium suppress the abiotic precipitation of calcium carbonate and prevent calcium and carbonate concentrations from dropping too low for successful coral growth (12).

The typical ocean water value for magnesium is 1280ppm, with reef aquaria usually being kept at a minimum of 1200ppm (5). It is often recommended to maintain artificially elevated levels of magnesium within the range of 1300-1400ppm as it assists in preventing precipitation of supersaturated calcium carbonate on pumps and heaters - simultaneously depriving corals of those ions and disrupting the function of aquarium equipment. Magnesium uptake by calcifying organisms may or may not be enough to cause detectable changes in the aquarium concentrations, depending on their growth rate, stocking density, and the size and frequency of water changes done which would serve to bolster magnesium levels. Addition of magnesium can be done with magnesium salts, most commonly $MgCl_2$ and $MgSO_4$. Magnesium should not be raised rapidly, and a maximum change of 100ppm per day is often cited (and this is best done over the course of the day, not in a single dose) (12).

Carbonates

Inorganic carbon exists in a complex axis of equilibrium in typical water. The majority of carbonates exist as bicarbonate (HCO_3^-) in the reef at any given time, but is in dynamic equilibrium with carbonate (CO_3^{2-}) and carbonic acid (H_2CO_3). Carbonic acid is in dynamic equilibrium with CO_2 as it carbonic acid decomposes to CO_2 and water, and CO_2 and water react to form carbonic acid (ChemO). Dissolved CO_2 is optimally in equilibrium with atmospheric CO_2, but may not be if aeration is insufficient and the rate of diffusion across with water's surface is insufficient (13). Because CO2 is ideally constant, only carbonate, bicarbonate, and carbonic acid need to be considered - theoretically knowing one concentration and the pH would allow you to calculate the others, but most tests report all three together as carbonate alkalinity. Carbonates have 2 main uses in the reef environment. They are a vital source of inorganic carbon used in photosynthesis by corals' symbiotic zooxanthellae, though some carbon dioxide may also be absorbed (14). Alternatively, carbonates are used in the formation of coral skeletal structure through biotic precipitation of aragonite, in this reaction carbonate alkalinity is believed to be the limiting reactant as bicarbonate addition resulted in increased growth rates for *Porites* (11).

Ocean water has an alkalinity of 7dKh (which is equal to 2.5meq/L) (5). As carbonates are the limiting reactant in coral mineral matrix production, 7dKh is the minimum that would be recommended for most aquaria aiming at growing corals. Artificially high alkalinity levels would be expected to potentially offer benefits to coral photosynthesis rates, but this was not found to be the case in *Acropora* (15), suggesting that something other than inorganic carbon abundance limits photosynthesis under normal conditions. It is rarely recommended for aquarists to exceed an alkalinity of 12 dKh, as carbonates can become harmful at very high levels, and an increase in alkalinity is often accompanied by changes in pH which may be unfavorable. Many anecdotal cases seem to show that alkalinity may be the most dangerous parameter to alter rapidly for corals, with downward swings considered more harmful than upward swings of the same magnitude; with alkalinity swings blamed for numerous massive tissue necrosis events. It is worth noting that the stress of a parameter being altered could be a function of the magnitude of the change, the direction of the change, and the speed of the change, with alkalinity also have effects on other parameters such as pH - making testing difficult. On the range of 7dKh to 12dKh it would probably be advisable to attempt keeping it around 10dKh, as it is difficult to keep higher alkalinity levels stable due to the increase rate of abiotic precipitation that would occur as carbonate concentrations increase.

Nitrate

Nitrate (NO_3^-) is a -1 anion as is produced as a result of microbiological metabolism. Nitrifying bacteria in oxic environments remove ammonia and ammonium (in equilibrium in an aqueous environment) and oxidize it first to nitrite (NO_2^-) and then to nitrate as a means of fueling their energy metabolism. Nitrite and ammonium should not be present in detectable quantities in healthy established aquaria. Nitrate is exported from the environment by bioassimilation into protein and nucleic acid (providing the nitrogen group) done by microbes and algae primarily, and through conversion into molecular nitrogen (N_2) by denitrifying bacteria as a result of their anaerobic respiratory metabolism. Nitrate is used as a terminal electron acceptor in the absence of oxygen, producing molecular nitrogen which is inert and insoluble, which then escapes into the atmosphere. Nitrate levels in the ocean virtually 0 (5), below the lower detection limit of the test kits used by hobbyists and therefore can effectively be considered as 0 for the purposes of aquarium husbandry. It is worth noting that a dissolve nitrate concentration that low does not mean there is no nitrate available, but rather that nitrate is immediately used up as soon as it becomes available. Nitrate is considered toxic to corals and has been shown to slow growth directly (16). It also leads to increased algal growth as it is often a limiting nutrient along with phosphate in most aquaria - the algae can then smother the coral if its growth is fast enough (17). However, as biomass density is much higher in aquaria than in the ocean, it is very difficult to both keep down inorganic nitrogen concentrations, and feed the inhabitants with enough frequency and quantity for nitrogen to be undetectable, and some nitrate in the aquarium does seem acceptable. Inhibition of growth in corals was not found at concentrations up to 5 micromolar total nitrogen (18) - or 0.31ppm, though both ammonia and nitrate were used, not exclusively nitrate. Generally aquaria run successfully at 5ppm and below, depending on the types of corals to be kept.

Phosphate

Phosphate in the ocean exists in equilibrium between various protonation states. The most abundant is HPO_4^{2-}, but PO_4 (3) and $H_2PO_4^-$ are present, and too a minute degree H_3PO_4. Phosphate is the main source of inorganic phosphorus on the reef environment, but is found in extremely low concentrations, measured at ppb (5), far lower than the lower detection limit of normally used test kits for aquaria. Phosphates do inhibit precipitation of aragonite, by competing with carbonate for calcium ions but by being below the saturation point, and limiting the available sites for the crystal lattice to grow (5). This effect exerts on both abiotic precipitation, as increased phosphate concentrations slow coral growth (8). Inorganic phosphorus availability is a major limit to the growth of many phototrophs on the reef, and increased phosphorus is linked to algal outcompetition of corals and the change of coral-heavy ecosystems to algal lawns (19).

Phosphorus is recommended to be kept at levels below 0.04ppm for most corals. At levels higher than that, a rapid change in coloration will occur as the corals turn brown from the overpopulation of zooxanthellae in their tissues due to the increased levels (20) - while this affect is only present when inorganic nitrogen is available, this is the usual case in our aquariums; the study cited used an ammonium and phosphate concentrations of 20micromolar. While coloration and growth rate are not always closely linked, color alone is a major contributor in the popularity of a coral, and "browning out" is perceived as a sign of improper parameters making the coral more difficult to sell. Increased phosphate load is linked to coral death in the wild, both directly, and from increased algal competition and increased sedimentation (due to the sediment trapping capacity of algal tissues) (19).

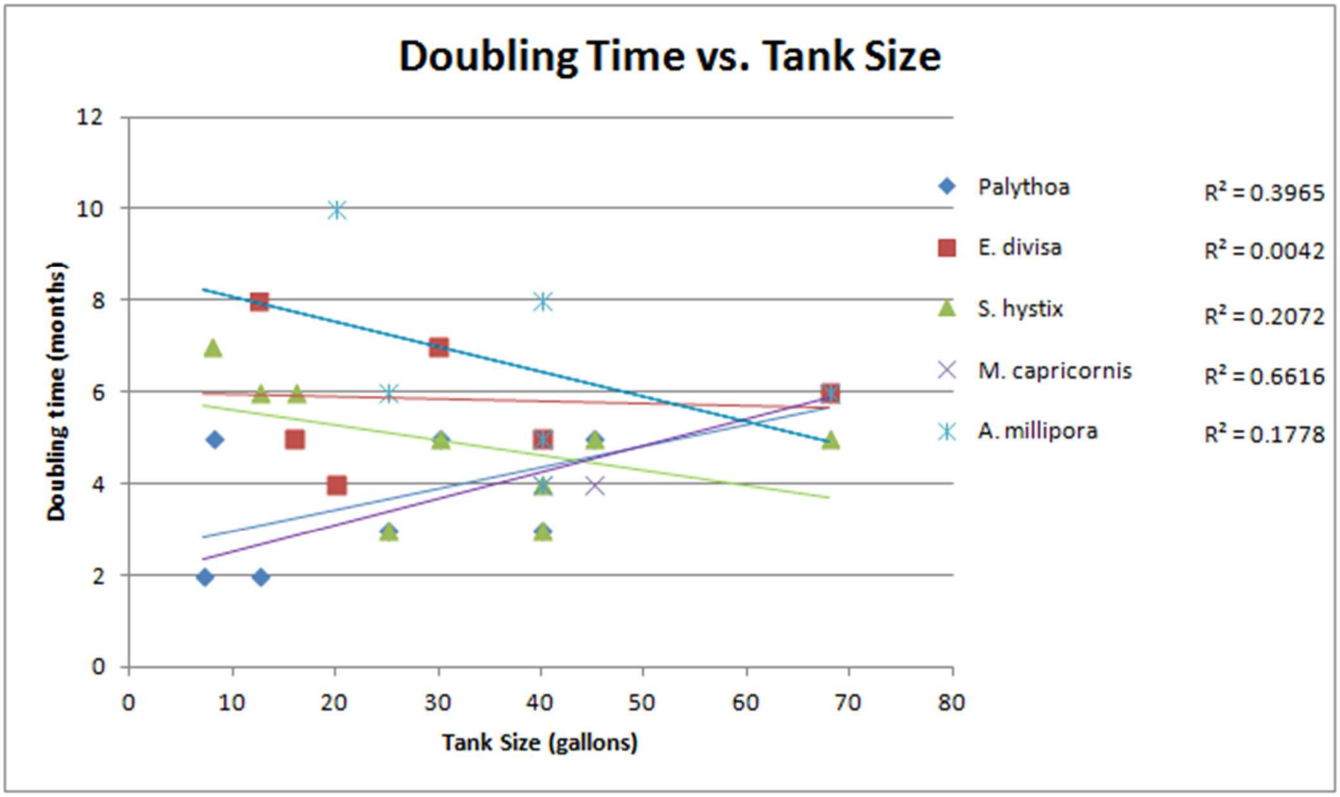
Community Action: Crowdsourced Data Collection on Coral Growth in Aquaria

Online aquarium journals were analyzed to observe the doubling times of small corals (frags or mini-colonies). Corals were selected based on their ability to be identified to the species level (with the exception of Palythoa), abundance, and representation of the 3 categories they are commonly divided into in the aquarium hobby - small polyped stony (SPS), large polyped stony (LPS), and soft coral (it is worth noting that the differentiation of stony corals by polyp size is not significant phylogenically). The aquariums used were from online published parameters and pictures with dates from primarily NanoReef.com, as well several other similar hobbyist forum websites such as ReefCentral.com. Tank parameters reported in journals were taken when available on concentrations of calcium, alkalinity, magnesium, nitrate, phosphate, and protons (pH), as well as temperature and aquarium size (total size, including volumes of aquarium and sump, not just total water volume, or total display tank volume). Images in the journal were examined against the date they were posted to see the coral's growth; when the corals approximate volume doubled, the time between the start and end photo was recorded in months and used a measure of growth rate. If the coral had been damaged or fragged in that period, it was discounted. SPS corals used were *Acropora millipora*, *Seriatopora hystix*, and *Montipora capricornis*, LPS corals were represented by *Euphyllia divisa*, and soft corals by genus Palythoa. SPS corals are disproportionately represented due to the ability to view their size simply, without worrying about variations in their polyp expansion, as is the case with LPS and soft corals. The doubling times were plotted versus the aquarium size, temperature, acidity, and concentrations for calcium, magnesium, carbonates, nitrate, and phosphates. Plots will be analyzed for statistical significance. Values and growth rates will not be used for times where there was a change in conditions reported that falls outside of the normal variations for the aquarium (ex. a change in salt used). Small corals were used as indicators of growth as they grow at faster rates as a proportion of current size than larger corals due to different energy allocations (8). So large colonies are not suitable for comparison to frags, and frags are more abundant in aquaria than mature colonies.

The data was analyzed with a simple linear regression. Not enough data points were collected to use an exponential curve (an "S" curve would be more indicative of the true growth rates) - an exponential curve would be able to fit the data very well regardless of how well the X and Y values correlate, obscuring the goodness of fit, measured as R^2. The results of the comparisons should show what offers the best likelihood of optimal growth rate in aquaria (for example, increased pH past a certain point offers no benefit to corals in literature, but would stabilize pH and could improve health through increased stability of a small, less stable, hobbyist aquarium). It shows trends toward increases or decreases, not the marginal benefits of increase or decrease from a point. The analysis was not meant to determine the best set of parameters for coral growth. No control group was set, and variation between groups is very large (differences in dosing frequency, water change size and frequency, and other factors were not controlled for at all). The results merely compare the levels of growth at various parameters to show the likelihood of utility from altering a particular parameter.

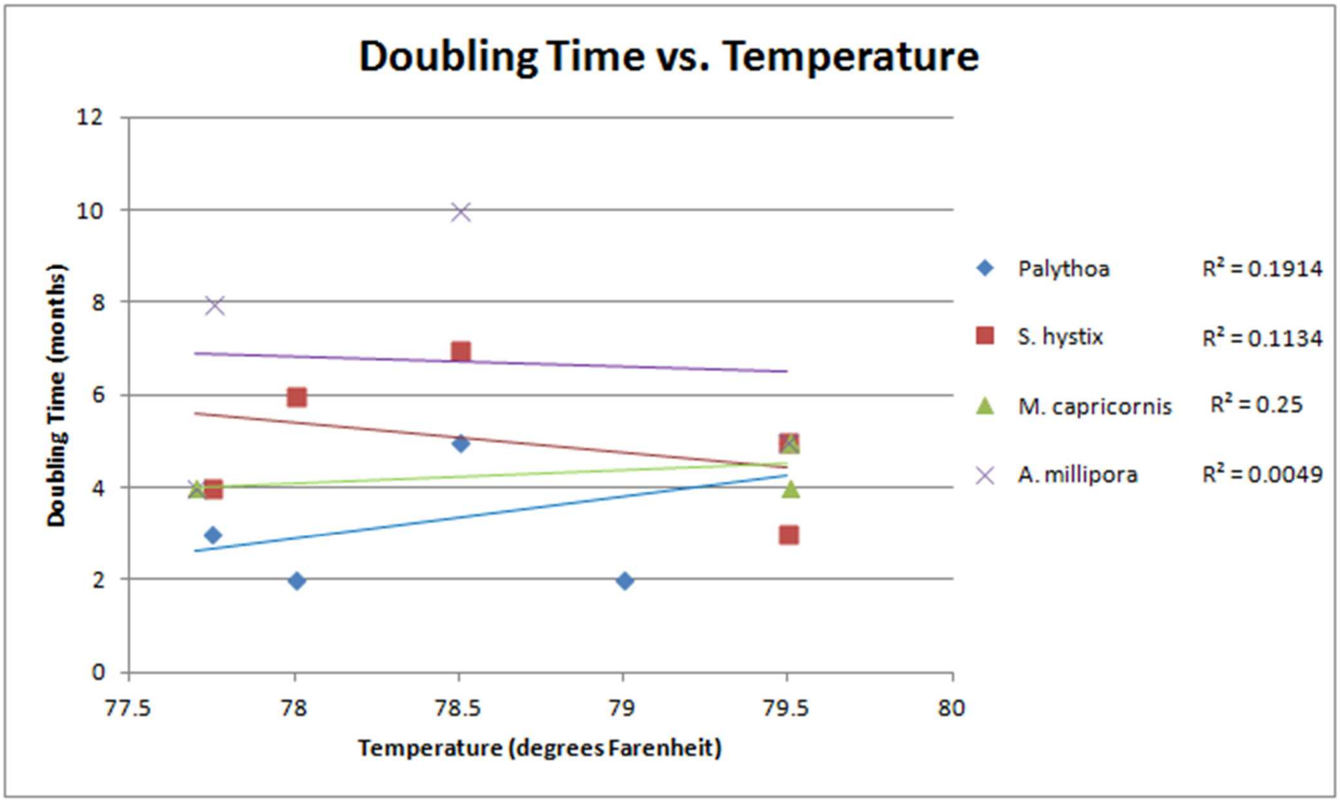
Graphical Results of Growth

Tank Size:



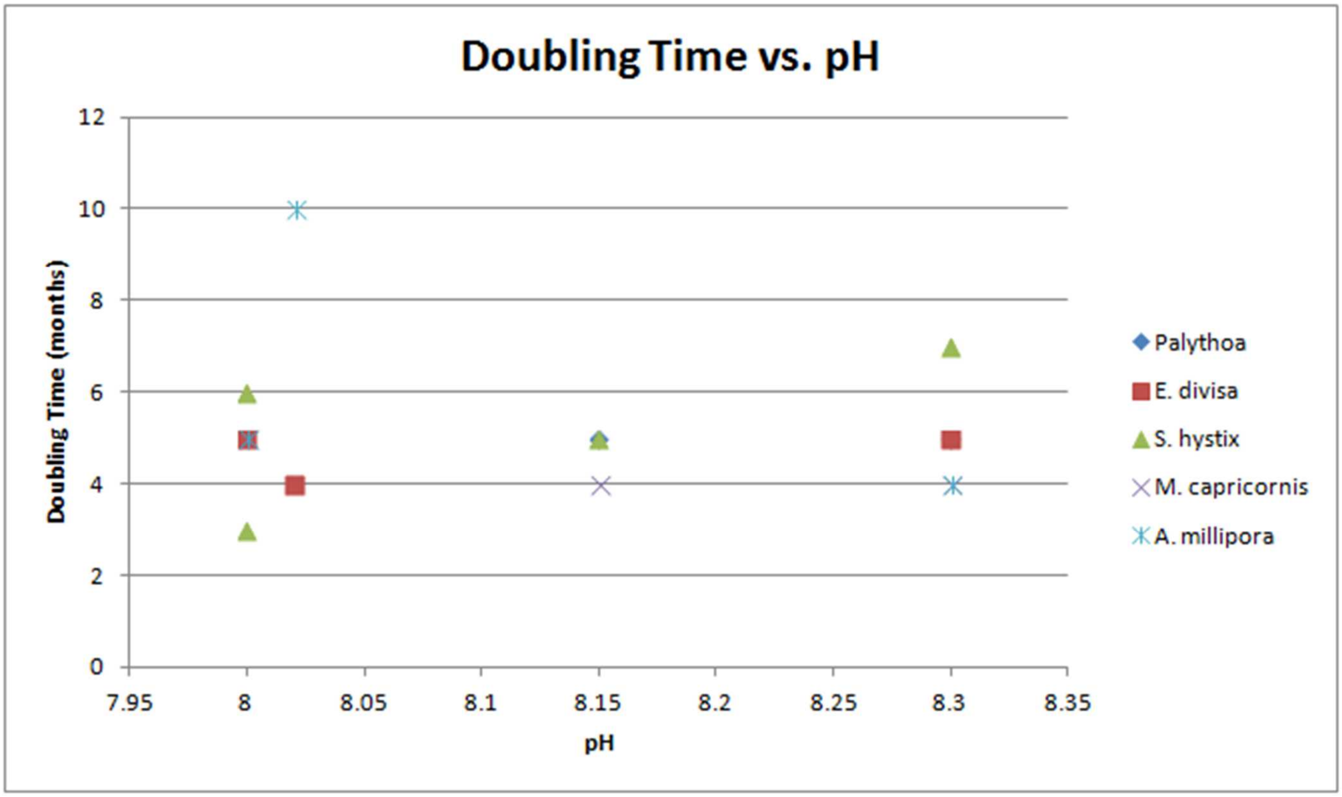
Only minor increases in growth rates resulted from increased tank size 3 of the species examined, suggesting that small aquariums can be kept at a sufficient stability for healthy coral growth. Palythoa species and *M. capricornis* experienced a decreased growth rate as tank size increased, I offer the hypothesis that larger tanks had decreased organic and inorganic nutrient loads, which these species prefer slightly elevated compared to some other corals such as *A. millipora*.

Temperature:



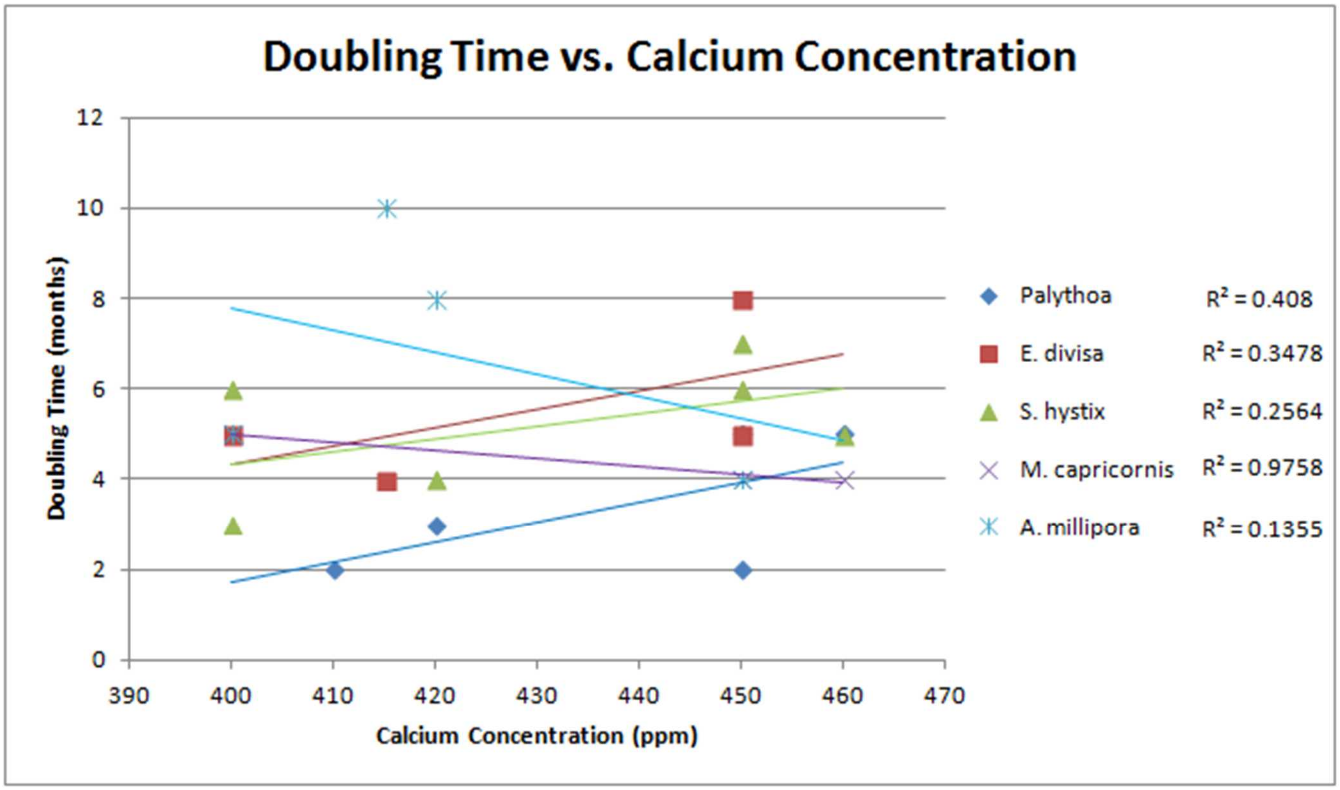
Temperature effects were very minor; and inconsistent across species, which is expected as different species prefer different temperatures correlating with their home range (4).

pH:



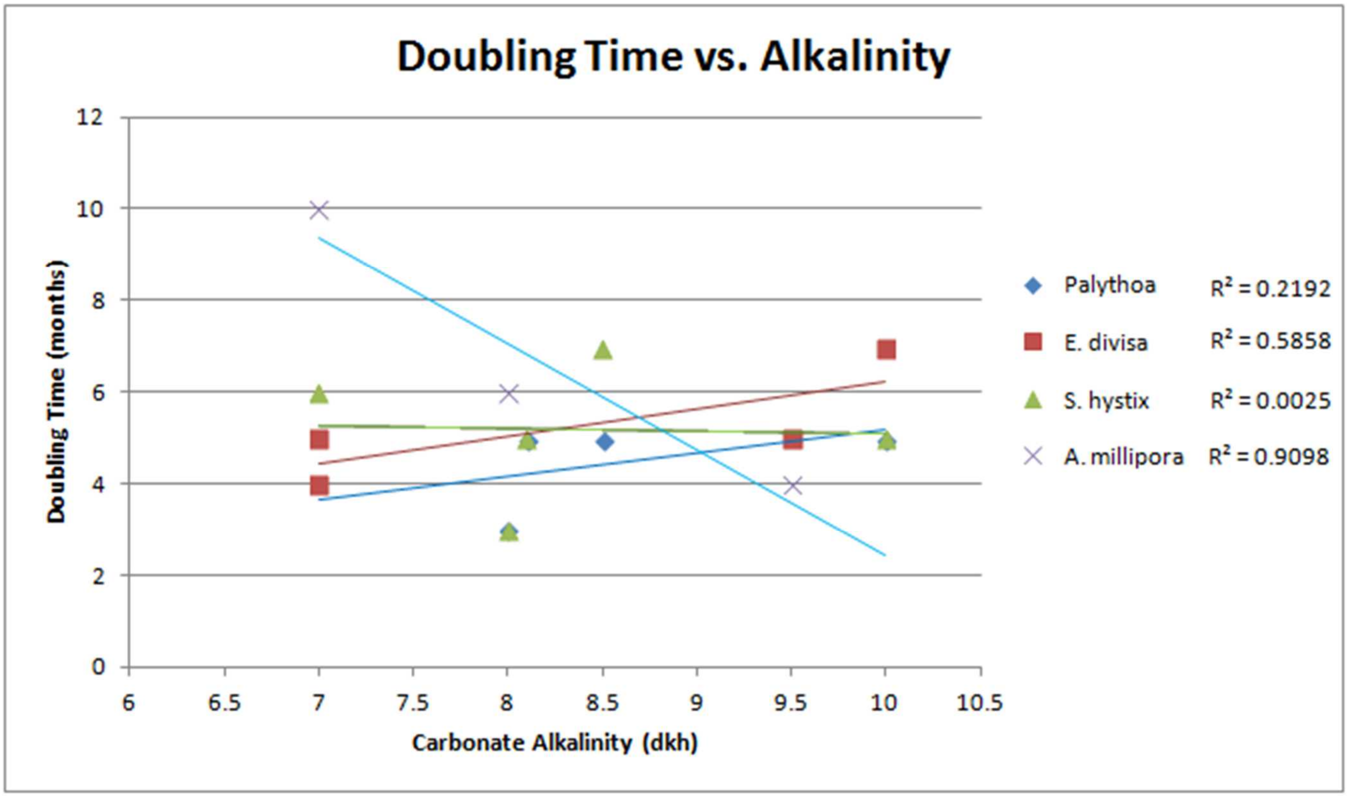
No effect was seen from pH, although ranges found were constrained within accepted literature values for healthy growth.

Calcium:



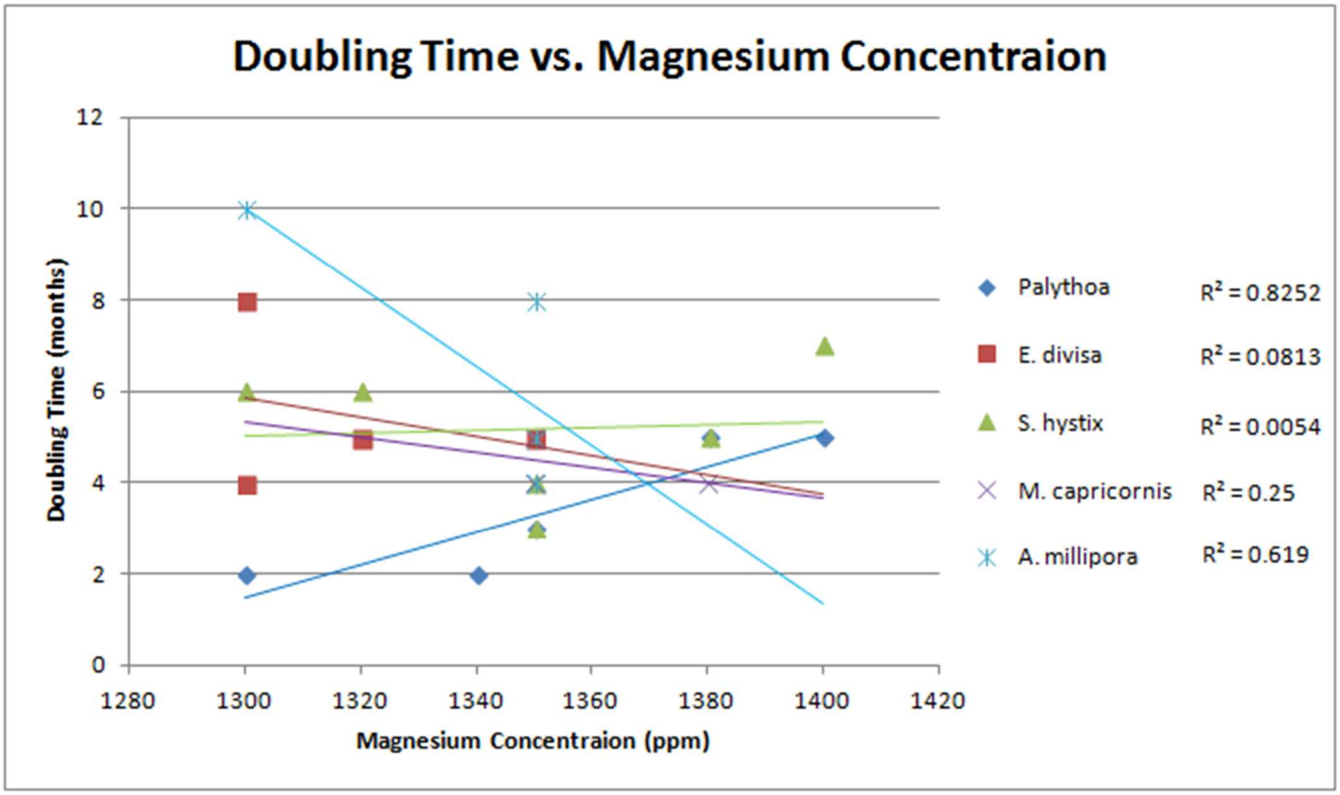
Changes in growth rate were inconsistent between stony corals examined. *A. millipora* benefited slightly but only by a statistically insignificant amount and *M. capricornis* growth rates benefited significantly, but minorly. *E. divisa* and *S. hystix* growth trended toward slower with increased calcium, but insignificantly. Palythoa showed slowed growth with increased calcium, with the offered hypothesis that the high calcium tanks were otherwise tailored toward stony coral husbandry, and Palythoas were added as extras.

Alkalinity:



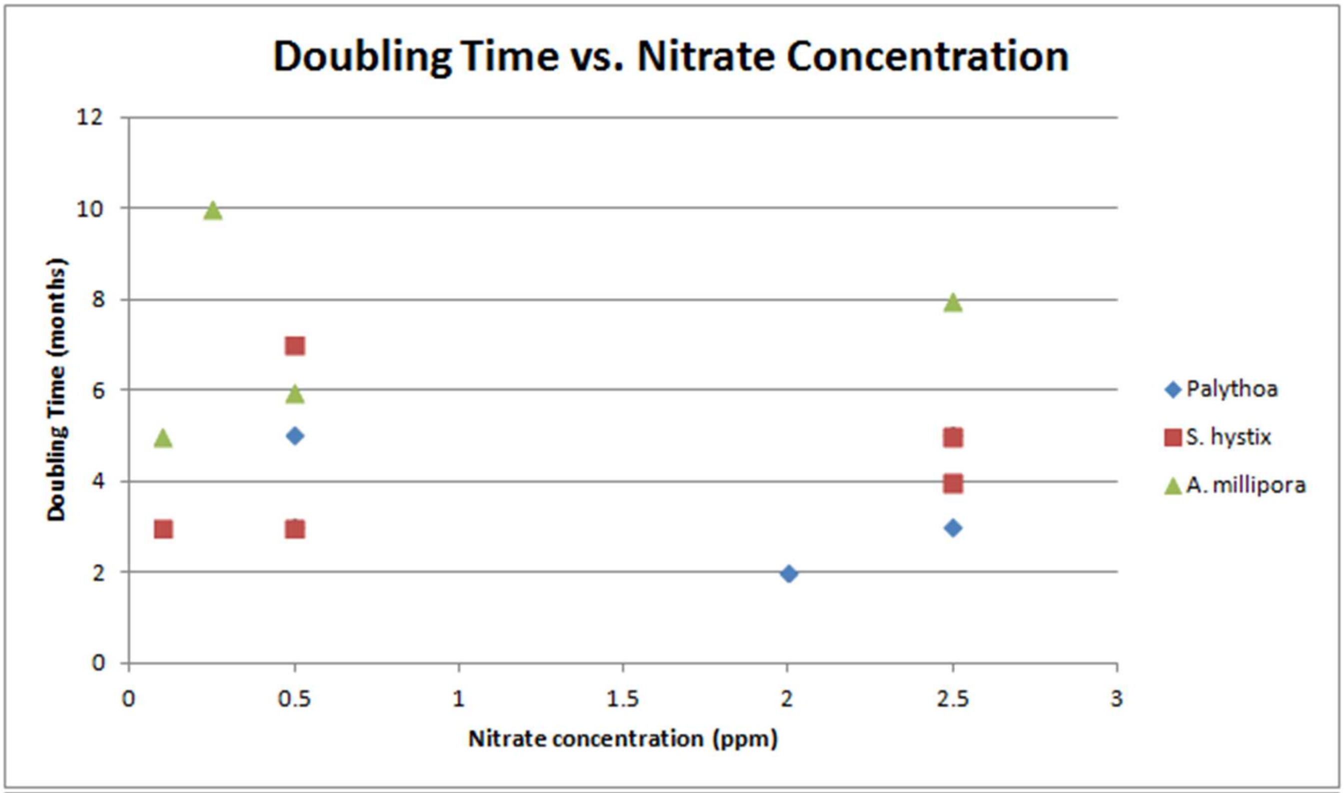
All effects were minor and/or insignificant, except for *A. millipora* which benefited greatly from increased alkalinity, and showed a statistically significant correlation.

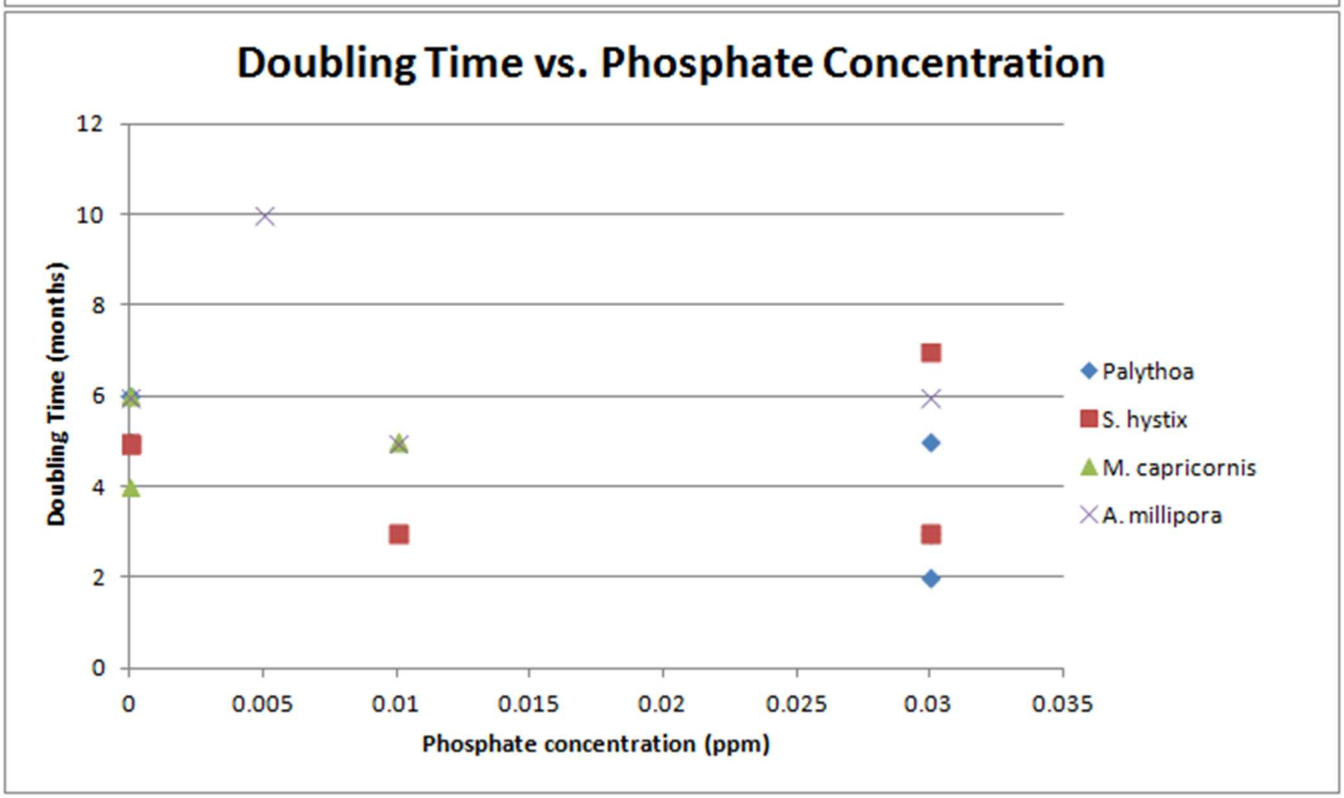
Magnesium:



Most corals showed no large nor significant effect from magnesium. *A. millipora* growth increased with increased magnesium, but to a statistically insignificant degree. The elevated magnesium likely served to make carbonates more available, affecting growth that way. Palythoa growth rates slowed significantly and strongly as magnesium levels increased, with the offered hypothesis that the high magnesium tanks were otherwise tailored toward stony corals.

Nitrate and Phosphate:





Nitrate and phosphate had no discernable effect on growth. However, all aquaria examined had low nitrates and low phosphates, with levels below the literature ranges often cited for causing growth inhibition.

Discussion

Interestingly, tank size correlated poorly with growth rate which was the opposite of what was expected. Larger tanks tend to anecdotally boast greater stability, which is important to coral health. That trend was not present to a large degree. Perhaps size once was vital to stability, but modern aquarium technology is seemingly able to stabilize even tiny pico aquariums' parameters. The use of automatic top-offs, redundant temperature controls, and peristaltic dosing pumps which can dose fractions of a milliliter multiple times a day, all serve to create very stable aquariums. Seemingly, this has overcome to a large degree the pitfalls of a small water volume to coral health.

In most aspects, reef aquaria were very similar. Lack of variation in parameters made analysis unlikely to yield useful results. This was the case with nitrate and phosphate, both of which were kept very low - presumably below a toxicity threshold, as no effect of their concentration on coral growth was found. Temperature variation was around 2 degrees Fahrenheit, less than found in some wild reefs - making it unsurprising that no effect was seen. Variation in pH was present, but minor; with all values falling within natural ranges. The only coral that was affected majorly by any parameter was *A. millipora*, adding some credence to the claims made by hobbyists that Acroporas are the most finicky of corals and shut down growth for small issues. Better results for other species may have been achieved with more data points, but data collection proved difficult as it was both time consuming and required several views to examine its accuracy. A more controlled study with the corals' growth rates examined as mass gained per unit time where frags are weighed would likely provide a tight-fitting "S" curve to allow hobbyists to better plan their aquarium values.

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Letter to the Tropical Fish Hobbyist Magazine

Letter posted to TFH Magazine online forums in the Q&A section where they ask for submissions to the "letters to the editor" section to be posted en lieu of emailing: http://forums.tfhmagazine.com/viewforum.php?f=126&sid=f4b01c27e0f79c1cb3e1a87242103450

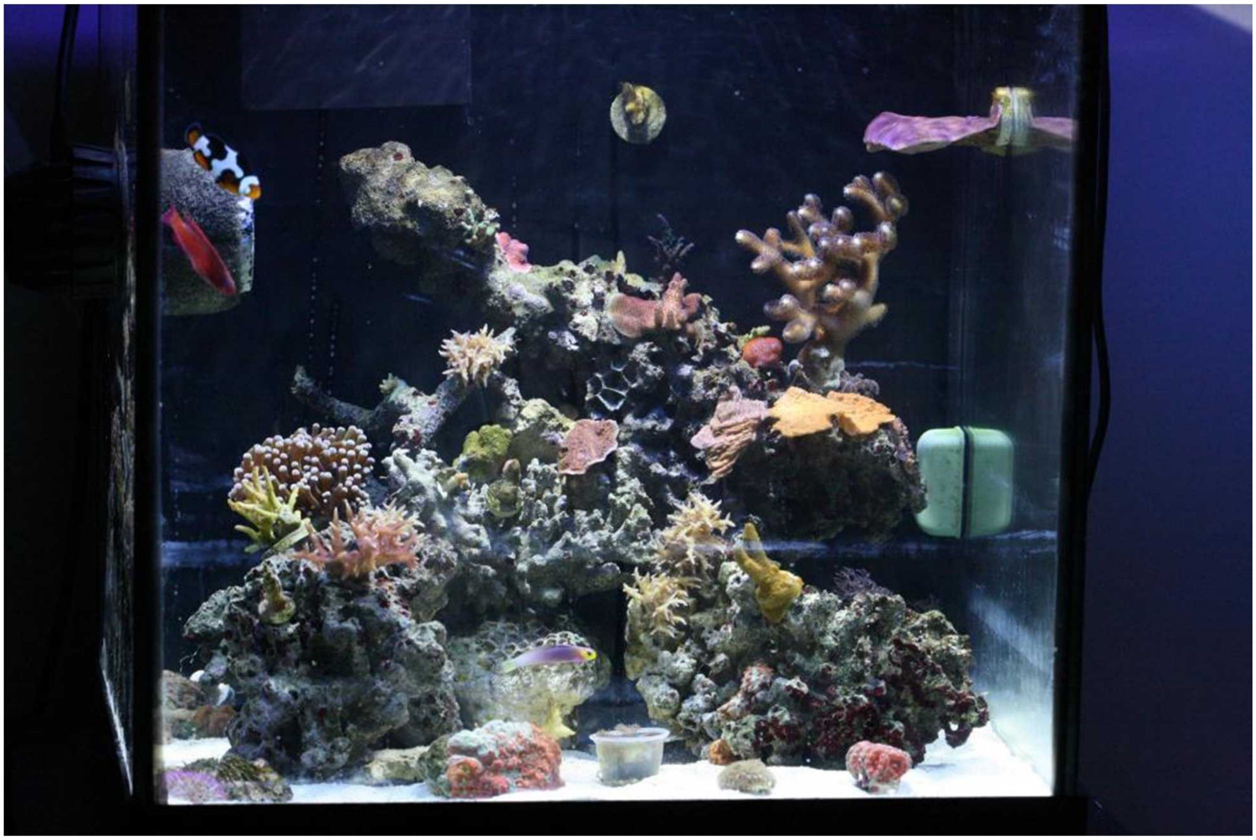
During the past few months, as part of a college class, I have been studying coral growth in captivity, and the factors that influence it. I jumped at the opportunity as I have been keeping a reef aquarium for years, and am always looking for ways to get more out of my corals. Currently many easily testable ions are kept at elevated levels under the hypothesis that growth is increased as result, and large tanks are promoted as being more stable and offering better growth.

I see many hobbyist aquariums kept with calcium levels that exceed 500ppm, as opposed to the natural level of 420ppm; magnesium sometimes kept in excess of 1500ppm, vs. the natural 1300ppm. However, most experimental data done on coral growth does not support increased levels of any mineral nutrient as statistically significant on increased growth, except for carbonates. Carbonates were shown to be the limiting factor in both photosynthesis and mineral matrix (skeleton) formation.

I became curious about how the parameters kept in various aquariums related to the success of their corals. I pulled water parameter data from journals kept of reefcentral.com and nanoreef.com and examined the images in the thread to estimate the doubling times of frags of several corals I could confidently identify to a species level. I used *Acropora millipora*, *Monitpora capricornis*, *Seriatopora hystix*, *Euphyllia divisa*, and genus *Palythoa* (I could not distinguish them to species, but included them due to their popularity and to have a soft coral included in the analysis). The doubling times were plotted against various factors, and linear regression of growth vs. various parameters did not show calcium, pH, temperature, and tank size as having any consistent nor statistically significant effects on growth rates in the coral species. The interesting point here is that it contradicted the anecdote that smaller tanks are less likely to be successful due to increased variability in the parameters and difficulty keeping such a small system stable. I offer the explanation that with increased use of automatic top-offs, nano-sized skimmers, peristaltic dosing pumps, and sensitive controlling equipment (for example heaters and chillers controlled not just by their own thermostats but by an external temperature probe and controller computer for redundancy and increased sensitivity), small aquariums can be kept just as stable as large ones without much issue - at least within the margin of error acceptable to captive cnidarians. Alkalinity (carbonate) and magnesium concentrations did have visible effects on increased growth rate. This was expected for alkalinity, as the literature states as much. For magnesium it was unexpected and supports the hobbyist tendency to keep elevated magnesium levels. I suspect it is because the increased magnesium allowed for higher, more stable carbonate levels, and only increased growth indirectly.

I wanted to share with your readers and my fellow hobbyists my video https://youtu.be/ae7VbnRPjhc which will soon contain the link to the original paper containing the data for the observations above.

Marko Drazenovic



My 30 gallon SPS dominant nano display tank.