IMPACTS OF SEDIMENTATION ON STONY CORALS

Oleh
Tri Aryono Hadi1)

ABSTRAK
PENGARUH SEDIMENTASI PADA KARANG KERAS. Aktivitas manusia baik di darat maupun di laut membawa banyak pengaruh negatif terhadap ekosistem laut. Terumbu karang yang utamanya disusun oleh karang keras mengalami degradasi akibat turunnya kualitas perairan, terutama akibat sedimentasi dan eutrofikasi. Secara umum hal ini akan menyebabkan menurunnya kelimpahan dan diversitas karang batu, dan secara khusus akan mempengaruhi proses fisiologis karang. Proses fotosintesis menurun sebagai imbas dari menurunnya penetrasi cahaya akibat tingginya turbiditas dan sedimen yang menempel di permukaan karang. Untuk menanggulangi defisit energi, maka karang meningkatkan aktivitas menangkap makanan sekaligus proses respirasi. Reproduksi dan rekruitmen juga akan menurun seiring rusaknya sperma karang dan tertutupnya substrat untuk perlekatan larva. Sedimen juga akan memicu penyakit karang karena produksi mokus yang berlebihan. Pengkayaan nutrien di laut akan meningkatkan proses fotosintesis sebagaimana tersedianya senyawa anorganik yang penting untuk transfer energi dan kandungan dari zooxanthellae, namun apabila berlebihan akan menimbulkan gangguan pada proses reproduksi dan meningkatkan wabah penyakit karang. Meskipun karang mampu merespon gangguan tersebut, untuk jangka waktu yang panjang akan menimbulkan efek yang mematikan. Oleh karena itu perlu dilakukan evaluasi mengenai aktivitas manusia disekitar wilayah pesisir untuk meminimalisir dampak negatif pada ekosistem pesisir.

INTRODUCTION
Coastal development has become a serious threat to marine life. Overexploitation, pollution, habitat transformation have caused marine degradation and biodiversity loss, thus hampering ecological resiliency of ecosystem (Nystrom et al., 2012). It is reported that coral reef and its associated ecosystem, such as seagrasses, have been declining massively in the global scale (Waycott et al., 2009). These losses are more attributable to declining water quality, particularly due to sedimentation (De’ath & Fabricius, 2010).

There are two major factors which can trigger sedimentation in marine habitats, including terrestrial run off and dredging (Fabricius et al., 2005; Erfteimejer et al., 2012). Terrestrial run off has continually increased sediment transport trough soil

1) Pusat Penelitian Oseanografi LIPI
erosion in global rivers by approximately $2.3 + 0.6$ billion metric tons per year (Syvitski et al., 2005). A study confirms that the impact of dredging activities could reach radius of 250 meters, in condition of dredge head concentration 204.3 mg/l, water velocity 0.3 m/s and turbulent diffusion coefficient 22 m$^2$/s (Je et al., 2007). Hence, it is predicted that the ecosystems surrounding the sources of sedimentation will be highly impacted.

Coral reefs are commonly perceived as biogenic structure, yet rarely considered that more than a half of the materials in most coral reef complexes is basically made up of sediment (Sorokin, 2013). Sediment on the most coral reefs consists of carbonate (aragonite, high magnesium calcite and calcite) which is produced by the growth and subsequent destruction of reef organisms as well as pre-existing reef rock through biological, chemical and physical processes; and sediment near shore fringing reef contains silicate grains from weathered and eroded igneous or metamorphic rock (terrigenous sediment) (Dudley, 2003). Through the time, loose sediments and the skeleton of primary and secondary organisms might be changed into reef rock and, in the end, it forms a dense solid limestone through consolidation of reef material, binding, cementation and diagenesis (Sorokin, 2013). Sediment is commonly accumulated in inshore reefs and sheltered, wave-protected parts of reef systems, but less accumulated in reef crest and outer reefs as the wave energy becomes increasing (Wolanski et al., 2005).

Sedimentation has contributed to the declining of coral reef habitats, either directly by burial reefs or indirectly as a consequence of lethal and sub lethal stress to corals which result from increased water turbidity (Piniak & Storlazzi, 2008). The effects may be abrupt or gradual for a longer period and this can be temporary or permanent in nature. Coral responses to sedimentation can be different among species; some of them are resistant and others are very vulnerable, and depend on local environment and vary between seasons (Wolanski et al., 2008). Hence, the impacts of sedimentation on corals are very complex and need to be investigated further.

**VARIOUS IMPACTS OF SEDIMENT ON CORALS**

There are some studies which have observed the impacts of sedimentation both resulting from dredging activities and terrestrial run off (Table 1).

| Location          | Issues                                                                 | Impacts                                                                                           | References                        |
|-------------------|------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|-----------------------------------|
| Hay Point, Australia | Dredging for port construction and expansion with total volume of dredging up to 9 million m$^3$ | Coral cover loos up to 2-5 % at 2 islands up to 6 kilometer away from the source                  | Smith et al. (2007)               |
| Singapore         | Coastal reclamation and dredging along the coastline                   | Approximately 60% of coral reefs has been degraded and the rest was subjected to impacts of sediment | Hilton & Manning (1995)           |
These studies confirm that both sedimentation from dredging and terrestrial run off bring negative impacts to coral reefs and enhance growth of macroalgae and *A. planci* as result of nutrient discharge from rivers. Although the studies provide general decline in coral reef conditions, the impact on corals as individual need to be understood. The impacts commonly occur in many aspects, such as physiological processes (photosynthesis, feeding and respiration), reproduction and recruitment, and diseases (Erftemeijer *et al*., 2012).

### a. Photosynthesis process

The main issue of increasing turbidity and sedimentation is related to shading which can limit the light intensity. Light will exponentially decrease with depth because of attenuation process; in this case the light will be absorbed and scattered by water molecules, dissolved matter and particle solids (Bridge & Demicco, 2008). The development and maximal growth of reef corals generally occur down to 30 – 40 % of subsurface irradiance (SI) and it is rarely to find a significant formation of reef below 10% SI (Achituv & Dubinsky, 1990). Light intensity also affects corals’ growth rates, given that there were variations in growth rate of *Montipora monasteriata* in the Great Barrier Reef (Anthony & Hoegh-Gulberg, 2003). Furthermore, a study reports that a linear extension rate of *Acropora valenciennesi* in sites with low sedimentation rate was approximately 200 mm/year, while in the highly sedimented sites it was around 90 mm/year (Crabbe & Smith, 2005).

Turbidity and sedimentation affect the photosynthesis process as it limits the light penetration. The turbidity will decrease the ambient photosynthetically active radiation (PAR) and cause zo-xanthellae productivity to decrease, resulting in starvation (Gilmour *et al*., 2006). While sedimentation will lead to addition shading and smothering, which can contribute to the decline of photosynthetic activity and even initiate bleaching...
(Anthony et al., 2007). It is reported that sedimentation (79-234 mg/cm²) for 36 hours could reduce approximately 6 fold maximal quantum yield of photosystem II compared to the control treatment, and this also reduced the zooxanthellae density and chlorophyll concentration per unit area (Phillipp & Fabricius, 2003). Furthermore, a study reports that gross photosynthesis/respiration (P : R Ratio) of Dichocenia stokesii and Meandrina meandrites fell from approximately 1.5 to 0.5 (Telesnicki & Goldberg, 1995). In addition, Goniastrea retriformis responded to the prolonged shading through both photo and heterotrophic plasticity, yet still could not compensate for the reduced light as daily respiration exceed daily photosynthesis (Anthony & Fabricius, 2000). The decline in alga productivity can cause nutrition, growth, reproduction and calcification rate to drop (Richmond, 1993). Thus, it is clear that sedimentation and turbidity will affect the photosynthesis process through light availability, resulting in different growth rate of corals.

Nutrient coming from rivers apparently has a positive effect on photosynthesis process. Dissolved Inorganic Nitrogen (DIN) increases the density of zooxanthellae as well as the content of nitrogen and chlorophyll a per zooxanthellae, and promotes photosynthesis process, transfer of energy, CO2 and nutrient between zooxanthellae and host (Koop et al., 2001). Another kind of nutrient is Dissolved Inorganic Phosphate which was found to enhance the photosynthesis rates of Stylophora pistilata up to 150% (Ferrier-Pages et al., 2000). Although it provides resources for corals’ physiological processes, excessive nutrient has potentially negative effects on coral growth and diseases. Nitrogen addition can hamper coral growth and phosphorus can reduce the formation of CaCO₃ crystal, making the density become lower (Fabricius, 2005). Furthermore, this issue enhances coral reef degradation by promoting macroalgal growth (Szmant, 2002). Hence, it may conclude that the drawbacks of nutrient discharge from rivers or eutrophication outweighs the benefits.

b. Feeding and Respiration

Sedimentation and burial bring negative impacts on corals as a sessile organism. Sediment which covers corals’ surfaces can initiate smothering of coral polyps (Fabricius & Wolanski, 2000). Moreover, a study confirms that photosynthesis rate in sediment-exposed corals during day time was decreasing, while the respiration rate during night time was increasing (Abdel-Salam et al., 1988). Sediment on the surface can interfere corals’ feeding apparatus; in this case it causes polyps to retract and cease tentacular actions and, if the sedimentation is very high, it will make polyps difficult to expand and eventually corals cannot compensate for the loss of energy from heterotrophic activities (Erftemeijer et al., 2012). However, sediment may bring organic material in which corals can feed on. A study reports that particle ingestion rate of Goniastrea retiformis was correlated positively with concentration of suspended particular matter (SPM) in the range of 1-30mg dry weight/l; in this case...
the particle feeding has doubled in response to prolonged shading (Anthony & Fabricius, 2000). In addition, it is reported that high turbidity level on coastal reefs will enhance the lipid stores by 4 and 2 folds for Turbinaria mesenterina and Acropora valida respectively compared to the same offshore species (Anthony, 2006).

c. Reproduction and recruitment

Coral reproduction and recruitment appear to be more sensitive to environmental changes, and dependent highly on clean water with low sedimentation rate (Humphrey et al., 2008). Suspended sediment inhibits coral fertilization, given that aggregation of eggs becomes more pronounced and this may reduce the success of fertilization, or, alternatively the sediment may hamper or damage the sperm (Gilmour, 1999). There was a significant decline in fertilization process of Acropora millepora by more than 50% in a treatment with suspended-sediment level at ≥ 100 mg/l with salinity 30 ppt (Humphrey et al., 2008). Another main cause is inorganic material which affects eggs production. A study reports that Acropora longyiathus which was exposed to increased nitrogen produced significantly fewer and smaller eggs, and even had less testes material compared to those which were in control treatment (Ward & Harrison, 2000). Furthermore, increased nitrogen also reduces egg fertilization rates by increasing rate of abnormally-formed embryos (Harrison & Ward, 2001). In addition, planulation of Pocillopora damicornis failed and the egg size was reduced after 4 months exposed to elevated ammonium (Cox & Ward, 2002).

Settlement and survivorship of larvae are the key factors for recruitment success. Low sediment level, in which it is only cover thinly the corals’ surfaces and not directly harmful to adult colonies, can hamper the recruitment process by inhibiting settlement and reducing the survivorship of larvae (Goh & Lee, 2008). A study confirms that settlement and survivorship of larvae reached only 71 % and 39 % respectively in a condition in which sedimentation rate ranged between 0.76 - 1.32 mg cm$^{-2}$ d$^{-1}$ (Babcock & Smith, 2002). Furthermore, 35 percent of recruits have died after a 43 day exposure to transparent exopolymer particle-enriched sediment and the mortality became 80% as the sediment increased by 50% (Fabricius et al., 2003).

In summary, declining water quality due to either sedimentation or eutrophication - particularly during spawning time of corals - may affect their reproduction success and hamper coral recruitment. This situation may compromise the resilience of coral reefs. Although the studies were conducted in laboratory, the same issues may possibly occur in natural environment which is polluted.

d. Disease

Sediment lying down on the corals’ surface can initiate mucus production. A potential issue from excessive mucus production is increasing populations of bacteria (Ritchie & Smith, 2004). The metabolism of bacteria may cause local anoxic conditions and high nutrient content in silt promotes the metabolism of bacteria (Weber et al., 2006). A study in Caribbean
reef finds that nutrient enrichment could increase severity of yellow band disease on *Montastrea annularis* and *M. franksii* (Bruno *et al.*, 2003). Nutrient enrichment can exacerbate the severity of black band diseases (BBD) by promoting migration rate of the infections (Voss & Richardson, 2006). Furthermore, a study reports that, by using stable isotope analysis, sewage-derived N was correlated significantly with the increase of severity of disease in *Porites* spp., accounting for more than 48% of the change variation in disease severity (Redding *et al.*, 2013). In addition, BBD and white plague type II became more prevalent at sewage-impacted environment (Kaczmarsky *et al.*, 2005). These studies imply that the prevalence of disease can be exacerbated by the nutrient on the sediment, and the sediment causes corals to spend more energy to eradicate sediment in surface, making corals weak and more vulnerable to disease.

**RESPONSES OF CORALS TO DIFFERENT ISSUES**

a. **Responses of corals to turbidity**

Low light intensity is attributable to high turbidity in water column. This will decrease calcification rate as the photosynthesis productivity declines, being approximately three times lower in darkness compared to normal condition (Gattuso *et al.*, 1999). Although corals obtain limited light intensity, adaptations by zooxanthellae allows maximal absorption and utilization of light; making gross photosynthesis rate increase (Tilyanov, 1991). A study indicates that there was photo-acclimation of *Porites lutea* in which the light saturation coefficient ($E_{\text{c}}$) and maximum relative electron transport rate ($r\text{ETR}^{\text{MAX}}$) decreased as the light became limited (Hennige *et al.*, 2008). Furthermore, it is found that community structure of *Symbiodinium* changed across environmental gradient in the Wakatobi Marine National Park; given that at optimal sites, the types of *Symbiodinium* were dominated by clade C, while in the impacted sites the most dominant type was clade D (Hennige *et al.*, 2010). Although corals are able to responds the limited light due to turbidity, long term impact of turbidity can cause coral reefs to lose its coral diversity (Done *et al.*, 2007). It is also found that turbidity affects the distribution of corals; *Pachyseris*, *Merulina* and *Mycedium*, which are generally deeper water genera, were found in shallow water in Singapore (Dikou & Van Woesik, 2006).

b. **Responses of corals to sedimentation**

Corals actively remove sediment on its surface to obtain light. Forty two species of corals showed the same mechanism to remove the sediment by ciliary currents, tissue expansion and mucus entanglement, and these capabilities are closely related with calice size; given that rejecting influxes become higher as the size of calice become bigger (Hoeksema & de Voogd, 2012). However, this active removal is costly and may not remain for long period, therefore dredging activities as the main source of sedimentation, should be monitored thoroughly to prevent environmental degradation (Erftemeijer *et al.*, 2012).
Figure 1 describes the energy budget when corals encounter high turbidity and sedimentation. The coral in the top receives maximum light and approximately 90% of productivity will be respired; 35% of which will be allocated for mucus production, while 65% will be allocated for metabolic functions. On the other hand, the bottom coral receive the least light intensity and is covered by sediment. In this situation, 245% of productivity will be utilized; 65% of which is for mucus production and the rest is used for metabolic function. Under this situation, corals cannot be autotroph as the light is very limited (Erftemeijer et al., 2012).

In summary, impacts of turbidity and sediment can be complicated as corals have to allocate energy budget efficiently. Although some mechanisms can be deployed to adapt with the situation, during this situation corals seem to obtain less energy particularly from photosynthesis. Thus, it will affect ability corals to maintain its colony if the water quality is still poor and, eventually, coral population will decline.

c. Responses of corals to nutrient enrichment

Nutrient discharge appears to have influence in metabolic functions of corals, such as photosynthesis, growth
and reproductions (Tanaka et al., 2007). The severe impacts are mostly from the organism which can take benefits from nutrient enrichment, such as bacteria and fungus (Lintlon et al., 2002), *Achantaster planci* (Brodie et al., 2005), filter feeders animals (Costa Jr. et al., 2000), and macroalgae (Szmant, 2002). In this situation, corals encounter a tough competition with other sessile biotas as well as diseases and predation. However, corals will have more responses in competition as it is not abrupt effect. Coral will inhibit other sessile organisms by overgrowing; shading; abrasion (whiplash); stinging which involves sweeper tentacles and polyps, and mesentrial filament; chemical; and mucus secretion (McCook et al., 2001). However, the responses of coral may depend on the environmental conditions in which corals obtain resources for its energy.

**MANAGEMENT OF CORAL REEF ECOSYSTEMS**

The feasible overview to obtain coral reef conditions is through field observation. Baseline data are quite important to understand the conditions before the impacts occur. Monitoring program is very essential to obtain the trend of the conditions. Hence, the solutions over the impact can be implemented after wards. It is also necessary to set the thresholds of each issue, therefore prevention efforts can be proceeded before the issues become more severe. Furthermore, human activities nearby ecosystems needs to be evaluated. In addition, socialization and education to local societies about the importance of coral reef ecosystems need to be improved, therefore, the local can be a part of management system (Sale, 2008).

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