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Coral growth: buoyant weight technique

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INTRODUCTION

This technique involves weighing the living coral while it is suspended in a buoyant medium of sea water. The authors have found this to be an attractive technique for the measurement of coral skeletal growth for the following reasons:

1. The technique is a direct physical measurement of aragonite. It is insensitive to factors such as the amount of water contained in the porous skeleton, amount of tissue and mucus present and biomass of commensal organisms on and within the skeleton.
2. Specimens are not removed from the water or damaged in any way by the procedure, allowing repeated growth determinations on the same specimen.
3. Sensitivity of the method can be refined to detect changes in mass over short time intervals (as little as 12 hours).
4. The method is inexpensive, rapid and easy to use; applicable to laboratory and remote field situations alike; and suitable for any size or shape of coral.

Although this technique has been applied to the measurement of coral skeletal growth by the authors of this paper (Franzisket, 1964; Maragos, 1972; Jokiel and Coles, in the press) and by Bak (1973), it has not been widely used, probably due to the difficulty involved in understanding and accounting for the major assumptions involved. Therefore in the following discussion we present: the theory behind the method, an empirical test of the theoretical relationship, various applications of the method, and comparisons with the classic weighing and geometric techniques commonly employed as indices of coral growth.

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BUOYANT WEIGHT METHOD

Derivation of theoretical model

It follows from Archimedes' Principle that the weight of an object in air is equal to the object's weight in a liquid medium plus the weight of the liquid displaced by the object. This principle allows objects to be weighed while they are submerged, including *in situ* weight determination for corals. Considering only the aragonite skeleton, a simple testable relationship between its buoyant weight and dry weight can be derived.

The following definitions will be used:

D_w = density of the buoyant fluid used in weighing (sea water).
D_a = density of the skeletal material (aragonite).
W_a = total dry weight of skeletal material (aragonite).
W_w = measured buoyant weight of specimen
V_a = volume of skeletal material (aragonite) in specimen
= volume of liquid (sea water) displaced by aragonite.

Archimedes' Principle can be rearranged in the from of the following equation:

$$W_a = W_w + (V_a \cdot D_w) \tag{1}$$

where $V_a \cdot D_w$ is equal to the weight of the liquid (sea water) displaced. Since $V_a = W_a \cdot D_a^{-1}$, substituting for V_a in equation (1) yields:

$$W_a = W_w + (D_w \cdot W_a \cdot D_a^{-1}) \tag{2}$$

or

$$W_a = \frac{W_w}{1 - (D_w \cdot D_a^{-1})} \tag{3}$$

Substituting the density of aragonite (D_a = 2.93 g/cc) and an approximate value for sea water (D_w = 1.03) into equation (3) yields:

$$W_w = W_a(1 - 1.03/2.93) \tag{2}$$

$$W_w = 0.649 W_a$$

$$\boxed{W_a = 1.54 W_w}$$

The density of sea water can vary considerably with changes in salinity and temperature. Therefore, accurate density measurements must be made on the water used in the buoyant weight determinations.

It is apparent from equation (3) that as the density of the object being weighed (D_a) approaches the density of the buoyant medium (D_w), the buoyant weight will approach zero, and the object becomes neutrally buoyant. Coral tissue and mucus, being composed largely of water, will have a density that is very close to that of sea water. Therefore the method is insensitive to tissue,

mucus, and water located in skeletal voids, but is quite sensitive to skeletal aragonite, which has a density of almost three times that of sea water.

Four basic testable assumptions are involved in using this method:

(1) The skeletal material of coral (dry weight of clean skeleton) consists entirely of aragonite. This is a safe assumption since the composition of coral skeletal material (*Pocillopora damicornis*) has been determined by Wainwright (1963) to consist of 99.9 per cent aragonite.

(2) The buoyant weight contributed by cryptic fauna which consists largely of neutrally buoyant tissue does not affect the buoyant weight of the coral skeleton. This assumption will not be equally important for all coral taxa. For example, the solitary coral *Fungia* offers no places of concealment for cryptic macro-organisms. Specimens of most colonial corals can be found that are relatively free of habitable crevices. Large highly branched corals, on the other hand, often contain an assemblage of associated crabs and shrimps which cannot be removed without damage to the coral.

In order to test the second assumption a large tightly branched *Montipora* fragment containing many cryptic organisms was weighed using the buoyant weighing method. The cryptic macrofauna were then removed by carefully breaking apart the coral head. Twenty-two ophiuroids, three polychaetes, one alpheid shrimp, one stomatopod, and one small hermit crab in a *Trochus* shell were removed from the specimen. The combined weight of the cryptic macro-fauna accounted for only 0.16 per cent (0.30 g) of the gross buoyant weight (196.8 g) of the whole specimen.

(3) Voids and spaces within the porous skeletal material are filled with liquid of the same density of the buoyant medium. This assumption can introduce errors if air bubbles are allowed to form on the underside of the coral during periods when the water is supersaturated with air.

(4) The densities of both living coral tissue and mucus are of the same density as sea water. This assumption is reasonable since mucus and tissue removed from coral skeletons can be observed to be nearly neutrally buoyant in sea water, although eventually this material will settle out.

Empirical test of model; comparison with other classic measurement techniques

The relationship between buoyant weight, dry skeletal weight, and various other classic growth parameters was established empirically on three dissimilar species of scleractinian corals representing three different families. *Fungia scutaria* Lamarck was chosen because of its dense skeleton, massive shape, and fleshy organic parts. *Pocillopora damicornis* (Linnaeus) was selected as a representative branching form. *Montipora verrucosa* (Lamarck) is typical of species with highly perforate skeletons.

The following data were recorded for each of 31 corals (three species): buoyant weight, wet weight, width (mean of four measurements), and height. Displacement (mean of three measurements) was determined by measuring the

overflow from a container full of sea water when the specimen was slowly lowered into the water on a string. The apparatus used in the buoyant weighing is described later in this paper. Afterwards each specimen was thoroughly cleaned, dried for several days at 90°C and weighed.

Correlation coefficients between the measurement of dry skeletal weight and each of the other measurements were calculated for each species (see Table 1).

TABLE 1. Dry weight (y) as a function of various other measurements (x) and percentage variance explained ($100\ r^2$).

Species	*P..damicornis*	*M. verrucosa*	*F. scutaria*
Number of specimens	12	9	10
Buoyant wt (g)	$y = 1.56x–0.42$ $100\ r^2 = 100$	$y = 1.55x–0.42$ $100\ r^2 = 100$	$y = 1.55x–0.12$ $100\ r^2 = 100$
Wet wt (g)	$y = 0.739x–4.24$ $100\ r^2 = 99.6$	$y = 0.591x–9.94$ $100\ r^2 = 99.3$	$y = 0.850x–10.76$ $100\ r^2 = 99.8$
Displacement (cc, mean of 3 measurements)	$y = 1.49x–1.28$ $100\ r^2 = 98.3$	$y = 0.943x–3.41$ $100\ r^2 = 98.8$	$y = 1.77x–2.65$ $100\ r^2 = 99.2$
Width (mm, mean of 4 measurements)	$y = 4.48x–248.36$ $100\ r^2 = 94.6$	$y = 4.54x–261.48$ $100\ r^2 = 88.2$	$y = 3.61x–186.53$ $100\ r^2 = 81.7$
Height (mm)	$y = 4.01x–139.35$ $100\ r^2 = 77.9$	$y = 3.89x–193.12$ $100\ r^2 = 78.2$	$y = 10.77x–133.84$ $100\ r^2 = 36.0$

The results demonstrate the validity of the assumptions used in the buoyant weighing technique as well as the accuracy of the method. A perfect correlation ($r^2 = 1.000$) existed between buoyant weight and dry skeletal weight. The derived slopes (1.55–1.56) are within 1–2 per cent of the value predicted by the model. Much of this difference can be attributed to the slight negative buoyancy of organic material on and within the skeleton. The y-intercept is nearly zero, as predicted.

It is apparent that the buoyant weight measurements showed the highest correlation with dry skeletal weight. The other methods based on weight or volume showed good correlations, while the linear measurement methods were the poorest indexes of dry skeletal weight (Table 1). Since a great deal of variation existed between successive determinations of displacement and width the correlations would be much lower if based on single measurements as was done for buoyant weight, wet weight and height rather than means of 3–4 measures. This analysis supports the belief of previous workers that changes in linear dimensions, volume, and wet weight correlate well with changes in skeletal weight. Also, the analysis shows that the slope and intercepts can be empirically derived for each of the various species, and that much diverse data existent in the literature can eventually be expressed in the common denominator of skeletal weight change.

The authors conclude that the buoyant weight method is a superior measurement technique because of, (a) a high correlation with dry skeletal weight, (b) the slope and x-intercepts of the regression line are nearly the same for all species, (c) the relationship between dry weight and buoyant weight can be determined with a high degree of accuracy from the theoretical model or can be established empirically, and (d) repeated measurements can be made on the same specimen.

Applications

The authors have used this method in a variety of experimental situations involving field and laboratory growth measurements of both long- and short-term duration. Selection of the proper weighing device and associated apparatus for a given experiment will depend upon a number of factors including degree of accuracy required, size range of corals to be studied, cost, portability, availability and time allowable per weight determination. Selection of the proper weighing technique should be considered to be an integral part of the experimental design, and the individual investigator must test the accuracy and reproducibility of measurements made with his apparatus. The three examples that follow were chosen as a guide to demonstrate weighing configurations and experimental procedures in a variety of sensitivities, and to demonstrate how several aspects of coral skeletal growth can be investigated using this technique.

Analytic balance method

Sensitivity 0.1–1.0 mg

Specimen size $\sim$10 grams buoyant weight

Weighing interval 12 hours

This variation was employed by L. Franzisket on the 1957/1958 Xarifa Expedition to the Maldive Islands, and represents the ultimate in the refinement of its sensitivity (0.1 mg). The basic configuration involves an analytic balance and beaker (see Fig. 1). The analytic balance requires a very stable platform and still air. Since the density of the water must be measured to as many significant figures as weight in air (see equation (1)) we must measure to five significant figures. Salinity and temperature of the water can be accurately measured and the density calculated using standard hydrographic tables. Sea-water hydrometers accurate to five significant figures are available and provide a faster and more direct measure. A monofilament (non absorbent) line to support the coral eliminates the error caused by wetting of the line. A similar technique has been used to measure daily oyster growth (Havinga, 1928).

During the period of 23 February 1958 to 20 March 1958, specimens of the corals *Fungia scutaria* Lamarck and *Porites maledivium tertium* (Bernard) were maintained on the reef at Ras-Du Atoll, being brought into the laboratory at 12-hour intervals (day/night) for weighing to the nearest 0.1 mg. These data (unpublished) are presented in Figure 2 and demonstrate the reproducibility of

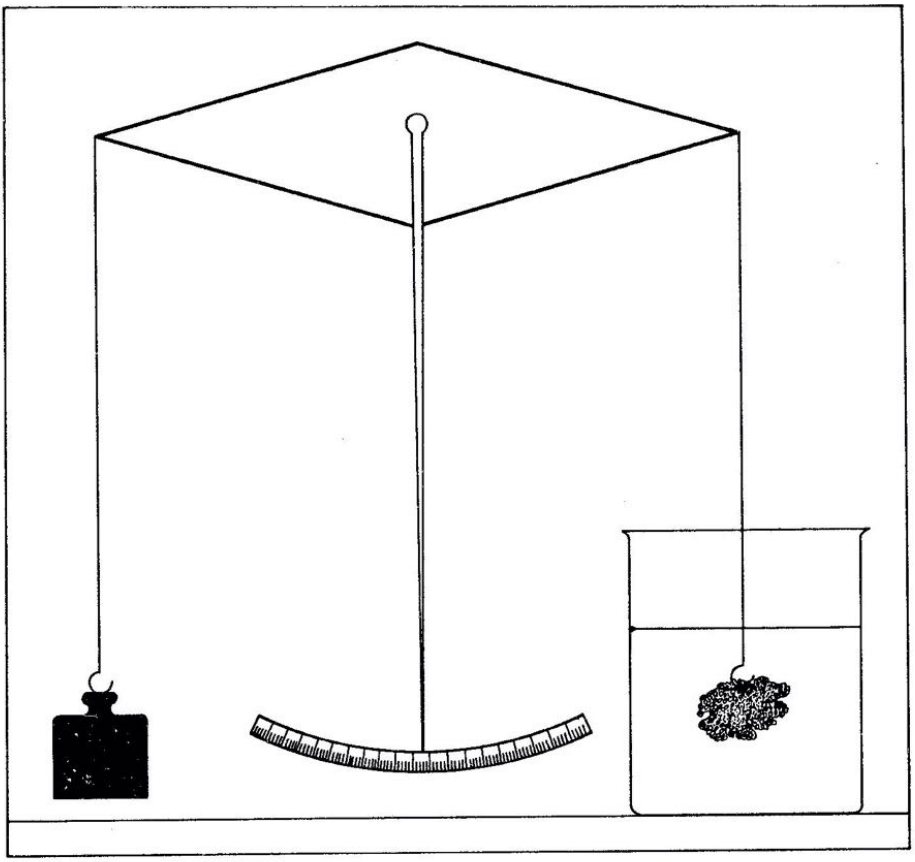

Figure 1
Schematic drawing of apparatus used in analytical balance method.

the results. The method was sensitive enough to detect differences between day and night incremental growths. The observed diurnal rhythm in calcification probably can be attributed to light, which is known to accelerate calcification in hermatypic corals (Goreau, 1959; Goreau and Goreau, 1959).

During a nine-day interval within the 25-day period (break in abscissa on Fig. 2) the ship visited another atoll and no measurements could be made. This event provided some interesting data. Table 2 compares daily growth increases over the 17-day period of frequent weighings with the daily growth increase during the 8-day period when the coral was undisturbed. It is apparent that coral growth was much slower during the period of frequent handling. This implies that manipulation of the experimental specimen which is often necessary during short-term measurements might yield calcification rate values that are lower than those occurring in nature.

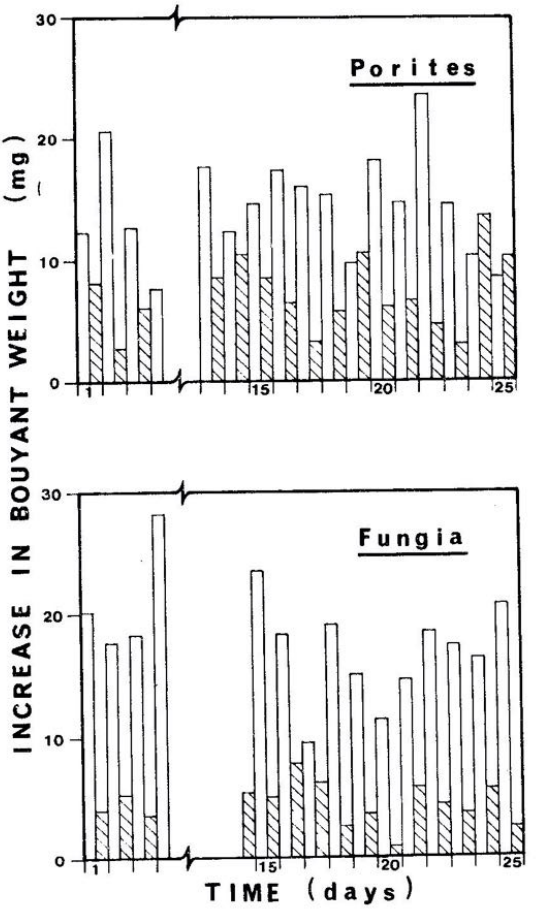

Figure 2
Growth data taken at twelve-hour intervals with apparatus shown in Figure 1 Unshaded bars represent daylight growth increments: shaded bars night growth increments.

TABLE 2. Comparison of growth during periods of daily weighing and period of no weighing.

	Porites	*Fungia*
Initial buoyant wt (gm)	7.1391	8.7003
Final buoyant wt (gm)	7.7440	9.2996
Days	25	25
Daily increase (mg/day) entire 25-day period	24.2	23.0
Daily increase (mg/day) for 17-day period of twice daily weighings	22.2	22.8
Daily increase (mg/day) for 8-day period of no weighings	30.0	29.2

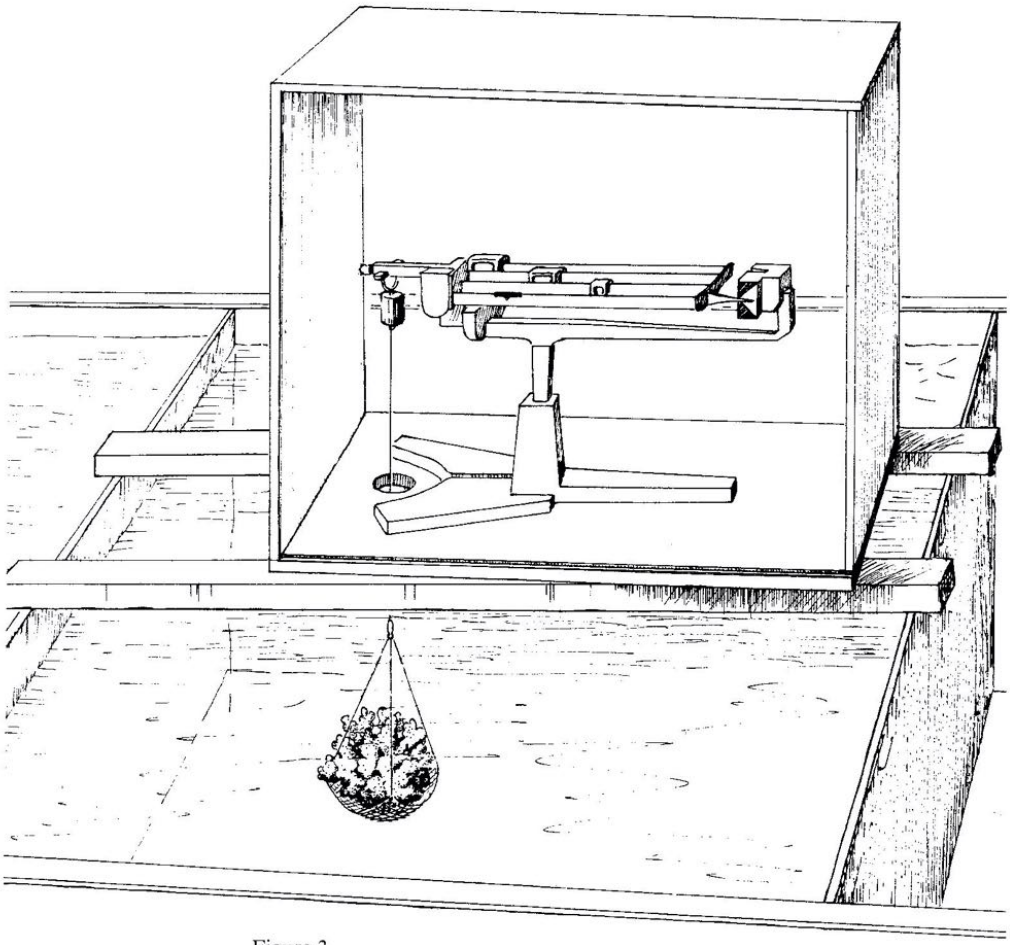

Figure 3
Apparatus used in utility balance method.

Utility balance method (*triple beam or platform balance*)
Sensitivity 0.01–0.50 g
Specimen size ~10–1000 g buoyant wt.
Weighing interval 30 days.

In this method two orders of magnitude in accuracy over the previously described method have been sacrificed in order to gain the advantages of lowered cost, reduced time involved in weighing, and use of larger corals. Water density needs to be known only to three significant figures, in normal sea water 1.03. Utility triple beam or pan balances are available with an accuracy of from 0.01 to 0.3 grams at only several per cent of the cost of analytic balances. These units are much less prone to damage, an important consideration in remote locations where quick repair or replacement is not feasible. Because of

the lower sensitivity the weighing interval was increased from 12 hours to at least several weeks in order to obtain a growth increment that is large in comparison with the absolute weighing error.

A typical laboratory configuration is presented in Figure 3. An inexpensive triple beam or torsion balance enclosed in a protective plywood case with sliding plastic door is shown supported over an experimental tank containing growing corals. The weighing pan has been replaced with counterweights and a weighing basket formed from plastic mesh and supported with plastic monofilament line. In the case of platform balances, the weighing basket can be suspended directly from a hook on the bottom of the pan support. Once the device is balanced, a coral can be gently moved into the weighing pan, weighed and replaced in the tank in a matter of one to two minutes. A Mettler-type balance which increases accuracy and speeds the process considerably, has been used in the buoyant weighing of oysters (Andrews, 1961).

An example of the use of such configuration is the study of the effect of initial size on percentage increase in skeletal weight in the coral *Fungia scutaria*. The increase in buoyant weight of 54 specimens of this species ranging from 1 gm to 190 gm buoyant weight was measured over a 30-day growth period. Percentage increase has been plotted against initial buoyant weight in Figure 4 (P. Jokiel, unpublished data). A clear effect of initial size on this growth parameter is apparent. This provides a warning to the investigator planning to design a growth experiment. Coral growth is size dependent if measured by a percentage increase method, even in highly symmetrical forms such as *Fungia*.

A great deal of additional scatter in growth data is encountered with the

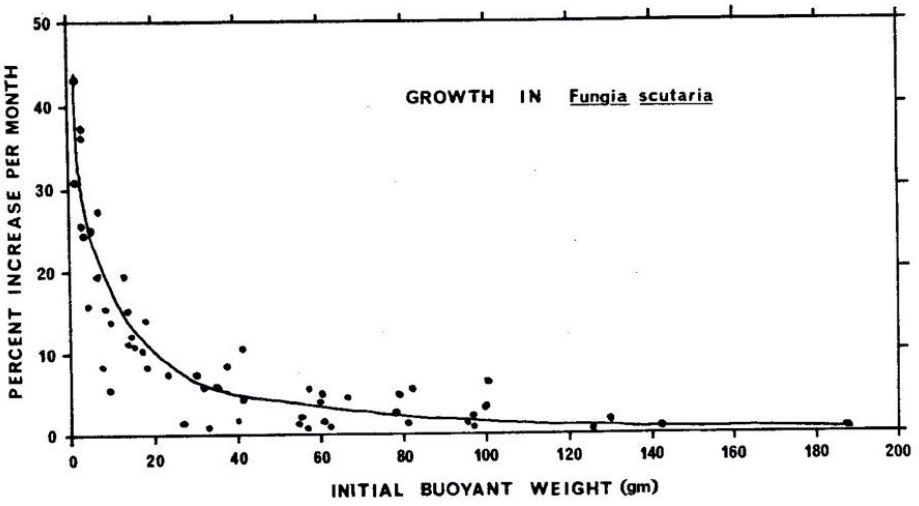

Figure 4
Per cent increase in skeletal weight for the solitary coral *Fungia scutaria* plotted against initial weight, data taken using apparatus shown in Figure 3.

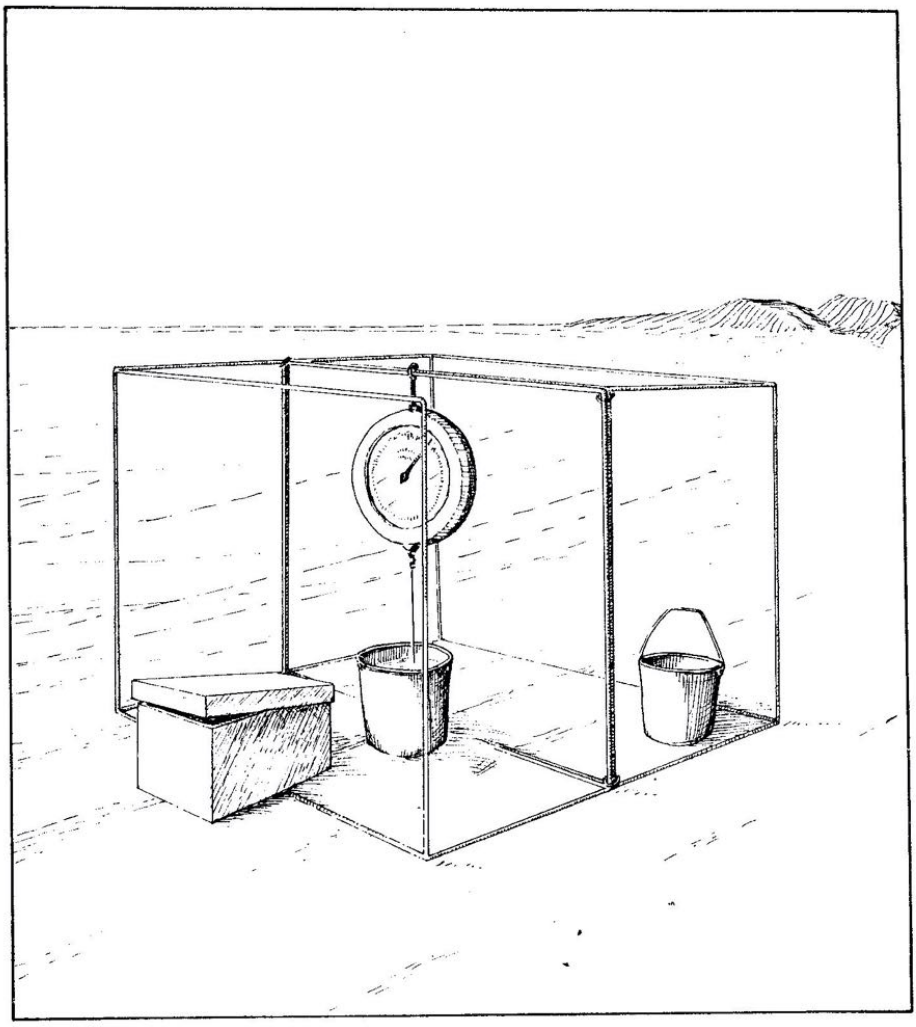

Figure 5
Weighing apparatus used in field method.

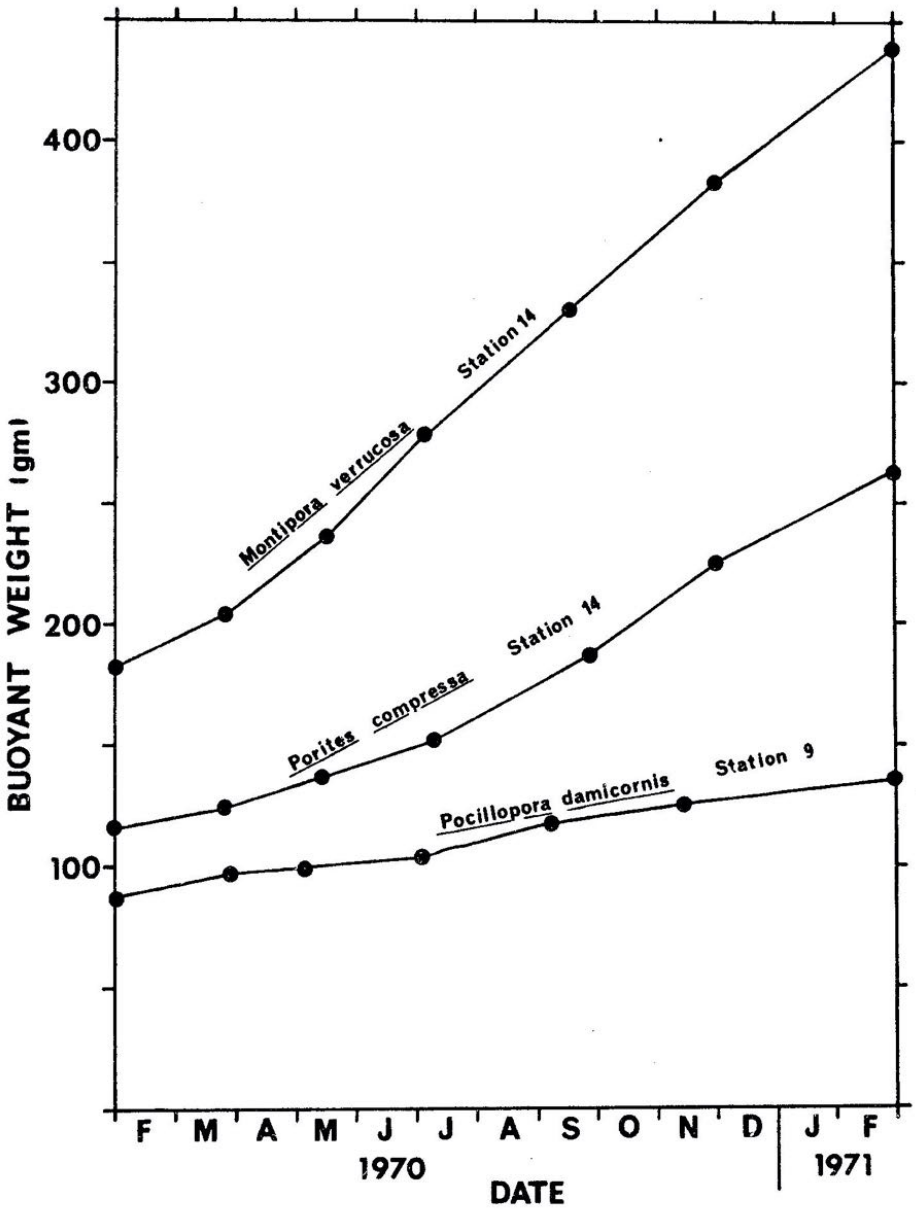

Figure 6
Sample growth data on three specimens (Maragos, 1972 and unpublished) taken with apparatus shown in Fig. 5.

use of complex asymmetrical forms such as *Montipora*. This scatter is not a measurement error but rather a basic characteristic of some species and can make comparison of growth between treatments quite difficult.

Field method

Sensitivity 1–2 g
Specimen size 1–5 kg buoyant weight
Weighing interval 1 month to 1 year

Use of a portable weighing device and associated apparatus allows buoyant weight measurements to be carried out on the reef. Maragos (1972) transported a spring balance to reef areas by small skiff. The spring scale was a Chatillon 6.8 kg capacity temperature compensated device having a precision and accuracy of ± 1.5 grams. The spring scale was suspended across a metal frame set up on a shallow patchreef or flat portion of the beach above sea level (Fig. 5). Corals were removed from their growing places and placed in buckets. The buckets with corals submerged in sea water were quickly transported to shore and placed under the scale and weighed while submerged. After weighing, the corals were promptly returned to their original locations. Data taken by this method is presented in Figure 6. It is unlikely that corals larger than 5 kg buoyant weight (>10 kg wet weight) can be transported to shore without damage. A device for measuring corals *in situ* on the reef has been described by Bak (1973). This device can be used to weigh quite large corals. Although less portable, this approach enables the investigator to avoid the necessity for transporting corals to shore and can be reduce handling of the corals and time spent in weighing. In studies involving measures of growth at depths greater than 10 m, Bak's technique is far more practical.

CONCLUSIONS

Buoyant weighing is a simple, inexpensive, flexible, and highly accurate technique for the determination of aragonite mass or mass increase in living corals. If the corals are not handled excessively, the method does not harm the coral in any way, allowing repeated measurements on the same specimen.

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