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Measures to Control Harmful Algal Blooms

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Abstract

Harmful algal blooms (HABs) occur globally and are caused by different species of microalgae. They can be harmful by producing toxins or by the rapid increase in biomass often leading to discoloration and hypoxic conditions. Toxins accumulating in shellfish and fish can cause shellfish poisoning in humans, major economical losses, especially damage to aquaculture, and affects on marine life. Bloom events are natural phenomena and have been reported for centuries but the recent increase in blooms and their global spread, which are often discussed in relation to human influences, has caused concern. In the absence of reducing such factors, controlling blooms and mitigating effects are essential. Here, methods of controlling HABs by directly targeting the causative algae are reviewed. Studies have shown many possible control measures, biological, chemical and physical, but many methods are restricted by cost, practicality and environmental toxicity. Research on mortality and cell lysis of algae in the wild has lead to studies on biological control by bottom-up and top-down control, but no achievable method has yet been suggested. Flocculation by clay appears promising and is currently used in some areas, but global use is restricted for practical and economical reasons. Many chemicals have also been suggested of which surfactants have received recent attention. Toxicity tests on other, non-target marine organisms are necessary before such chemicals can be considered for use in the field. In the absence of successful control measures, mitigation to minimize effects is often important and widely employed.

Keywords: Harmful algal blooms; mitigation; control; flocculation

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Introduction

Harmful algal blooms (HABs) are global occurrences caused by various species of microalgae. High densities of algae can, in some cases, cause discolouration of the water, misleadingly known as “red-tide”. Of the thousands of species approximately 150 are toxic or harmful (Landsberg 2002). Species that can be harmful at low algal densities are distinguished from non-toxic species, which can cause detrimental effects by the extensive growth and high biomass often leading to hypoxic conditions (Anderson et al. 2002). Although HABs occur naturally and have been reported for centuries, the recent increase in bloom events and extended geographic range has caused concern (Fig 1)(Anderson et al. 2002; GEOHAB 2001; Kirkpatrick et al. 2004; Millie et al. 1999; Smayda 1989). Several explanations have been suggested to account for these observations, many related to human activities, with most attention on nutrient enrichment (Anderson et al. 2002; GEOHAB 2001).

By consuming contaminated shellfish, toxins can cause paralytic, neurotoxic, diarrheic, amnesic and azaspiracid shellfish poisoning in humans. The toxins can also affect wildlife, e.g. massive fish kills and high mortalities in the endangered manatees associated with blooms on the west coast of Florida (Boesch et al. 1997). Every year economic losses in coastal regions due to reduction in tourism and recreation, costs of public health, as well as significant losses to commercial fisheries and aquaculture, are estimated at millions of U.S. dollars in several countries (Hoagland et al. 2002). Many countries encountering problems with HABs have established organizations and research programs to increase knowledge about algal species, bloom dynamics as well as to develop monitoring and management tools. But as HABs are globally spread, coordinated international programs and workshops are important, e.g. the GEOHAB (Global Ecology and Oceanography of Harmful Algal Blooms) (GEOHAB 2001). With increasing occurrences of HABs, causing major economic as well as wildlife losses, there is a growing need for control measures and mitigation of the impacts. Mitigation measures to reduce impacts of HABs on e.g. aquaculture, can be distinguished from control actions that aim to minimize the occurrences and spread of HABs. Furthermore, the separation of indirect (treating the cause of HABs, e.g. nutrient enrichment) and direct control measures (prevention and reduction of blooms by targeting the causative algal species) can be identified. This review will focus on the direct control measures, referring to previously tested methods, recent advances and development of new techniques as well as emphasizing risks and problems with such approaches.

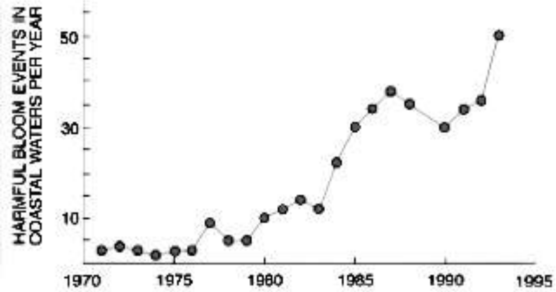

Fig 1. Harmful-bloom events in Chinese coastal areas (adapted from Zhang et al. 1994).

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1. Biological control

For bloom events to occur, the growth rate must exceed losses, through biological and physical processes (Caron et al. 1989; Mitra & Flynn 2006; Tillmann 2004). Biological techniques use top down grazing and bottom up bacterial and viral infections observed in natural populations and examine possibilities to imply such methods for control of HABs (Table 1).

1.1 Grazing

A natural biological limitation for phytoplankton is grazing by microzooplankton, which may be important in the population dynamics of HABs (Caron et al. 1989; Tillmann 2004). In situations with large microalgae (2-200µm), growth can exceed the consumption rate of the predators, leading to a bloom event (Caron et al. 1989). In contrast, bactivorous and herbivorous protozoa can feed at a sufficiently high rate that eliminates their prey, *A. anophagefferens* (Caron et al. 1989). Several studies, both laboratory and field based have shown that protozoan species graze on phytoplankton in high abundances during bloom events (Tillmann 2004). Effective grazing can thereby prevent blooms but where grazing is prevented by defense mechanisms (e.g. change in growth pattern, production of toxins), this may favour bloom events (Tillmann 2004). Control mechanisms using zooplankton would require cultivation in tanks in preparation for when algae biomass increases. According to calculations by Shirota (1989) tanks are required to hold a volume of 33×10^3 m^3, which is unpractical and expensive.

Planktonic algae are not only consumed by zooplankton but also by other filterfeeding animals such as bivalves. For example, in the San Francisco Bay, the invasion of the suspension-feeding clam *Potamocorbula amurensis* has caused decreased summer phytoplankton biomass maximum, presumably as a result of grazing (Alpine & Cloern 1992). With a greater filtration rate than zooplankton, bivalves such as oysters, clams and mussels have been considered for HAB control, but again the quantity needed for this technique are unrealistic (Shirota 1989). Furthermore, at high densities of algae, toxins produced can inhibit the filtration by bivalves, and reduce the filtration rate. Bivalves may be capable of controlling the blooms at lower densities and can prevent the initiation of blooms, however, if a bloom is to occur, filtration by bivalves is not capable of reducing or eliminating blooms (Bricelj et al. 2001).

1.2 Viruses and bacteria

There are several bacteria and viruses that have algicidal or algistatic effects on HAB species (Brussaard 2004; Hare et al. 2005). Viruses and bacteria are naturally found in marine phytoplankton populations and are thought to account for a large proportion of natural mortality through cell lysis (Bratbak et al. 1993; Brussaard 2004; Tarutani et al. 2000). Viruses can both cause accelerated declines in phytoplankton densities as well as preventing blooms by restricting population growth (Brussaard 2004; Gastrich et al.

2004). The effect on an algal population is virus-specific but also strongly influenced by the environment and physiology of the host species (Lawrence et al. 2006).

Phytoplankton have several defense mechanisms against viral infections, e.g. change in morphotype of the algae, enhanced sinking rate to avoid spread of infection and resistance to viral attack (Brussaard 2004). The possible use of a virus (HaV01) to control *Heterosigma akashiwo* was studied by Nagasaki et al (1999). Growth was inhibited during laboratory assays but little inhibition was detected in a natural population, demonstrating that specificity of the virus is a problem (Nagasaki et al. 1999)

Bacteria have also been shown to be lethal to certain HAB species (Doucette et al. 1999; Frazier et al. 2007). In a study by Doucette (1999), an isolate of the bacteria strain 41-DBG2 was tested against isolates *Karenia brevis (*previously *Gymnodinium breve).* The bacteria were effective against four of the toxic strains of *K. brevis* from Florida bay. In a screening of bacteria, Hare et al. (2005) found that Shewanella IRI-160 had growth-inhibiting effects on three species of dinoflagellates. The absence of effect on non-flagellates demonstrates desired specificity and possible use against HABs (Hare et al. 2005). Furthermore, Frazier et al (2007) demonstrated algicidal effects of several bacteria on *Aureococcus anophagefferens* and presented a possible use in control measures.

Problems that prevent the use of viruses and bacteria in the control of HAB are related to the host-specific nature of many viruses, the unspecificity demonstrated in bacteria, the documented co-existence of viruses with phytoplankton which may indicate the inability to control the algae in nature, and reduced controlling effects in natural mixed populations of bacteria (Frazier et al. 2007; Nagasaki et al. 1999). More research is needed before it would be possible to release viral particles or bacteria in the field.

2. Physical control

There have been several earlier studies on the use of physical methods to eliminate HAB, in most cases unsuccessful (reviewed in Shirota 1989). In one study conducted in the 1970s in Japan, techniques to skim the surface water to remove algae were assessed (Shirota 1989). The methods consisted of the generation of fine bubbles attaching to the algae, which were then collected by a skimmer. This technique failed in many aspects including difficulties in filtration of the algae, and no further studies were conducted (Shirota 1989). The use of ultrasonic waves was studied in the laboratory in Japan in 1974, but the technique only worked on the top 50 cm of the water and is not applicable to lower abundances, therefore the method was not practical (Shirota 1989). In a recent study by Xu et al (2007), electrolysis showed a promising method with demonstrated inhibition of the growth of the cyanobacterium *Microcystis areuginosa*. They concluded that it may be possible for this method to be used in control of HAB, but further research with other species is required (Xu et al. 2007).

Table 1. Biological control of HABs.

Control method	Algal species	Results and comments	References
Grazing			
- Protozoans- 5 different species	*Aureococcus anophagefferens*	Two of five species able to consume algae but complicated interactions in nature.	Caron et al. 1989
- Zooplankton- various species	Various species of algae	Multi predator-prey model revealing how HAB species compete for nutrients and are able to prevent grazing	Mitra & Flynn 2006
- *Potamocorbula amurensis* (clam*)*	Various species of algae	Invasion by filter feeding clam has impact on algal abundance in San Francisco Bay	Alpine & Cloern 1992
- *Oxyrrhis marinaI* (heterotrophic dinoflagellate)	*Heterosigma akashiwo*	Grazing by mass culture of the heterotrophic dinoflagellate, suggested for use in semi-closed and closed aquaculture.	Jeong et al. 2003
Virus			
	Emiliania huxleyi	Mortality of algae due to virus infection shown important in natural systems	Bratbak et al. 2003
	Aureococcus anophagefferens	Infection of VLP in natural populations and laboratory experiments	Gastrich et al. 2004
	Heterosigma akashiwo	Inhibition and cell lysis due to viral infection of HaV, but less effects in natural populations	Nagasaki et al. 1999
	Heterosigma akashiwo	Natural mortality due to HaV, but some cells show resistance, which will have effect on population dynamics and composition	Tarutani et al. 2000
Bacteria			
- 41-DBG2	*Karenia brevis*	Effective algacide against 4 strains of *K. brevis*.	Doucette 1999
- Shewanella IR 160	*Pfisteria piscicida,* *Prorocentrum minimum,* *Gyrodinium uncetenum*	Growth inhibition in dinoflagellates, no effect on other groups of algae	Hare et al. 2005
- Several bacteria species	*Aureococcus anophagefferens*	Of 32 isolates from field, 6 had algicidal effects and demonstrated inhibition of algae	Frazier et al. 2007
- Several bacteria species	*Chattonella antiqua*	Complex system of several bacteria, both proliferation and inhibition of algae	Furuki & Kobayashi 1991
- HAK-13 *Pseudomonas fluorescens*	*Heterosigma akashiwo,* *Alexandrium tamarense,* *Cochlodinium polykrikoides*	Strong suppression of growth, causing cell lysis and death of algae. Suggested control measure, but need of more testing.	Kim et al. 2007

3. Flocculation

A relatively new and promising method is flocculation by clays and various long-chained polymers. By using a flocculant, the algal cells are concentrated and clustered together, becoming heavier and will eventually sink. Inorganic flocculants such as aluminium sulfate and ferrates have been used extensively in the purification of water (Shirota 1989). The flocculant with greatest potential is clay; it has a natural water clearing property (Anderson et al. 2001). Clay particles absorb inorganic and organic materials, minute plankton, fragments of plants and animals and form a floc, which sinks to the bottom (Shirota 1989). There have been numerous studies on clay flocculation as a method to control HABs conducted with different species of algae, but also a wide range of clays has been used with varying success (Table 2) (Pierce et al. 2004; Sengco et al. 2005; Sengco et al. 2001; Yu et al. 2004). Modifications to clays, using polyaluminum chloride (PAC), sophorolipid and chitosan-modified sepiolite have demonstrated increased removal efficiency of algae (Pierce et al. 2004; Sengco et al. 2005; Sun et al. 2004a).

Studies have shown that the type of clay, algae species targeted and treatment conditions can all influence the removal efficiency of this technique (Pan et al. 2006; Sengco et al. 2005; Yu et al. 2004). Clay flocculation have already been put into practice in the field to treat natural occurring blooms, e.g. in Japan and Korea (Shirota 1989). The clay treatments have had great results, but the concern of the cost influenced by the local availability and consequent transport, needs to be resolved (Shirota 1989).

Also to be considered is the effect on other marine organisms by suspended particles and sedimentation. There are different opinions on this matter; with some studies showing little or no affect by clay on benthic communities (Anderson et al. 2001; Shirota 1989). In a study by Howell and Shelton (1970) to investigate the effects of china clay waste on the benthic fauna in St Austell and Mevagissey Bays (Cornwall, UK), they found increased biomass mainly sedentary polychaetes, and deposit feeding lamellibranches. In contrast, harmful effects of suspended particles have been demonstrated in the growth, clearance rates, and respiration of filter feeding animals (Cranford & Gordon 1992; Grant & Thorpe 1991; Shumway et al. 2003). A study by Shumway (2003) demonstrated detrimental effects on filter feeding animals as a response to clay and loess, which differed between species (Shumway et al. 2003).

Water flow is an important parameter to consider when predicting the effect of clay addition to the seabed (Archambault et al. 2004; Beaulieu et al. 2005). For example, Archambault (2004) demonstrated two possible scenarios as a result of adding phosphatic clay, a low flow resulting in high sedimentation and formation of a sediment layer on the benthos, and a high flow with clay particles kept in suspension, with the latter having a more damaging effect on the growth rate of the hard clam, *Mercenaria mercenaria*.

The "positive effects", of increased biomass demonstrated by Howell and Shelton (1970) and Shirota (1989), were obtained from studies on deposit feeding organisms, whilst the negative effects have mainly been demonstrated using filter-feeding animals (e.g Shumway et al. 2003). It is likely that the effects on varying groups of organisms will differ, and it is therefore important to broaden the research to a wider range of organisms but also to consider the overall impact on the community structure and to fully understand the impacts of clays in different environmental conditions. Other areas of concern that require more attention include the effects of sedimented and resuspended toxins, and possible oxygen depletion with increased nutrient load on the benthos (Anderson et al. 2001).

Table 2. Flocculation by clay for HAB control.

Type of clay	Algal species	Results and comments	References
Phosphatic clay (IMC-P4)	*Heterocapsa triquetre*	Flow environment will have effect on removal efficiency of clay, and addition of PAC (polyaluminium hydroxychloride) will increase resuspension.	Beaulieu et al. 2005
Phosphatic clay and PAC mixture	*Prymnesium parvum*	Higher removal efficiency against nutrient sufficient cultures than nutrient deficient.	Hagström & Granéli 2005
26 different types of clays	*Microcystis aeruginosa*	Classification of clays and minerals according to 8-h equilibrium removal efficiency. High efficiency demonstrated for spiolite even at lower clay loading.	Pan et al. 2006
Phosphatic clay	*Karenia brevis*	Successful removal of algae and brevetoxins, but 58% of toxins were still present in clay after 14 days.	Pierce et al. 2004
25 clays and loess clay	*Karenia brevis, Aureococcus anophagefferens*	Removal efficiencies differed between clays but also between algal species. Addition of PAC decreased amount clay needed for successful removal.	Sengco et al. 2001
Dry bentonite, kaolinite, illite-clay minerals from Sweden	*Prymnesium parvum*	Effective clay flocculation only under specific conditions. Addition of PAC increased removal efficiency.	Sengco et al. 2005
Kaolinite (H-DP), phosphatic clay (IMC-P2)	*Aureococcus anophagefferens*	Dispersal methods have effect on removal efficiency of algae, higher success when collision frequency was increased, e.g. by mixing.	Yu et al. 2004
Yellow clay and biosurfactant sophorolipid	*Cochlodinium polykrikoides, Alexandrium tamarense*	Laboratory and filed studies revealing higher removal with addition of sophorolipid than clay alone as well as lower effects on other organisms.	Lee et al. 2007; Sun et al. 2004b

4. Chemicals

Pesticides and numerous chemicals have been used extensively in terrestrial environments and some argue similar methods for the marine environment are appropriate (Boesch et al. 1997). However the use of chemicals to control HABs requires specific caution and certain specificity towards target algal species in order to exclude detrimental affects on other non-target aquatic organisms (Anderson et al. 2001). There has been a range of chemicals tested for HAB control with variable success, many of which are not discussed in this review (Table 3). Instead this section focuses on larger projects and recently discovered and promising methods.

4.1 Early studies

One of the first attempts to control HABs with chemicals occurred in Florida in 1957 where copper sulfate was sprayed over large areas in order to control *Karenia* brevis (Rounsefell & Evans 1958). For nearshore and shallow water, the treatment was successful in extinguishing *K. brevis*, but the effect was not long lasting and the bloom re-established within 10-14 days (Rounsefell & Evans 1958). The authors concluded that copper sulfate was too expensive as a control measure but could be used locally to provide immediate temporary relief from the airborne toxin associated

with this species. Furthermore, the chemical itself, copper sulfate may cause great harm in other aquatic organisms (Anderson et al. 2001)

In an attempt to find a chemical to control HABs without causing harmful effects to the aquatic environment the U.S. Fish and Wildlife Service Bureau of Commercial Fisheries conducted a major research project in screening chemicals to control *K.brevis* (Marvin 1964). The study included testing 4,700 chemicals for their ability to cause high mortality in the dinoflagellate at relatively low concentrations and with low toxicity to other marine organisms. The results were disappointing with few compounds meeting the criterion and additional testing of these compounds revealed high variability in natural seawater (Marvin 1964).

4.2 Aponin

Surfactants (surface active agents) are compounds that lower the surface tension between liquids, solids and gases (Sun et al. 2004c). Surfactants accumulate at interfaces and therefore the cell wall of the target species is important for the effects (Ukeles 1965). Species with similar cell wall thickness, composition and structure are more likely to react similarly to addition of surfactants. As the variation in cell walls is large between algal species, the effects of surfactants are likely to be variable (Ukeles 1965).

The compound aponin is a sterol surfactant produced by the blue green alga *Gomphosphaeria aponina* and suggested as a control agent for HABs after the presence of *G. aponina* demonstrated reduction of viability and growth, and caused cytolysis of *K. brevis* within 4-10 days (McCoy & Martin 1977). Steidinger (1983) highlights several problems using aponin against HABs, including cost, practicality of the large amounts needed and modification of the characteristics of the compound required for use in the field. The effect of aponin depends on the algal species, armoured flagellate species being less sensitive (Moon & Martin 1981). The effects aponin might have on other aquatic organisms have not been studied thoroughly although Maestrini and Bonin stated aponin to have "no effect on fishes, crustaceans and bacteria" (1981 referenced in Steidinger 1983).

4.3 Other surfactants

Surfactants have recently been considered for controlling HABs, as a result of high biodegradability and low toxicity (Baek et al. 2003). One example is the biosurfactant sophorolipid (Baek et al. 2003; Sun et al. 2004b). Initial tests on four common HAB species by Baek et al (2003) showed high mobility inhibition (90% after 10min) and no recovery when adding 20mg/l sophorolipod to algal cultures. The results are consistent with other studies and a concentration of 20mg/l has been suggested for mitigation of HABs (Baek et al. 2003; Sun et al. 2004b). There is a difference in responses between different algal species, especially in relation to cell wall, with lysis occurring more rapidly in species lacking cell walls e.g. *Heterosigma akashiwo* (Sun et al. 2004b). The biosurfactant attacks the biological membrane and leakage of nucleotides from algal cells, which explains the inability to recover (Sun et al. 2004b).

This appears to be a promising method at this point in time, but further studies to evaluate the toxicity, specificity towards algal species and practicality must be studied further before sophorolipid could be used in the field. The combination of sophorolipid and yellow loess (a flocculant) has shown synergistic effects on removal of *Cochlodinium polykrikoides,* and more cost effective than any method alone (Sun et al. 2004a).

Several other surfactants have also been evaluated, for example polyoxyethylene alkyl esters have been tested against *Chattonella marina and C. antiqua* and were found to be efficient against the algae but also ichthyotoxic against several species of fish, as the lysis of the algal cells released endotoxins (Ono et al. 1998).

Table 3. Chemicals tested for HAB control.

Chemical	**Algal species**	**Results and comments**	**References**
Copper sulphate	*Karenia brevis*	Treatment successful in killing algal species, but no long lasting effect,	Rounsefell & Evans 1958
Aponin (sterol surfactant)	*Karenia brevis* *Prymnesium parvums*	Causing growth inhibition, and cell lysis in *K. brevis*	McCoy 1977; Moon & Martin 1981
Sophorolipid (biosurfactant)	*Heterosigma akashiwo* *Scripsiella trochoidea* *Prorocentrum minimum* *Alexandrium tamarense* *Cochlodinium polykrikoides*	High mobility inhibition, and cell lysis. High biodegradability and low cost, also synergistic effects with loess treatment.	Baek et al. 2003 Sun et al 2004a Sun et al. 2004b
Cocamidopropyl betaine (CAPB, surfactant)	*Cochlodinium polykrikoides* *Alexandrium tamarense*	High mobility inhibition and cause of cell lysis. Further studies required.	Sun et al. 2004c
Polyoxyethylene alkyl esters (surfactants)	*Chattonella marina* *Chattonella antiqua*	Destroyed cultured algal cells, but also increased ichthyotoxicity.	Ono 1998
Anionic, non-ionic and cationic surfactants	12 species of algae	Inhibition of algae by surfactant was species specific. Cationic surfactants have greater effect	Ukeles 1965
Biocides- SeaKleen ®, Peraclean ® Ocean, Vibre ®	*Gymnodinium catenatuni* *Alexandrium catenella* *Protoceratium reticulatum*	Use against dinoflagellates cysts in ballast water, Peraclean ® Ocean greatest effect	Gregg & Hallegraeff 2007
Hexadecyltrimethyl-amine bromide (HDTMAB)	*Alexandrium* spp.	The addition of HDTMAB contributed to cupric glutamate toxicity	Li et al. 2006
Cystein compounds	*Gymnodinium mikimotoi* *Gymnodinium cf maguelonnense*	Mitigation of cytotoxicity and rheotoxicity which causes fish mortality	Jenkinson & Arzul 2001
Sodium hopchlorite (NaOCl)	Various species of dinoflagellates	NaOCl produced by electrolysis of seawater mostly effective against dinoflagellates, but also non target heterotrophic dinoflagellates	Jeong et al. 2002
Ozone	Various species	Successful use in ballast water treatments, and in aquaculture.	Herwig et al. 2006; Rosenthal 1981
Hydrogen peroxide	*Alexandrium tamarense* *Alexandrium catenella* *Polykrikos schwartzii*	Potential use for extermination of dinoflagellate cysts in ballast water	Ichikawa et al. 1993

In a recent study that screened several surfactants, the chemically synthesized amphoteric surfactant cocamidopropyl betaine (CAPB) appeared most promising (Fig 2)(Sun et al. 2004c). It’s high biodegradability, low cost and relative high removal rate of *Cochlodinium polykrikoides* and *Alexandrium tamarense* encourages further studies (Sun et al. 2004c). However, toxicity testing of CAPB is essential if this surfactant is to be considered for use in the field, as its effects on non-target species are unknown.

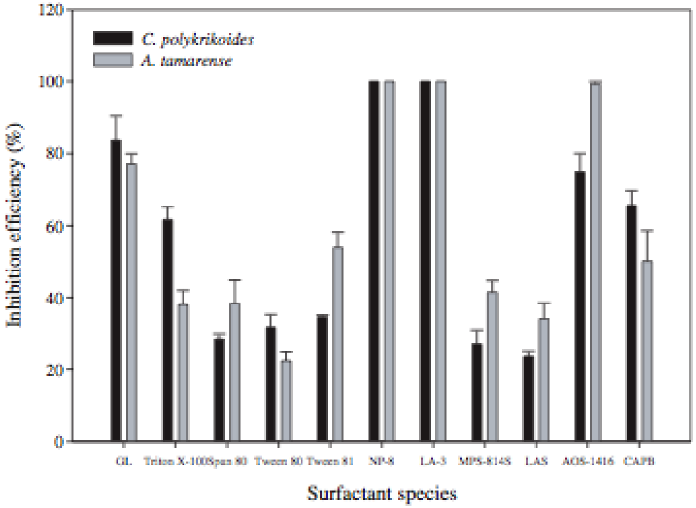

Fig 2. Inhibition rations of 11 surfactants on HAB organisms (surfactants: 10mg/l, contact time 5 min). Bar= SD, n=3. (From Sun et al. 2004c)

One issue of using chemicals in HAB control is the consequence of possible cell lyses of toxic algal cells, as endotoxins will be released into the water, possibly causing more harm. This has been highlighted as a concern in the review by Steidinger (1983) for use of copper and aponin, and the study on polyoxyethylene alkyl esters (Ono et al. 1998), but has not been considered in the use of the surfactants sophorolipid and CAPB (Sun et al. 2004b; Sun et al. 2004c). It may be important to agree on whether cell lysis of algal cells is an acceptable strategy, and whether the losses due to release of endotoxins are causing more harm than benefit.

Conclusions and further studies

The increase in HAB occurrences and global spread is a known fact and many countries suffer severe economic and ecological losses as a consequence. Although there is debate as to whether such effects should be treated (Steidinger 1983), numerous studies have looked at methods to eliminate and reduce algal blooms. The study of natural losses of phytoplankton has lead to investigations of top-down control in the form of grazing as well as algicidal affects of bacteria and viruses, but many issues need to be resolved if any biological measures are to be used as a control against HABs. Flocculation by clay is one of the few methods already put in to practice and has proven to be efficient. Problems with cost and availability of suitable clay are restraining the use in some places. On land, chemicals have long been used for fighting pests and unwanted growth, and the search for chemicals for use in the marine environment has been a long and still ongoing process. Recent advances have concentrated on the use of surfactants as these have often demonstrated high degradability and low toxicity. Toxicity tests are often conducted on commercially important species, especially if chemicals are considered for use in aquaculture, but a wider range of organisms used for toxicity tests is needed and should be examined carefully before tests in the field are possible.

At this point in time, there is no existing method to control HABs, but several promising methods are being investigated. The ultimate control would be treating the cause of the increased blooms such as limiting nutrient enrichment, although this is a longer process and will not give any rapid relief. In the absence of effectively controlling HABs, mitigation of the effects is commonly applied, especially in aquaculture.

References

Alpine, A. E. & Cloern, J. E. 1992 Trophic Interactions and Direct Physical Effects Control Phytoplankton Biomass and Production in an Estuary. *Limnology and Oceanography* **37**, 946-955.

Anderson, D. M., Andersen, P., Bricelj, V. M., Cullen, J. J. & Rensel, J. E. 2001 Monitoring and Management Strategies for Harmful Algal Blooms in Coastal Water. In *APEC 201-MR-01.1, Asia Pacific Economic Program, Singapore, and Intergovernmental Oceanogrpahic Commission Technical Series NO. 59, Paris*.

Anderson, D. M., Glibert, P. M. & Burkholder, J. M. 2002 Harmful Algal Blooms and Eutrophication: Nutrient Sources, Composition, and Consequences. *Estuaries* **25**, 704-726.

Archambault, M. C., Bricelj, V. M., Grant, J. & Anderson, D. M. 2004 Effects of Suspended and Sedimented Clays on Juvenile Hard Clams, Mercenaria Mercenaria, within the Context of Harmful Algal Bloom Mitigation. *Marine Biology* **144**, 553-565.

Baek, S. H., Sun, X. X., Lee, Y. J., Wang, S. Y., Han, K. N., Choi, J. K., Noh, J. H. & Kim, E. K. 2003 Mitigation of Harmful Algal Blooms by Sophorolipid. *Journal of Microbiology and Biotechnology* **13**, 651-659.

Beaulieu, S. E., Sengco, M. R. & Anderson, D. M. 2005 Using Clay to Control Harmful Algal Blooms: Deposition and Resuspension of Clay/Algal Flocs. *Harmful Algae* **4**, 123-138.

Boesch, D. F., Anderson, D. M., Horner, R. A., Shumway, S. E., Tester, P. A. & Whitledge, T. E. 1997 Harmful Algal Blooms in Coastal Water: Options for Prevention, Control and Mitigation, pp. 46 pp + appendix. NOAA Coastal Ocean Office, Silver Spring, MD: NOAA Coastal Ocean Program decision Analysis Series No. 10.

Bratbak, G., Egge, J. K. & Heldal, M. 1993 Viral Mortality of the Marine Alga *Emiliania Huxleyi* (Haptophyceae) and Termination of Algal Blooms. *Marine Ecology Progress Series* **93**, 39-48.

Bricelj, V. M., MacQuarrie, S. P. & Schaffner, R. A. 2001 Differential Effects of Aureococcus Anophagefferens Isolates ("Brown Tide") in Unialgal and Mixed Suspensions on Bivalve Feeding. *Marine Biology* **139**, 605-615.

Brussaard, C. P. D. 2004 Viral Control of Phytoplankton Populations - a Review. *Journal of Eukaryotic Microbiology* **51**, 125-138.

ISSN 1754-2383 [Online]

Caron, D. A., Lim, E. L., Kunze, H., Cosper, E. M. & Anderson, D. M. 1989 Trophic Interactions between Nano- and Microzooplankton and the Brown Tide. In *Novel Phytoplankton Blooms: Causes and Impacts of Recurrent Brown Tides and Other Unusual Blooms* (ed. E. M. Cosper, V. M. Bricelj & E. J. Carpenter), pp. 265-294. New York: Springer-Verlag.

Cranford, P. J. & Gordon, D. C. 1992 The Influence of Dilute Clay Suspenstion on Sea Scallop (*Placopecten Magellanicus)* Feeding Activity and Tissue Growth. *Netherlands Journal of Sea Research* **30**, 107-120.

Doucette, G. J., McGovern, E. R. & Babinchak, J. A. 1999 Algicidal Bacteria Active against *Gymnodinium Breve* (Dinophyceae). I. Bacterial Isolation and Characterization of Killing Activity. *Journal of Phycology* **35**.

Frazier, A. D., Rowe, J. M., Rentz, C. A., Gobler, C. J. & Wilhelm, S. W. 2007 Bacterial Lysis of Aureococcus Anophagefferens Ccmp 1784 (Pelagophyceae). *Journal of Phycology* **43**, 461-465.

Furuki, M. & Kobayashi, M. 1991 Interaction between Chatonella and Bacteria and Prevantion of This Red Tide. *Marine Pollution Bulletin* **23**, 189-193.

Gastrich, M. D., Leigh-Bell, J. A., Gobler, C. J., Anderson, O. R., Wilhelm, S. W. & Bryan, M. 2004 Viruses as Potential Regulators of Regional Brown Tide Blooms Caused by the Alga, Aureococcus Anophagefferens. *Estuaries* **27**, 112-119.

GEOHAB. 2001 Global Ecology and Oceeanogrpahy of Harmful Algal Blooms, Science Place (ed. P. Gilbert & G. Pitcher), pp. 87 pp. Baltimore and Paris.

Grant, J. & Thorpe, B. 1991 Effects of Suspended Sediment on Growth, Respiration, and Excretion of the Soft-Shell Clam (*Mya Arenaria*). *Canadian Journal of Fisheries and Aquatic Sciences* **48**, 1285-1292.

Gregg, M. D. & Hallegraeff, G. M. 2007 Efficacy of Three Commercially Available Ballast Water Biocides against Vegetative Microalgae, Dinoflagellate Cysts and Bacteria. *Harmful Algae* **6**, 567.

Hagstrom, J. A. & Graneli, E. 2005 Removal of Prymnesium Parvum (Haptophyceae) Cells under Different Nutrient Conditions by Clay. *Harmful Algae* **4**, 249-260.

Hare, C. E., Demir, E., Coyne, K. J., Cary, S. C., Kirchman, D. L. & Hutchins, D. A. 2005 A Bacterium That Inhibits the Growth of Pfiesteria Piscicida and Other Dinoflagellates. *Harmful Algae* **4**, 221-234.

Herwig, R. P., Cordell, J. R., Perrins, J. C., Dinnel, P. A., Gensemer, R. W., Stubblefield, W. A., Ruiz, G. M., Kopp, J. A., House, M. L. & Cooper, W. J. 2006 Ozone Treatment of Ballast Water on the Oil Tanker S/T Tonsina: Chemistry, Biology and Toxicity. *Marine Ecology Progress Series* **324**, 37-55.

Hoagland, P., Anderson, D. M., Kaoru, Y. & White, A. W. 2002 The Economic Effects of Harmful Algal Blooms in the United States: Estimates, Assessment Issues, and Information Needs. *Estuaries* **25**, 819-837.

Ichikawa, S., Wakao, Y. & Fukuyo, Y. 1993 Hydrogen Peroxide an Extermination Agent against Cysts of Red Tide and Toxic Dinoflagellates. In *Toxic Phytoplankton Blooms in the Sea* (ed. T. J. Smayda & Y. Shimizu), pp. 133-138. Amsterdam: Elsevier.

Jenkinson, I. R. & Arzul, G. 2001 Mitigation by Cysteine Compounds of Rheotoxicity, Cytotoxicity and Fish Mortality Caused by the Dinoflagellates, *Gymnodinium Mikimotoi* and *G.* Cf. *Maguelonnense*. In *Harmful algal blooms 2000* (ed. G. M. Hallegraeff, S. I. Blackburn, C. J. Bolch & R. J. Lewis), pp. 461-464. Paris: IOC-UNESCO.

Jeong, H. J., Kim, H. R., Kim, K. I., Kim, K. Y., park, K. H., Kim, S. T., Yoo, Y. D., Song, J. Y., Kim, J. S., Seong, K. A., Yih, W. H., Pae, S. J., Lee, C. H., Huh, M. D. & Lee, S. H. 2002 Naocl Produced by Electrolysis of Natural Seawater as Potential Method to Control Marine Red-Tide Dinoflagellates. *Phycologia* **41**, 643-656.

Jeong, H. J., Kim, J. S., Yoo, Y. D., Kim, S. T., Kim, T. H., Park, M. G., Lee, C. H., Seong, K. A., Rang, N. S. & Shim, J. H. 2003 Feeding by the Heterotrophic Dinoflagellate Oxyrrhis Marina on the Red-Tide Raphidophyte Heterosigma Akashiwo: A Potential Biological Method to Control Red Tides Using Mass-Cultured Grazers. *The Journal of Eukaryotic Microbiology* **50**, 274-282.

Kim, J.-D., Kim, B. & Lee, C.-G. 2007 Alga-Lytic Activity of Pseudomonas Fluorescens against the Red Tide Causing Marine Alga Heterosigma Akashiwo (Raphidophyceae). *Biological Control* **41**, 296-303.

Kirkpatrick, B., Fleming, L. E., Squicciarini, D., Backer, L. C., Clark, R., Abraham, W., Benson, J., Cheng, Y. S., Johnson, D., Pierce, R., Zaias, J., Bossart, G. D. & Baden, D. G. 2004 Literature Review of Florida Red Tide: Implications for Human Health Effects. *Harmful Algae* **3**, 99-115.

Landsberg, J. H. 2002 The Effects of Harmfgul Algal Blooms on Aquatic Organisms. *Reviews FIsheries Science* **10**, 113-390.

Lawrence, J. E., Brussaard, C. P. D. & Suttle, C. A. 2006 Virus-Specific Responses of Heterosigma Akashiwo to Infection. *Applied and Environmental Microbiology* **72**, 7829-7834.

Lee, Y. J., Choi, J. K., Kim, E. K., Youn, S. H. & Yang, E. J. 2007 Field Experiments on Mitigation of Harmful Algal Blooms Using a Sophorolipid—Yellow Clay Mixture and Effects on Marine Plankton. *Harmful Algae*.

Li, H., Miao, J.-l., Cui, F.-x. & Li, G.-y. 2006 Promotion of Hexadecyltrimethyleamine Bromide to the Damage of Alexandrium Sp. Lc3 by Cupric Glutamate. *Journal of Environmental Sciences* **18**, 1152-1156.

Marvin, K. T. 1964 Screening of Chemicals for the Control of *Gymnodinium Breve*. In *Symposium on Red Tide.* . Biological Station, St Petersburg, FL: U.S Fish and Wildlife Service, Bureau of Commercial Fisheries report.

McCoy, L. F. & Martin, D. F. 1977 The Influence of Gomphospaeria Aponina on the Growth and Gymnodinium Breve and the Effect of Aponin on the Ichthytoxicity of Gymnodinium Breve. *Chemico-Biological Interactions* **17**, 17-24.

Millie, D. F., Dionigi, C. P., Schofield, O., Kirkpatrick, G. J. & Tester, P. A. 1999 Preface the Importance of Understanding the Molecular, Cellular, and Ecophysiological Bases of Harmful Algal Blooms. *Journal of Phycology* **35**.

Mitra, A. & Flynn, K. J. 2006 Promotion of Harmful Algal Blooms by Zooplankton Predatory Activity. *Biology Letters* **2**, 194-197.

Moon, R. E. & Martin, D. F. 1981 The Cytolytic Substance Aponin on Prymnesium Parvum and Ptychodiscus Brevis, a Comparative Study. *Botanica Marina* **24**, 591-593.

Nagasaki, K., Tarutani, K. & Yamaguchi, M. 1999 Growth Characteristics of Heterosigma Akashiwo Virus and Its Possible Use as a Microbiological Agent for Red Tide Control. *Appl. Environ. Microbiol.* **65**, 898-902.

Ono, Arakawa, Onoue, Matsumoto, Shihara, Takeda, Nakanishi, Yamaji, Uemura & Ogawa. 1998 Synthetic Surfactants for Protecting Cultured Fish against Toxic Phytoplankton. *Aquaculture Research* **29**.

Pan, G., Zou, H., Chen, H. & Yuan, X. 2006 Removal of Harmful Cyanobacterial Blooms in Taihu Lake Using Local Soils Iii. Factors Affecting the Removal Efficiency and an in Situ Field Experiment Using Chitosan-Modified Local Soils. *Environmental Pollution* **141**, 206-212.

Pierce, R. H., Henry, M. S., Higham, C. J., Blum, P., Sengco, M. R. & Anderson, D. M. 2004 Removal of Harmful Algal Cells (Karenia Brevis) and Toxins from Seawater Culture by Clay Flocculation. *Harmful Algae* **3**, 141-148.

Rosenthal, H. 1981 Ozonation and Sterilization. In *World Symposium on New Devlopments in the Utilization of Heated Effluents and Reciculating Systems*. Stavanger, Norway: European Inland Fisheries Commission.

Rounsefell, G. A. & Evans, J. E. 1958 Large-Scale Experimental Test of Copper Sulfate as a Control for the Florida Red Tide, pp. 57: U.S. Fish and Wildlife Serv. Spec. Sci. Rep. 270.

Sengco, M. R., Hagstrom, J. A., Graneli, E. & Anderson, D. M. 2005 Removal of Prymnesium Parvum (Haptophyceae) and Its Toxins Using Clay Minerals. *Harmful Algae* **4**, 261-274.

Sengco, M. R., Li, A. S., Tugend, K., Kulis, D. & Anderson, D. M. 2001 Removal of Red- and Brown-Tide Cells Using Clay Flocculation. I. Laboratory Culture Experiments with Gymnodinium Breve and Aureococcus Anophagefferens. *Marine Ecology Progress Series* **210**, 41-53.

Shirota, A. 1989 Red Tide Problem and Countermeasures (2). *International Journal of Aquaculture and Fisheries Technology* **1**, 195-233.

Shumway, S. E., Frank, D. M., Ewart, L. M. & Evan ward, J. 2003 Effect of Yellow Loess on Clearance Rate in Seven Species of Benthic, Filter-Feeding Invertebrates. *Aquaculture Research* **34**, 1391.

Smayda, T. J. 1989 Primary Production and the Global Epidemic of Phytoplankton Blooms in the Sea: A Linkage? In *Novel Phytoplankton Blooms: Causes and Impacts of Recurrent Brown Tides and Other Unusal Blooms* (ed. E. M. Cosper, V. M. Bricelj & E. J. Carpenter), pp. 449-483. New York: Springer-Verlag.

Sun, X.-X., Lee, Y.-J., Choi, J.-K. & Kim, E.-K. 2004a Synergistic Effect of Sophorolipid and Loess Combination in Harmful Algal Blooms Mitigation. *Marine Pollution Bulletin* **48**, 863-872.

Sun, X. X., Choi, J. K. & Kim, E. K. 2004b A Preliminary Study on the Mechanism of Harmful Algal Bloom Mitigation by Use of Sophorolipid Treatment. *Journal of Experimental Marine Biology and Ecology* **304**, 35-49.

Sun, X. X., Han, K. N., Choi, J. K. & Kim, E. K. 2004c Screening of Surfactants for Harmful Algal Blooms Mitigation. *Marine Pollution Bulletin* **48**, 937-945.

Tarutani, K., Nagasaki, K. & Yamaguchi, M. 2000 Viral Impacts on Total Abundance and Clonal Composition of the Harmful Bloom-Forming Phytoplankton Heterosigma Akashiwo. *Appl. Environ. Microbiol.* **66**, 4916-4920.

Tillmann, U. 2004 Interactions between Planktonic Microalgae and Protozoan Grazers1. *The Journal of Eukaryotic Microbiology* **51**.

Ukeles, R. 1965 Inhibition of Unicellular Algae by Synthetic Surface-Active Agents. *Journal of Phycology* **1**.

Xu, Y., Yang, J., Ou, M., Wang, Y. & Jia, J. 2007 Study of Microcystis Aeruginosa Inhibition by Electrochemical Method. *Biochemical Engineering Journal* **36**, 215-220.

Yu, Z. M., Sengco, M. R. & Anderson, D. M. 2004 Flocculation and Removal of the Brown Tide Organism, Aureococcus Anophagefferens (Chrysophyceae), Using Clays. *Journal of Applied Phycology* **16**, 101-110.

Zhang, J. 1994 Atmospheris Wet Deposition of Nutrient Elements: Correlation with Harmful Biological Bloosm in Nortwest Pacific Coastal Zones. *Ambio* **23**, 464-468.