Collection of Marine Research Works, 2002, XII: 215-232

ON LONG-TERM MAINTENANCE AND CULTIVATION OF HERMATYPIC CORALS UNDER ARTIFICIAL CONDITIONS

E.A. Titlyanov[1], Vo Si Tuan[2], T.V. Titlyanova[1]
[1]Institute of Marine Biology, Far East Branch of Russian Academy of Sciences
[2]Institute of Oceanography (Nha Trang)

ABSTRACT Long term maintenance and cultivation of hermatypic corals have been newly practiced in the world for different purposes. Based on published researches and the experiences from studies and experiments, the papers introduced principles and methodic approaches to long-term maintenance and cultivation of corals under artificial conditions. Methods and aquaria structures for long-term maintenance and cultivation of corals are suggested. Results of experiments on study of physiological state of corals under change of environmental factors such as light intensity, ammonium concentration and food additions with zooplankton under continuous maintenance and cultivation in aquaria are also presented.

VEÀ VIEÄC NUOÂI GIÖÕ SAN HOÂ TAÏO RAÏN TRONG MOÂI TRÖÔØNG NHAÂN TAÏO

E. A. Titlyanov[1], Voõ Só Tuaán[2], T. V. Titlyanova[1]
[1]Vieän Sinh Hoïc Bieån, Chi Nhaùnh Vieãn Ñoâng Vieän Haøn Laâm Khoa Hoïc Nga
[2] Vieän Haûi Döông Hoïc (Nha Trang)

TOÙM TAÉT Nuoâi giöõ san hoâ trong ñieàu kieän nhaân taïo laø moät lónh vöïc coøn töông ñoái môùi meû treân theá giôùi vaø ñaõ ñöôïc tieán haønh theo caùc muïc ñích khaùc nhau nhö nghieân cöùu khoa hoïc, taïo taäp ñoaøn treû cho phuïc hoài heä sinh thaùi, phuïc vuï cho caùc aquarium, cung caáp san hoâ cho thöông maïi san hoâ soáng vaø baûo toàn ña daïng sinh hoïc. Döïa treân caùc taøi lieäu ñaõ coâng boá treân theá giôùi vaø nhöõng kinh nghieäm coù ñöôïc qua nghieân cöùu vaø thöû nghieäm, baøi bao moâ taû nhöõng nguyeân taéc lieân quan ñeán tính töï nhieân, choïn loaøi nuoâi giöõ, kieåm soaùt ñieàu kieän moâi tröôøng vaø caùc phöông phaùp tieáp caän trong kyõ thuaät nuoâi giöõ. Ñoái hoûi veà caùc nhaân toá moâi tröôøng trong ñieàu kieän nhaân taïo nhö aùnh saùng, nhieät ñoä, ñoä muoái, muoái dinh döôõng, löôïng traàm tích, cung caáp khí, thöùc aên cho san hoâ, neàn ñaùy vaø veà löïa choïn kích thöôùc san hoâ nuoâi giöõ cuõng ñöôïc thaûo luaän

I. INTRODUCTION

Attempts of long-term maintenance and cultivation of corals under artificial conditions have been undertaken in many laboratories of the world and especially in public aquaria, oceanaria and private aquaria (e.g. Stepanov, 1994; Carlson, 1999; Becker and Mueller, 2001; Titlyanov et al., 2001a). However, maintenance of corals under artificial conditions often led to a gradual dying of polyps and thereafter to death of entire colony due to known and unknown reasons. Growth and viability of corals under the entire artificial conditions are species-specific. Some coral species easily withstand transfer from natural to artificial conditions and acclimate to new conditions (e.g. fragments of the hermatypic coral Stylophora pistillata) (Titlyanov et al., 2000a, 2001a, b, c). Others do not adapt to such changes and die. The investigators have different methods of maintenance and cultivation of corals. Based on worldwide publications and personal experiences, we herein provide an overview on the issues concerning with maintenance and cultivation of corals in artificial conditions.

II. RESULTS

1. Purposes of continuous maintenance and cultivation of corals under artificial conditions

Aim 1: Cultivation of corals for scientific investigations:

Study of productional capacities, reproduction and other physiological indicators of some coral species and their assemblages were traditionally conducted under field conditions (e.g. Falkowski and Dubinsky, 1981; Titlyanov et al., 1981; Hoegh-Guldberg et al., 1997) or under laboratory conditions in short-term experiments on colony fragments taken from reefs (e.g. Leletkin et al., 1996; Nakano et al., 1997). However, not all physiological questions may be understood. For example, reacclimation of corals from one light regime to other takes some months (Titlyanov et al., 2001c, d) and the study on dynamics of the process needs constant factors and controlling changes in aquaria under the continuous maintenance. The same problems arise in experiments on re-acclimation of corals to changed seawater temperature, on the study of coral growth, reproduction and etc. Thus, scientific experiment is one of the main aims of continuous maintenance under artificial conditions. For this aim we need installations with many changed and controlled parameters, especially such as quantity and spectral composition of light, temperature, the rates of exchange and seawater flow, concentration of mineral nutrition, animal food and mineral sediments in the water. Installation of such aquaria is the most complicate task. However, hobbyists and some scientists have persevered and developed aquarium systems and techniques capable of maintaining corals in apparently healthy and controlled conditions for many years (Stepanov, 1994; Atkinson et al., 1995; Carlson, 1999).

Aim 2: Cultivation of planting stock of young colonies for rehabilitation of coral reef:

Catastrophic reduction in live coral coverage in coastal and barrier reefs, and biodiversity of coral reefs worldwide occurred during the last 20 years (ICLARM, 2000). Local changes depend mainly on anthropogenic action on coral reef (Connell, 1997). Human impacts composed of sediment stress due to construction of ports and other structures, deforestation, agriculture, discharge of toxic pollutants, damage from grounding and ship removal activities, underwater explosions, overfishing, eutrophication, use of corals for lime, damage of reef community by anchors and by the vessels hulls, sampling corals and mollusks for souvenirs and etc. (Counell, 1997; ICLARM, 2000; Bruckner and Bruckner, 2001). Negative changes on coral reefs occur by global warming causing bleaching and death of corals and also by hurricanes causing extensive damage to the reefs (Ware, 1997; ICLARM, 2001). Coral farming for reef rehabilitation and ecotourism development could model the way for a new approach to serve the people and the reefs (Heeger and Sotto, 2000). Rehabilitation is a relatively new science that soon may need to be applied on a larger scale to mitigate effects of local damage on coral reefs (Precht, 1998).

Current research is focusing on methods to enhance coral recruitment to maintain coral nurseries to rescue and rehabilitate fragments generated by physical disturbances for use as transplantants for degraded areas (Tunnicliffe, 1981; Bruckner and Bruckner, 2001). Recently, there are three main trends in restoration of coral reefs.

The first trend in restoration of coral reefs is carried out by stabilizing fragments of resident coral colonies directly at the sites of damage (Gittings et al., 1994; Backer and Mueller 1999; Jaap, 1999; Quirolo, 1999; Bruckner and Bruckner, 2001). Such works are more often conducted at sites where the coral reef was partially damaged by such events as dynamite blasting, hurricanes, and ship groundings, anchoring. In this case, enormous numbers of fragments are generated without permanently altering water quality. However, coral recruits, supplying recruits or fragmentation of donor colonies in the sites of damaged reef is difficult and depends on many circumstances. In nature, survival, attachment and continuous growth of coral fragments are limited by the substrate type where dislodged fragments land (Fong and Lirman, 1995; Bruckner and Bruckner, 2001). Fragments deposited in sand are at risk of being abraded or smothered and have no solid substrate for attachment. The timely, stabilization of fragments to the substrate could enhance coral survivorship and expedite the recovery process. Under different methods of fragments fixation to the substrate (stainless steel wire, portland cement or two-part marine epoxy) successful coral fusion to the substrate is from 10 to 40% (Lirman and Fong, 1997a, b; Bruckner & Bruckner, 2001). In nature, fragmented corals at damaged reef sites are affected by partial colony mortality due to various factors. Lirman and Fong (1997a, b) observed tissue loss in many (73%) of their tagged fragments. Bruckner and Bruckner (2001) observed tissue loss in surviving fragments of Acropora palmata on approximately half of their upper branch surfaces after 2 years. This investigation showed a higher rate of mortality among those fragments placed in contact with the invasive sponge Cliona spp. that was found commonly overgrowing elkhorn skeletons. Chronic partial mortality from natural stressors like white-band disease (WBD), predation, overgrowth by algae and other factors may be largely responsible for the inability of fragments to successfully fuse to their attachment sites that, unfortunately, led to detachment of fragments from the substrate and led to the coral's death (Bruckner and Bruckner, 2001).

The second trend for coral reef restoration is transplantation of fragmented donor colonies from healthy reef sites to degraded reef sites (Birkeland, 1977; Gittings et al., 1988; Clark and Edwards, 1995; Raymundo, 2001). The method may be applicable for restoration of degraded coral reefs with lowered diversity following changes in quality of water and substrate. Such changes occur as a result of pollution, sewage, oil, high concentrations of nutrients, soil runoff, coastal constructions, episodic fresh water flows, repeating bleaching events and etc. This method of coral reef rehabilitation is complicated by many problems. First of all, there are necessary thorough investigation of environmental conditions at the rehabilitation sites and at donor reef, study of species composition, coral distribution and their associated organisms if necessary. Study of the physiology of transplanted coral species in mono- and polyculture should be also implemented (Raymundo, 2001). Mass transplantation of coral fragments to degraded sites is more expensive than fixation of local fragments to the reef substrates on the original coral reef. The mass transplantation needs preliminary large-scale experiments.

The third trend of rehabilitation of coral reef is transplantation of young colonies growing under artificial conditions to the rehabilitation site. Little is known about planting young coral colonies from a single polyp, group of polyps or from planulae (e.g. Atkinson et al., 1995; Titlyanov et al., 2001a, d). Artificial cultivation of planting material for rehabilitation of coral reef may allow young, healthy colonies to fuse to substrates within 4-6 months with subsequent removal of the colonies to degraded reefs (Atkinson et al., 1995; Titlyanov et al., 2001a). Moreover, the experiment on elucidation of influence of new (changed) surrounding conditions on transplant and their competition between aboriginal corals could be conducted under artificial conditions in outdoor, indoor and semi-open aquaria.

Aim 3: Planting corals in public aquaria and oceanaria:

Many corals in oceanaria and home aquaria live for a short period. Aquarium staff or hobbyists need to replace dead corals by living ones taken from nature. Unfortunately, only painted skeletons of dead hermatypic corals (artificial coral reef) are demonstrated in some oceanaria (Stepanov, 1994). Demands of establishing living coral reefs in oceanaria are obvious. However, this task is more difficult compared with aquaria for scientific investigations and solution of the task is complicated at least by two circumstances:

- Needs of maintenance of large coral numbers in aquaria.
- Maintenance of corals with other marine inhabitants such as fish, mollusks, algae and other associated coral reef organisms in the same aquarium.

Aim 4: Planting corals for trade:

Problem of planting corals for production of souvenirs for tourists is arising in some tropical countries. This business faces difficulties because of reduction in coral stock or new legislation prohibiting coral sampling. Methods of coral planting for the trade could be developed in aquaria as in nature.

Cultivation of corals for trade under artificial conditions is a possible solution. However, slow growth of many coral species means that coral colonies reach the trade size only after 4 - 5 years of cultivation. In this connection, the method of the cultivation of corals for the trade must be simple and cheap. At present, projects on coral cultivation for trade are developed, but so far without estimation of their economic effectiveness.

Aim 5: Conservation of coral reef biodiversity under artificial conditions:

Over the last 20 years, repeating coral bleaching events have caused mass mortality of corals and their associated organisms (ICLARM, 2000). Extensive coral bleaching will continue because of continuous global warming in this century, as long - term predictions for the period to the year 2100 indicate that seawater temperature in the World Ocean will increase and average monthly temperature will increase to 31-32°C during hot seasons (Ware, 1997). Elevated seawater temperature disrupts a complicated and unstable interrelation between zooxanthellae and their coral host and can cause death of the symbiotic organism. In the future, it is difficult to predict if adaptation of corals to global warming will occur. The most negative predictions says that in the coming century corals, as symbiotic organisms, will die forever (Ware, 1997; Hoegh-Guldberg, 2000). In our opinion, an option is to do biodiversity conservation of coral reefs in the areas with low temperature in summer. The surveys in Vietnam (Vo Si Tuan, in print) showed good recovery of corals after bleaching event in 1998 at Cu Lao Cau Island. Decreased temperature during upwelling saved a lot of corals due to reducing the length of period of high temperature in the area. Following this direction, transplantation of uncommon or rare coral species to upwelling areas should be trialled. It is also thought that transplantation of corals to lower temperature regions of subtropical latitudes will be considered. Cultivation of corals under artificial conditions is useful for these experiments.

2. Main principles for maintaining and cultivation of corals under artificial conditions

Corals should be maintained under conditions close to natural conditions:

It is known that different corals can live in a wide range of variation in environmental conditions. The majority of coral species of the Indo-Pacific inhabit tropic and subtropical zones (Veron, 1986; Latypov and Dautova, 1998). In some areas of the Indo-Pacific coral reefs (for instance, reefs in the South China Sea), the most species of corals (to 80% of species) lives at wide light range from 90 to 10% of incident photosynthetically active radiation (PAR_0) or at depths ranging from 2 to 18 m (Titlyanov and Latypov, 1991). Such a wide habitat distribution of corals in the tropics and subtropics and depth distribution depend on high acclimative capabilities either genotypic and/or phenotypic of symbiotic organisms to environmental factors. The acclimative capabilities depend on a variety of feeding ways; various composition of different types of symbionts and hosts; acclimative features between symbionts and hosts (Sorokin, 1990; Muller-Parker and D'Elia, 1997; Titlyanov, 1999; Titlyanov and Titlyanova, 2002b).

Hobbyists or scientists knowing the principles of cultivation should not achieve the same conditions of nature in a given locality. It is necessary to maintain some average conditions of living coral reef on the main environmental abiotic and biotic factors including light, temperature, hydro-chemical water parameters, autotrophic and heterotrophic feeding to prevent corals from diseases, predators, competitors. Such conditions in aquaria and oceanaria allow the survival of corals with an average growth rate. If it is necessary (for instance, commercial farming corals for trade) it is possible to try to increase the growth rate of corals by changing parameters of medium (e.g. to elevate the level of heterotrophic feeding) (Witting and Sebens, in print).

Selection of appropriate species for different aim of cultivation:

To achieve success in long-term cultivation, species and methods should be rightly chosen for certain aim of the cultivation. For instance, under the long-term maintenance for study of the dynamics of acclimation to environ-mental factors, eurybiotic, widespread and mass species should be chosen. Such species are less conservative and it is most likely they have the greatest set of adaptive reactions and they more defended from an influence of unpleasant factors such as a temporary temperature rise or decline, a shortage of animal food and etc. (Titlyanov and Titlyanova, 2002b). It is important that coral species used in scientific experiments could be easily identified and could not be confused with other species. Moreover, planting objects could be "convenient" for fulfillment of the experiments on the study of growth, photosynthesis, respiration and other physiological parameters. In experimental samples, zooxanthellae could be easily and purely released (the condition for work with healthy zooxanthellae), surface of the coral living tissue must be flat (the best for calculation of the rates of physiological processes per surface unit of the coral colony). However, the world scientific experiences have some coral species convenient for ecophysiological experiments. First of all, it is Stylophora pistillata (Falkowski and Dubinsky, 1981; Titlyanov et al., 2001b), species of the genus Pocillopora (Titlyanov et al., 1988b; Patton et al., 1977), Seriatopora caliendrum (Bil' et al., 1992; Titlyanov et al., 2001d), species of the genus Montastrea (Porter, 1974; Dustan, 1979; Graus and Macintyre, 1982) and species of the genera Porites, Galaxea, Echinopora and the hydroid polyp Millepora (Titlyanov et al., 2001d).

Most often, coral branch fragments or individual polyps (e.g. corallites of Galaxea fascicularis) are used for investigation. Outer branches and pieces, evenly lighted and streamlined are broken off colonies. Branch tips (2 - 5 cm length) are used in experiments. It was shown on some coral species that smaller pieces of coral have better starting growth rates and less suffers from lesions (Becker and Mueller, 2001).

The only criteria in coral selection for planting for the souvenir trade are colonies with attractive appearance for buyers and faster growth (branching species). The objects for such planting are Stylophora pistillata (Loya, in print) or the fast growing species such as Acropora (Bruckner and Bruckner, 2001). Stony corals of the genera Euphyllia, Goniopora, Catalaphyllia, Trachyphyllia, Plerogyra and Pocillopora are also used for exhibition of coral reef in public aquaria and oceanaria. These corals are well suited to transfer, but they are slow growing (with the exception of Pocillopora). These coral species are annually exported by Indonesia and Fiji (more than 700 t and more than 1.5 million items) mostly for aquaria in United States (Bruckner and Daves, in print).

Coral farming for reef rehabilitation also needs selection of object. For instance, if the coral reef is degraded partly or completely and rehabilitation will be attempted on silted substrate or turbid water, selected corals should tolerate sediment rich environments. Corals such colonies as Porites spp. with good self-cleaning systems are often dominant in silt rich areas with poor water exchange. The fast-growing and/or more aggressive Galaxea, Goniopora, Acropora take advantage in favorable conditions (Dautova et al., 2000).

Degraded reef hardly may be recovered to its original state. That is why a selection of suitable coral species for rehabilitation depends on changed environmental conditions and on acclimation of these species to new conditions (Todd at al., in print). For example, it was shown that growth responses of some Acropora corals to elevated nutrients are different to those of other coral taxa. Colonies of the coral Acropora longicyathus well withstood elevated concentrations of ammonium and/or phosphate in experimental treatments. Linear extension was accelerated in phosphate treatments and depressed by elevated ammonium. Buoyant weight growth was accelerated by elevated ammonium on an annual basis, but significant reductions occurred in some seasons (Bucher and Harrison, in print)

For rehabilitation of degraded reefs by coral fragment transplantation, it is necessary to choose donor sites with high natural abundance of corals, and without damage by fishes and other predators. Donor colonies are without any signs of coral diseases such as well-known black-band disease (BBD), white-band disease (WBD), tissue bleaching (TBL), shut-down-reaction (SDR) (Antonius, in print)

Biological studies of cultured species:

It is not possible to maintain and culture coral species under artificial conditions without knowledge on their biology and physiology. However, these knowledges have been limited for many coral species. Aquarists or researchers should try the best to consider following questions before coral cultivation:

- What are possibilities of distribution of certain species? (Biogeographical zones and ecological niches, vertical distribution, light conditions, eutrophication, water turbidity).

- The main biological indicators: genetic diversity of cultivated colonies (species, types, clones), reproductive models, and frequency of spawning and release of planulae, main feeding features and kind of food.

- The main ecophysiological characteristics: the ranges of tolerance to light, temperature, salinity, adaptive capabilities to environmental factors, the main acclimative reactions and their dynamics; maximum and an average rates of photosynthesis, respiration and growth; light and temperature correlation of photosynthesis and growth. Rhythm of the main physiological processes: photosynthesis, growth, cell (zooxanthellae) division and their degradation. Competition among colonies of the same species and among various species. Mechanisms of interaction of certain species and their associated organisms: aggression, predation, grazing and susceptibility to diseases.

- The main characteristics of symbiotic interactions of animal polyp and algae-symbionts in coral: genotypic symbiont composition, normal, minimum and maximum densities of zooxanthellae in polyp tissue, distribution of zooxanthellae in the polyp tissue. These issues have been mentioned in some publications (e.g. Sorokin, 1990; Muller-Parker and D'Elia, 1997; Titlyanov et al., 1999...).

Control of the physiological state of corals and environmental factors during their maintenance:

Under maintenance of corals in aquaria, control should be conducted to check their physiological state as visually as by consecutive measurements. It is necessary to notice in time sickly state of corals and to prevent coral mortality by changing the environmental factors or by medication. Visual tests for normal physiological state of corals are extension of tentacles and active predation (hunting) of polyps at night and early morning hours, tentacles and polyps are retracted by touch with hand, equally colored living tissue (from yellowish to dark-brown) excepting growing tips, no fouling organisms or predators.

The test measures of normal physiological state of corals are measurement of the rates of photosynthesis, dark respiration, growth, reparation, zooxanthellae division, the ratio of proliferating zooxanthellae frequency (PZF) to degrading zooxanthellae frequency (DZF) (Titlyanov et al., 1996). At the beginning of coral planting (initial state) and during maintenance, analyses should be conducted to measure some hydrochemical and hydrobiological characteristics of seawater: salinity dissolved organic substances (DOS), nitrogen, phosphorus, sediments, quality and composition of zoo- and phytoplankton.

3. Methodical approaches to long-term maintenance and cultivation of hermatypic corals

The approaches described in this paper are mainly based on own experience on study and cultivation of hermatypic corals (Titlyanov and Latypov, 1991; Vo and Hodson, 1997; Vo Si Tuan, in print; Titlyanov et al., 2001a, b, c, d) and also on some literature data (Atkinson et al., 1995; Carlson, 1999; Osinga et al., 1999; Reynaud-Vaganay et al., 1999; Becker and Mueller, 2001).

The most natural and simple method of continuous maintenance and cultivation is planting corals under natural light conditions, seawater with natural autotrophic and heterotrophic feeding of corals (Fig. 1). This approach allows cultivation of corals in outdoor aquaria with light intensity close to nature from 90 to 10% PAR_0 with running seawater pumped from the adjacent fringing reef (e.g. Atkinson et al., 1995; Titlyanov et al., 2001d). Aquaria are supplied with seawater without filtration or settling. Zooplankton, organic remnants and nutrition in the aquaria were the same as the reef. The main criterion in such method is healthy coral reefs. The turnover rate required for sufficient animal feeding is approximately 30% h^{-1}. Compulsory water-cooling is needed during hot period (approximately 2°C lower compared to the surface seawater temperature). Necessary cleaning of aquaria, substrates for coral fragments and basal parts of the fragments from sediments and algal fouling at least with week interval are also needed.

This methodic approach to coral planting is more suitable for scientific aims to study physiology of corals under conditions close to nature; for mass cultivation of coral colonies; for coral farming of rehabilitation of damaged coral reef; and for trade.

The second methodic approach is based on purification of seawater and artificial food provisioning with zooplankton (Fig. 2). Seawater is derived from any adjacent sites and cleaned by filtration or settling and then pumped into aquaria. In daytime the seawater drains with the turnover rate about 10% h^{-1}. At night and early morning the seawater flow is not necessary. Food supply is needed at nighttime. The necessary terms of such method are:

- Absence of toxic or inhibitory substances in flowing seawater;
- Appropriate sizes and quality of animal food supplied for corals;
- Corals should be fed, in accordance with natural rhythms.

The third methodic approach of maintenance and cultivation of corals is suitable for sites without adjacent healthy coral reef and effective for the study of coral feeding, starving, influence of extreme environmental factors and also for farming corals of rehabilitation of coral reef. This approach assumes the maintenance and cultivation of corals in closed-system aquaria with maximum number of controlling and regulating parameters (Fig. 3). The conditions required for coral cultivation are smaller variability of all parameters of medium with fast and easy regulation of each of them; daily change of seawater in the closed-system aquaria or cleaning system of particles of animal food and dissolved proteins using biofilters (Stepanov, 1994; Titlyanov et al., 2001d); or protein skimmers (Atkinson et al., 1995). Seawater in the aquaria should be intensively aerated. Two-closed system recirculating aquaria were used at the Waikiki Aquarium, Honolulu, Hawaii. One of them had a big protein skimmer (70-cm high), the other had a small protein skimmer and a 2-liter trickle-filter with bioballs, gravel and activated charcoal. As show by maintenance of hermatypic corals (fifty-seven species) from the Pacific Ocean, the corals grew (the growth rates were near the upper rates reported from the field) in all three tested systems: outdoors tanks, indoor tanks and the two closed-system aquaria (Atkinson et al., 1995).

The approach is rational in scientific investigations on study of action of biotic and abiotic environmental factors on physiological state of corals. The method is suitable for closed public oceanaria and room aquaria (Stepanov, 1994) and also for fulfillment of more complicated experiments. The closed - system aquaria with recirculating water are used for scientific experiments.

4. Functional loading abiotic and biotic factors under maintenance and cultivation of corals

Light intensity: If you do not plan to study the influence of bright or extremely low light or its spectral composition on corals, the light intensity should be close to natural from 80 to 30% PAR_0. Recently, it was shown that corals transferred from any habitats easily adapted to new light conditions (from 80 to 30% PAR_0) (Titlyanov et al., 2001a, b, c, d). In addition, it is known that corals dwelling at the light range from 90 to 30% PAR_0 usually had similar level of the primary production (Titlyanov, 1991). Coral planting under 100% PAR_0 is also possible (Atkinson et al., 1995).

Temperature: The water temperature in aquaria, required for coral cultivation, should be kept close (±1-2°C) to the field seawater temperature and should be not higher than of 29°C during hot season. Temporary increase in the average temperature during hot season only 1°C caused mass bleaching and death of a lot of corals (Brown, 1997).

Salinity: The salinity of seawater usually ranges between from 30 to 36‰. In addition, it was shown that some coral species were able to withstand the increase in salinity to 39‰ (Nakano et al., 1997) and reductions to 26‰ (Marcus and Thorhang, 1981). High salinity evokes shrinkage of polyps, gaping mouths of polyps, necrosis of the coelenteron and bleaching of the colony (Nakano et al., 1997). Reduced salinity also caused mass expulsion of zooxanthellae (Titlyanov et al., 2000c).

Mineral nutrition: Concentrations of ammonium, nitrates, nitrites and phosphates in aquaria may fluctuate at the level of changes in nature. Lower concentrations of the elements of mineral nutrition are preferable to higher. The highest values of nutrients for natural water, as reported in reviews (Crossland, 1983; D'Elia and Wiebe, 1990) are 3.8 μM for NH_4^+ plus NO_3^{--} and 0.56 μM for PO_4^{--}. Increase in ammonium concentration higher than 10 μM can evoke disruption in symbiosis between zooxanthellae and their animal host and cause death of corals (Titlyanov et al., 1999; Leletkin, 2000). The major impacts of nutrients on coral reefs usually appear to be indirect with overgrowth by filamentous algae, bryozoans and barnacles, increased bioerosion of corals (Smith and Buddemeier, 1992; Kiene, 1997; Lapointe et al., 1997). The direct effects of nutrient loading on coral growth are less clear although reduced calcification has been noted (Dubinsky and Jokiel, 1994). By contrast, concentrations of organic nutrients in seawater of the Waikiki Aquarium were high relative to most natural reef ecosystems: PO_4^{--} about 0.6 μM; NO_3^{--} about 5 μM; NH_4^+ about 2 μM and were successfully used for coral maintenance.

Sediments: Under maintenance of corals in aquaria, it is preferable to use clean seawater cleaned by settling or filtration. At the same time, it is known that all coral species are capable of self-cleaning of mineral and organic sediments (Sorokin, 1990) and most coral species are capable of dwelling in turbid water conditions (Back and Meesters, 2000). At the same time, it is known that high sedimentation leads to lesions of living coral tissue (Szmant et al., in print).

Air supply: Intensive aeration of seawater is compulsory condition of coral cultivation by any methods. Aeration enriches the seawater with oxygen, lead to mixing of the water and establishes the water current near corals. Oxygen cessation for 2-3 hours can lead to coral's death. The seawater aeration may occur in aquaria, or seawater is aerated through the special aerator pump and pumped into aquaria (Atkinson et al., 1995).

Artificial feeding of corals with zooplankton and other animal food: Scleractinian corals, even with small-sized polyps, such as Stylophora pistillata and Seriatopora caliendrum are capable of capture and digestion of zooplankton with sizes from some micrometers to 2 mm length (Sorokin, 1990). The majority of scleractinian corals hunt at night and early morning (Sorokin, 1990; Titlyanov et al., 2000c). That is why artificial food provisioning with zooplankton is recommended at night. As was shown by Sorokin (1990), coral growth depends on zooplankton concentration in seawater. However, the most rational concentration of zooplankton in aquaria is established by hobbyists or researchers experimentally and depends on kind of zooplankton, their size, coral species and their hunting abilities, aquarium volume and structure. For artificial coral feeding with zooplankton, Artemia salina nauplii were mainly used (e.g. Muscatine et al., 1989; Titlyanov et al., 2000a). For the first time, Stylophora pistillata corals were fed with rotifers (Branchionus plicatilis O.F. Muller) (Titlyanov et al., 1999; 2001b). Sometimes, under long-term maintenance, corals were fed with small pieces of meet, fish, crab and squid, but such food decayed and released into water dissolved protein and other high-molecular compounds becoming food not only for corals but for bacteria also. Mass forming of bacteria can evoke diseases of the corals. When corals are supplied with zooplankton, it is necessary to avoid the elevated ammonium concentration in the medium (Titlyanov et al., 2000a).

Substrate: Quality of substrate for coral fixation depends on aims of coral planting. If corals are farmed as a planting material for coral reef rehabilitation, the substrate should be solid and suitable for simple fixation of coral fragments. The substrate should not give corrosion at the proposed rehabilitation site. The substrate surface should not limit further attachment to the substrate by formation of stable secondary basal discs. Such materials as concrete, ceramic tiles, shells, limestone slabs are suitable for coral attachment. The substrate surfaces should be clean with no fouling with algae, hydroids, sponges and other organisms.

Sizes and numbers of coral fragments in aquaria: Size of coral fragments depends on aims of cultivation. The extent of survival and potential for regrowth may be affected by fragment size. Modular organisms are known to allocate different proportions of their energy and resources to reproduction, with larger colonies of some species investing more energy in reproducing than in growth (Jackson and Hughes, 1985). If this is the case of artificial cultivation of fragments for rehabilitation of damaged coral reef, smaller fragments potentially have a better chance of survival because they may concentrate their ability to re-attach rapidly. Small fragments are best suitable for further growth. Basing on our experiments, we can say that branches of Stylophora pistillata, Seriatopora caliendrum and S. hystrix (3-5 cm length branch tips) attached to substrates within 4-5 months of maintenance in outdoor aquaria. They had a high growth rate (about 8 mg of fresh weight per g per day). Biomass of cultivated corals depends on aquaria volume and the rate of input of seawater and aeration of the water that is established by researcher. Distance between fragments is defined by aggression of coral species. For instance, Galaxea species need more distance to other colonies because they extend up to 15 cm long sweeper tentacles and may harm other polyps (Heeger and Sotto, 2000).

III. CONCLUSION

Long term maintenance and cultivation of hermatypic corals under artificial conditions have been carried out in recent years with limited results. However, these activities have attracted some scientists, managers and businesses and considered as an option to improve our understanding on biology of corals and restore coral reefs, which are impacted by human threats and natural catastrophes.

The analysis on environment factors in maintenance and cultivation of hermatypic coral under artificial conditions suggested an idea on conservation and rehabilitation of coral reefs in the areas without or less temperature increase due to global warming. This suggestion requires experiments in order to understand adaptation and acclimination of corals with change of seawater temperature and environment conditions of new sites. In this case, maintenance of corals in laboratories will support for transplantation of them form donor sites to appropriate areas more effectively. The issues concerning with cost – benefit analysis which were not discussed in this paper require more attention in all further activities.

Based on the discussed principles and methodical approaches, some practices of maintenances and cultivation of hermatypic corals were implemented in H. Steiniz Marine Biology Laboratory (Eilat, Israel), University of Ryukyus (Japan) and Institute of Oceanography (Nha Trang, Vietnam) with the positive perspectives. The concrete results will be published in forthcoming papers.

ACKNOWLEDGEMENTS

The Russian authors thank the Director of the Institute of Oceanography (Nha Trang, Vietnam), Professor Nguyen Tac An and the President of the University of the Ryukyus, Professor Keishin Sunagawa for the invitations to work at their institutions as visiting foreign researchers. Special thanks are to Dr. DeVantier for his comments and English edition. We are also grateful to staff and colleagues of the Institute of Oceanography and the Sesoko Station for use of facilities, technical help and convenience of research work.

REFERENCES

1. Antonius A., in print. Biogeography of old and new coral diseases. Proceeding of 9th Int. Coral Reef Symp., Bali, 2000
2. Atkinson M. J., Carlson B., Crow G.L., 1995. Coral growth in high-nutrient, low-pH seawater: a case study of corals

cultured at the Waikiki Aquarium, Honolulu, Hawaii. Coral Reefs 14: 215–223.

3. Becker L. C., Mueller E., 2001. The culture transplantation and storage of Montastrea faveolata, Acropora cervicornis and Acropora palmata: What we have learned so far. Bull. Mar. Sci. 69(2): 881–896.
4. Bil' K. Y., Kolmakov P. V., Muscatine L., 1992. Photosynthetic products of zooxanthellae of the reef-building coral Stylophora pistillata and Seriatopora caliendrum from different depths of the Seychelles Islands. Atoll Res. Bull. V. 377, pp. 1–8.
5. Birkeland C., 1977. The importance of rate of biomass accumulation in early successional stages of benthic communities to the survival of coral recruits. Proc. 3rd Coral Reef Symp. 1: 15–21.
6. Bruckner A. W. and Bruckner R. J., 2001. Condition of restored Acropora palmata fragments of Mona Island, Puerto Rico, 2 years after the Fortuna Reefer ship grounding. Coral Reefs, 20: 235–243.
7. Bruckner A. W. and Daves N. K., in print. International trade in cites-listed corals and live rock. Proceeding of 9th Int. Coral Reef Symp., Bali, 2000
8. Bucher D. J. and Harrison P. L., in print. Is the growth response of Acropora corals to elevated nutrients different to that of other coral taxa? Proceeding of 9th Int. Coral Reef Symp., Bali, 2000.
9. Carlson B. A., 1999. Organism responses to rapid change: What aquaria tell us about nature. American zoologist, 39(1): 44–55.
10. Clark S. and Edwards A. J., 1995. Coral transplantation as an aid to reef rehabilitation: evaluation of a case study in the Maldive Islands. Coral Reefs, 14: 201–213.
11. Connell J. H., 1997. Disturbance and recovery of coral assemblages. Proc. 8th Int. Coral Reef Symp. 1: 9-22.
12. Crossland C. J., 1983. Dissolved nutrients in coral reef waters. In: Barnes D.J. (ed). Perspectives on coral reefs. Aust. Inst. Mar. Sci. Publ., pp. 56-68.
13. D'Elia C. F. and Wiebe W. J., 1990. Biogeochemical nutrient cycles in coral-reef ecosystems. In: Dubinsky Z. (ed). Ecosystems of the World: Coral reefs. Elsevier, 25: 49–70.
14. Dubinsky Z. and Jokiel P. L., 1994. Ratio of energy and nutrient fluxes regulates symbiosis between zooxanthellae and corals. Pacific Science, 48: 313–324.
15. Dustan P., 1979. Distribution of zooxanthellae and photosynthetic chloroplast pigments of the reef-building coral Montastrea annularis in relation to depth on a West Indian coral reef. Bull. Mar. Sci., pp. 79–95.
16. Falkowski P. G. and Dubinsky Z., 1981. Light-shade adaptation of Stylophora pistillata a hermatypic coral from the Gulf of Eilat. Nature, v. 289, ¹ 5794, pp. 172–174.
17. Fong P. and Lirman D., 1995. Hurricanes cause population expansion of the branching coral Acropora palmata (Scleractinia) wound healing and growth patterns of asexual recruits. Mar. Ecol., 16: 317–335.
18. Gittings S. R., Bright T. J., Barnett R.R., 1988. The recovery process in a mechanically damaged coral reef community: recruitment and growth. Proc. 6th Int. Coral Reef Symp. 2: 225–230.
19. Graus R. R. and Macintyre I. V., 1982. Variation in growth forms of the coral Montastrea annularis (Ellis and Solander): a quantitative evaluation of growth response to light distribution using computer simulation. The Atlantic barrier reef ecosystem at Carrie Bow Cay, Belize. I. Structure

and communities. Washington: Smithsonian Inst. Press, pp. 441–464.

20. Heeger T., Sotto F. (Ed), 2000. Coral farming: A tool for reef rehabilitation and community ecotourism. BMU: Philippines, 93 pp.
21. Hoegh-Guldberg Ove, Takabayashi Misaki, Moreno Guillermo, 1997. The impact of long-term nutrient enrichment on coral calcification and growth. Proc. 8th Int. Coral Reef Symp. 1: 861–866.
22. Jaap W. C., 1999. An historical review of coral reef restoration in Florida. In: Proc. Int. Conf. on Scientific Aspects of Coral Reef Assessment, Monitoring and Restoration. Progr. Abstr., p. 111.
23. Jackson J. B. C. and Huges T. P., 1985. Adaptive strategies of coral-reef invertebrates. Am. Sci. 73: 265–273.
24. Kiene W. E., 1997. Enriched nutrients and their impact on bioerosion: results from ENCORE. Proc. 8th Int. Coral Reef Symp. 1: 897–902.
25. Lapointe B. E., Littler M. M., Littler D.S., 1997. Macroalgal overgrowth of fringing coral reefs at Discovery Bay, Jamaica: bottom-up versus top-down control. Proc. 8th Int. Coral Reef Symp. 1: 927–932.
26. Latypov Y. Y. and Dautova T. N., 1998. Scleractinian corals of Vietnam. Part I. Dal'nauka: Vladivostok, (in Russian), 165 pp.
27. Leletkin V. A., Titlyanov E. A., Dubinsky Z., 1996. Photosynthesis and respiration of the zooxanthellae in hermatypic corals habituated on different depths of the Gulf of Eilat. Photosynthetica. V. 32, pp. 481–490.
28. Leletkin V. A., 2000. Trophic status and zooxanthellae population density in hermatypic corals. Russia Journ. Mar. Biol. V. 26. ¹ 4, pp. 221–230.
29. Lirman D., 2000. Fragmentation in the branching coral Acropora palmata (Lamarck): growth, survivorship, and reproduction of colonies and fragments. JEMBE, 251: 41–57.
30. Loya Y., in print. Homage to Stylophora pistillata: an important coral in coral reef research. Proceeding of 9th Int. Coral Reef Symp. Bali, 2000.
31. Marcus J. and Thorhaug, 1981. Pacific versus Atlantic responses of the subtropical hermatypic coral Porites spp. to temperature and salinity effects. Proc. Fourth Int. Coral Reef Symp., 2: 15–20.
32. Muller-Parker G. and D'Elia C.F., 1997. Interactions between corals and their symbiotic algae. Chapter 5: Life and death of coral reefs. Ed. C. Birkeland. Chapman and Hall Publ., pp. 96–113.
33. Muscatine L., Falkowski P. G., Dubinsky Z., Cook P. A., McCloskey L.R., 1989. The effect of external nutrient resources on the population dynamics of zooxanthellae in a reef coral. Proc. R. Soc. London B 222: 311–324.
34. Nakano Y., Yamazato K., Masuhara H., and Iso S., 1997. Responses of Okinawan reef-building corals to artificial high salinity. Galaxea, 13: 181–195.
35. Osinga R., Tramper J., Wijffels R.H., 1999. Cultivation of marine sponges. Marine Biotechnology 1(6): 509–532.
36. Patton J. S., Abrahams S., Benson A.A., 1997. Lipogenesis in the intact coral Pocillopora capitata and its isolated zooxanthellae: evidence for a light driven carbon cycle between symbiont and host. Mar. Biol. V. 44, pp. 235–247.
37. Porter J. W., 1974. Zooplankton feeding by the Caribbean reef-building coral Montastrea cavernosa. In: A.M. Cameron et al., Eds Proc. 2nd Int. Coral reef Symp. Brisbane. Australia, pp. 111–125.
38. Precht W. F., 1998. The art and science of reef restoration. Geotimes 43: 16–19.

39. Quirolo C., 1999. Coral nursery project at Western Sambo Reef, Florida Keys. Reef Relief. Florida.

40. Raymundo L.J., 2001. Mediation of growth by nonspecific neighbors and the effect of site in transplanted fragments of the coral Porites attenuata Nemenzo in the central Philippines. Coral Reefs, 20:263–272.

41. Reynaud-Vaganay S., Gattuso J. P., Jaubert J., Juillet-Leclerc A., 1999. A novel culture technique for scleractinian corals: application to investigate changes in skeletal $\delta^{18}O$ – as a function of temperature. Mar. Ecol. Prog. Ser. 180: 121–130.

42. Smith S. V., Buddemeir R. W., 1992. Global change and coral reef ecosystems. Ann. Rev. Syst. 23: 89–118.

43. Sorokin Y. I., 1990. Ecosystems of coral reefs. M: Nauka. 503 pp.

44. Stepanov D., 1994. Marine aquarium at home. Ecocenter, Moscow (in Russian), 172 p.

45. Szmant A. M., Yeung C. and Cohen K., in print. Turbidity and sedimentation as stressors to Florida reef corals. Proceeding of 9th Int. Coral Reef Symp., Bali, 2000.

46. Titlyanov E. A., 1991. The stable level of coral primary production in a wide light range. Hydrobiologia, 216 / 217: 383–387.

47. Titlyanov E. A., 1999. Zooxanthellae in hermatypic corals: Life strategy. 57th Timiryazev's course of lectures. Kursanov A.L. (Ed). Vladivostok: Dal'nauka (in Russian), 63 pp.

48. Titlyanov E. A., Zvalinsky V. I., Shaposhnikova M.G., Leletkin V.A., 1981. Some mechanisms of reef-building corals in Australia to light intensities. Russian Journ. Mar. Biol. (In Russian, with English abstract). Vladivostok, No 2, pp. 23–31.

49. Titlyanov E. A., Zvalinsky V. I., Leletkin V. A., Shaposhnikova M. G., 1983. Photosynthesis of zooxanthellae of reef-building corals in different light conditions. In: Krasnov, Y. V. (Ed.). Biology of coral reefs. Investigations on the Phantom Bank (Timor Sea) (In Russian, with English abstract), Far East Sci. Center USSR, Vladivostok, pp. 51–74.

50. Titlyanov E. A., Magomedov I. M., Kolmakov P. V., Butorin P. V., 1988a. Adaptation to light, primary production and its utilization in reef-building corals of Indo-Pacific. In: Sorokin, Y. I. (Ed.). Biology of coral reefs. Photosynthesis of reef-building corals. (In Russian, with English abstract), Far East Sci. Center USSR, Vladivostok, pp. 19-51.

51. Titlyanov E. A., Kolmakov P. V., Le Nguyen Hieu, Yermak V. D., Nechai E. G., Peshekhod'ko V. M., Lapshina A. A., and Hoang Thi Linh, 1988b. Structure and productive function of coral colonies of the genus Pocillopora in the range of light limit of their habitat. In: Sorokin, Y.I. (Ed.). Biology of coral reefs. Photosynthesis of reef-building corals. (In Russian, with English abstract), Far East Acad. Sci. USSR, Vladivostok, pp. 52–71.

52. Titlyanov E. A., Latypov Y. Y., 1991. Light dependence in scleractinian distribution in the sublittoral zone of South China Sea Islands. Coral Reefs 10: 133–138.

53. Titlyanov E. A., Titlyanova T. V., Leletkin V. A., Tsukahara J., Van Woesik R., Yamazato K., 1996. Degradation and regulation of zooxanthellae density in hermatypic corals. Mar. Ecol. Prog. Ser. 139: 167–178.

54. Titlyanov E. A., Titlyanova T. V., Loya Y., Yamazato K., 1998. Degradation and proliferation of zooxanthellae in planulae of the hermatypic coral Stylophora pistillata. Mar. Biol. 130: 471–477.

55. Titlyanov E. A., Titlyanova T. V., Tsukahara,J., Van Woesik R.,

Yamazato K., 1999. Experimental increases of zooxanthellae density in the coral Stylophora pistillata elucidate adaptive mechanisms for zooxanthellae regulation. Symbiosis, 26: 347–362.

56. Titlyanov E., Bil' K., Fomina I., Titlyanova T., Leletkin V., Eden N., Malkin A., Dubinsky Z., 2000a. Effects of dissolved ammonium addition and host feeding with Artemia salina on photo-acclimation of the hermatypic coral Stylophora pistillata. Mar. Biol., 137: 463–472.
57. Titlyanov E. A., Leletkin V. A., Dubinsky Z., 2000b. Autotrophy and predation in the hermatypic coral Stylophora pistillata in different light habitats. Symbiosis, 29: 263–281.
58. Titlyanov E. A., Tsukahara J., Titlyanova T. V., Leletkin V. A., Van Woesik R., Yamazato K., 2000c. Zooxanthellae population density and physiological state of the coral Stylophora pistillata during starvation and osmotic shock. Symbiosis, 28: 303–322.
59. Titlyanov E. A., Titlyanova T. V., Yamazato K., 2001a. Formation, growth and photo-acclimation of the hermatypic coral Galaxea fascicularis under different light conditions. Symbiosis, 30: 257–274.
60. Titlyanov E. A., Titlyanova T.V., Yamazato K., Van Woesik R., 2001b. Photo-acclimation of the hermatypic coral Stylophora pistillata while subjected to either starvation or food provisioning. J. Exp. Mar. Biol. Ecol. 257: 163–181.
61. Titlyanov E. A., Titlyanova T. V., Yamazato K., Van Woesik R., 2001c. Photo-acclimation dynamics of the coral Stylophora pistillata to low and extremely low light. JEMBE, 263: 211–225.
62. Titlyanov E. A., Titlyanova T. V., Amat A., Yamazato K., 2001d. Morpho-physiological variations of symbiotic dinoflagellates of hermatypic corals from a fringing reef at Sesoko Island. Galaxea, 3:
63. Titlyanov E. A. and Titlyanova T. V., 2002a. Reef-building corals are symbiotic autotrophic organisms. I. General features of structure, feeding ways, light-dependent distribution on the shelf. Russia Journ. Mar. Biol., in press.
64. Titlyanov E. A. and Titlyanova T. V., 2002b. Reef-building corals are symbiotic autotrophic organisms. II. Ways and mechanisms of adaptation to light. Russia Journ. Mar. Biol., in press.
65. Todd P. A., Sanderson P. G., Chou L.M., in print. Phenotypic plasticity in two scleractinian corals around Singapore. Proceeding of 9th Int. Coral Reef Symp., Bali, 2000.
66. Tunnicliffe V., 1981. Breakage and propagation of the stony coral Acropora cervicornis. Proc. Natl. Acad. Sci. USA 78: 2427–2431.
67. Veron J. E. N., 1986. Corals of Australia and the Indo-Pacific. Angust and Robertson Publishers, London, 644 p.
68. Vo Si Tuan and Hodgson G., 1997. Coral reefs of Vietnam: recruitment limitation and physical forcing. Proc. 8th Int. Coral Reef Symp. 1: 477–482.
69. Vo Si Tuan, in print. The corals of Con Dao Archipelago (South Vietnam) - before, during and after the bleaching event in 1998. Proceeding of 9th Int. Coral Reef Symp., Bali, 2000.
70. Ware J. R., 1997. The effect of global warming on coral reefs: acclimate or die. Proc. 8th Coral Reef Symp., 1: 527–532.
71. Witting J. and Sebens K. P., in print. The role of zooplankton capture in six Caribbean scleractinian corals: in situ evidence that heterotrophy limits coral growth. Proceeding of 30th Annual Marine Benthic Ecology Meeting. University of New Hampshire, Durham NH, 2001.

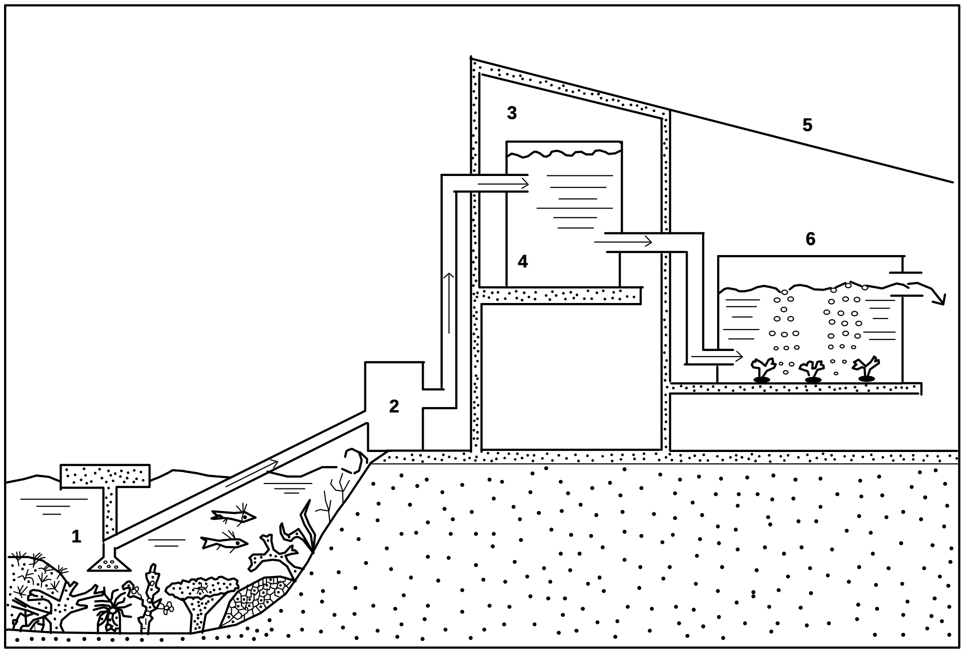

Fig. 1: Scheme of installation for long-term maintenance and cultivation of corals by the first approach (see text). 1 – Seawater derivation from a depth of 2–3 m above live coral reef; 2 – Water pump; 3 – Cooling room; 4 – Consumption tank; 5 – Light filter; 6 – Aquarium with corals.

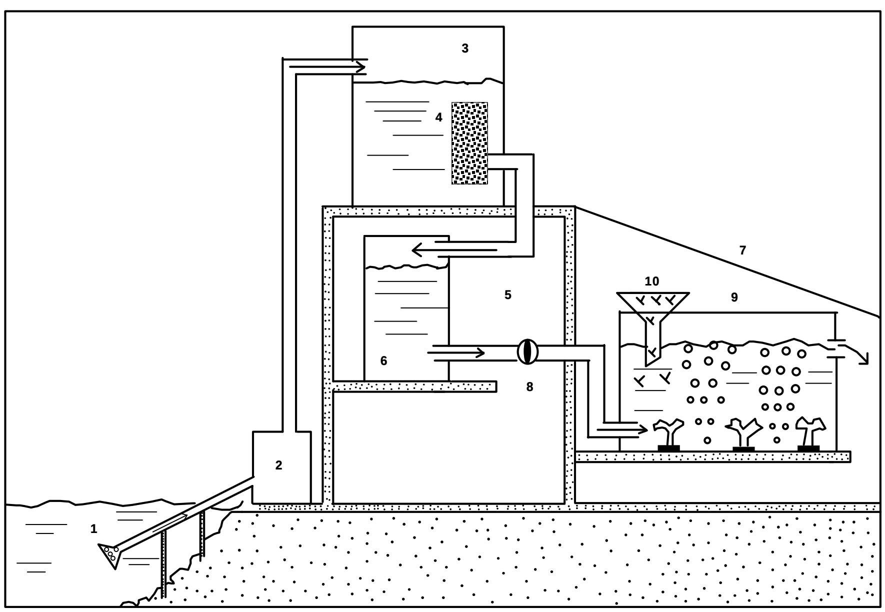

Fig. 2: Scheme of installation for long-term maintenance and cultivation of corals by the second approach. 1 – Seawater derivation from any site of adjacent bay; 2 – Seawater pump; 3 – Sump tank for sediments settling; 4 – Seawater filter; 5 – Cooling room; 6 – Consumption tank; 7 – Light filter; 8 – Valve (for water supply); 9 – Aquarium with corals; 10 – Source of zooplankton supply.

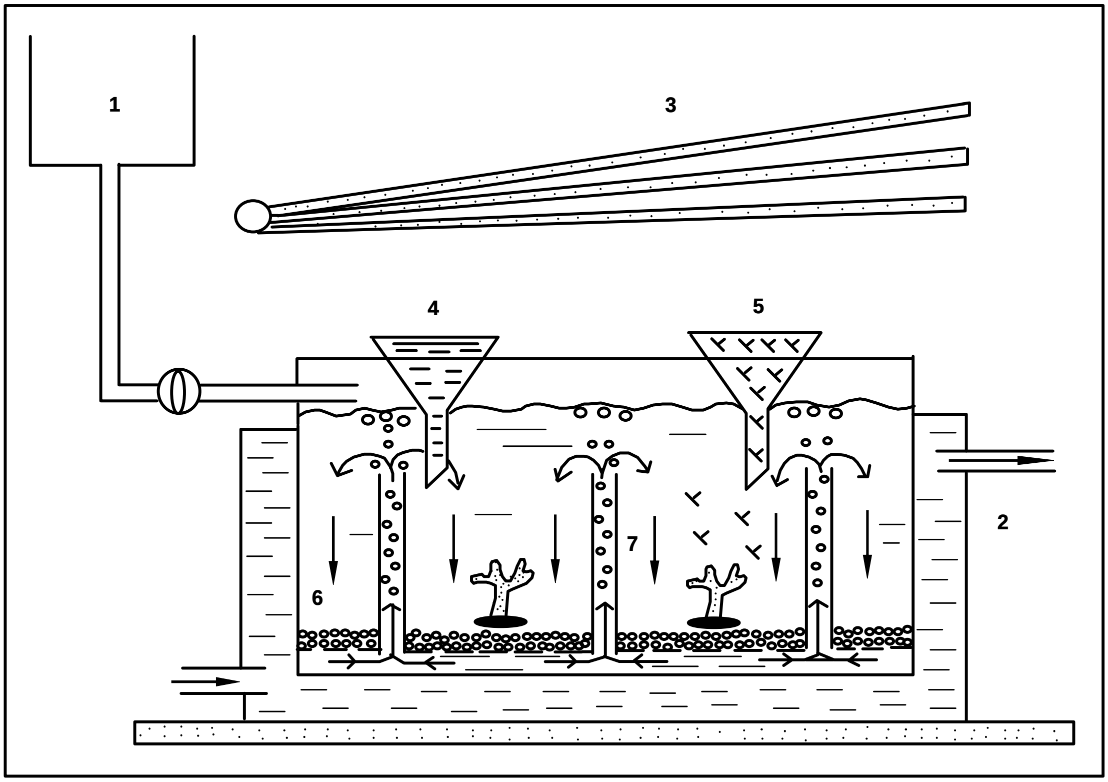

Fig. 3: Scheme of installation for long-term maintenance and cultivation of corals by the third approach. 1 – Installation for supply with clean seawater; 2 – Seawater thermostat; 3 – light filters; 4 – Source of supply with inorganic nutrition; 5 – Source of zooplankton supply; 6 – Biological filter; 7 – Airlift. Arrows shows direction of seawater flow established by airlift in aquarium.