# Bloom Control Strategies for Harmful Algal Blooms

**Donald M. Anderson and Mario R. Sengco**
**Senior Scientist, Biology Department**
**Woods Hole Oceanographic Institution**

# Management of harmful algae

- ***Prevention***

  options for reducing the incidence and extent of HABs before they begin

  **- alteration of nutrient inputs**

  **- ballast water management**

- ***Mitigation***

  when a bloom is present, reduce the loss of resources and minimize health risks

  **- monitoring for cells and toxins**

  **- forecasting and public communication programs**

  **- transfer of fish pens to clean sites**

- ***Control***

  during an outbreak, methods that target and attack the causative organisms

  **- biological**

  **- chemical**

  **- ultrasonics**

  **- ozonation**

  **- chemical flocculation**

  **- clay flocculation**

# Chemical Control

**Inorganic chemicals**

$CuSO_4$, $KMnO_4$, $FeCl_3$, chlorine,
ozone
NaOCl (from electrified seawater)
$H_2O_2$ (against cysts)
…….others

**Organic chemicals**

APONIN (from alga *Nannochloris* sp.)
Sophorolipids (from fungus *Candida bombicola*)
phlorotanins (from brown alga *Ecklonia kurome*)
Barley straw bales and extract
…….others

**With one or two exceptions, chemical control of HABs has not been attempted on any significant scale in natural marine waters.**

# Chemical control of freshwater algal blooms
## - copper sulfate, algicides, barley straw

**Barley straw:**

**<u>Application rates</u>: Based on pond surface area rather than volume - about 225 lbs/acre.**

Figure 1. For treatments of larger ponds, barley straw can be repacked using a Christmas tree baler to feed the straw into a mesh bag. Photo courtesy of Steve McComas, Blue Water Science, St. Paul, MN.

***Source*: Lembi, C.A. Aquatic Plant Management, Purdue Univ. Cooperative Extension Office, APM-1-W, 8/02**

- Decomposing barley straw releases inhibitory compounds, possibly oxidized polyphenolics derived from lignins and tannins. It is considered more environmentally benign than other chemical treatments.
- These do not kill the algae, but limit or prevent cell proliferation.
- Effects seen days to months after use, and can last several months.
- This method is used in freshwater systems. Very little work has been done on brackish, estuarine or marine environments.
- Some controversy remains regarding mode of action and effectiveness.
- Will this work on *P. parvum*, and especially, in the winter?

Figure 2. A large barley bag being anchored into a lake. Photo courtesy of Steve McComas, Blue Water Science, St. Paul, MN.

*Source*: Lembi, C.A. Aquatic Plant Management, Purdue Univ. Cooperative Extension Office, APM-1-W, 8/02

*Hydrobiologia* **340:** 307–311, 1996.
*J. M. Caffrey, P. R. F. Barrett, K. J. Murphy & P. M. Wade (eds), Management and Ecology of Freshwater Plants.*


# The control of diatom and cyanobacterial blooms in reservoirs using barley straw

[1]P. R. F. Barrett, [2]J. C. Curnow, [3]J. W. Littlejohn
[1] *8 Sunderland Avenue, Oxford OX2 8DX, England*
[2] *Environmental Medicine, Grampian Health Board, Aberdeen, Scotland*
[3]*Grampian Regional Council, Depatment of Water Services, Aberdeen, Scotland*

- This (small) reservoir had a long history of cyanobacterial blooms, with well-recorded observations of algal types and cell counts.
- During 17-mo. trial, level of tested chemicals remained within acceptable limits and there were no customer complaints
- A marked reduction in algal populations occurred over the 2 summers with straw application. However, no definite conclusions can be drawn due to lack of a legitimate control.

*Table 1*. Mean Monthly Algal Counts in Reservoir 1 Cells per ml

| Year | 1991 | 1992 | 1993 | 1994 |
|---|---|---|---|---|
| January | N/C | 10,000 | 10,000 | 400 |
| February | 13,000 | 18,000 | 17,500 | 6,200 |
| March | 21,500 | 28,000 | 22,800* | 7,800 |
| April | 57,400 | 38,000 | 29,000 | 8,700 |
| May | 67,500 | 25,200 | 14,500 | 3,400 |
| June | 45,000 | 16,500 | 6,800 | 106* |
| July | N/C | 17,700 | 3,000 | 57 |
| August | 2,000 | 10,500 | 4,500 | 440 |
| September | N/C | OS | 1,500 | |
| October | 4,000 | OS | 1,000 | |
| November | 10,000 | 4,000 | 1,000 | |
| December | 2,000 | 7,000 | 1,000* | |

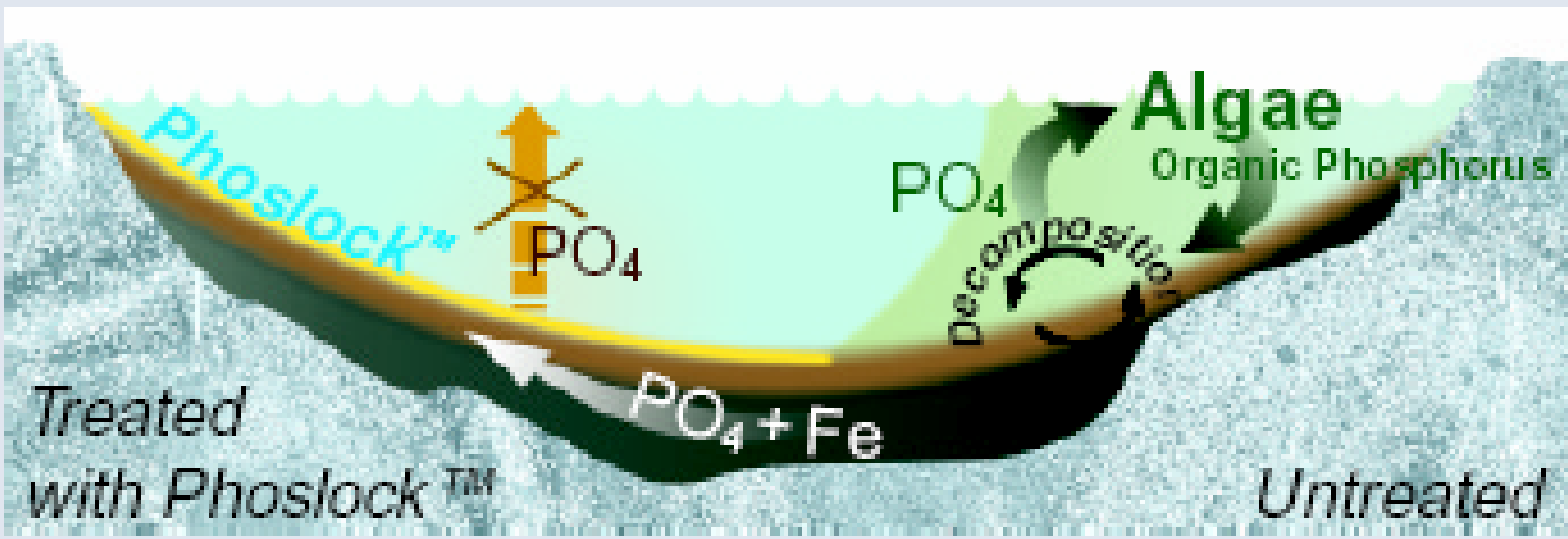
* Straw introduced after the sampling dates in March and December 1993 and June 1994.

**Source: Barrett et al., 1996**

# Chemical flocculants - Phosphorus Control

**alum**
**polyaluminum chloride**
**Phoslock (clay-based)**

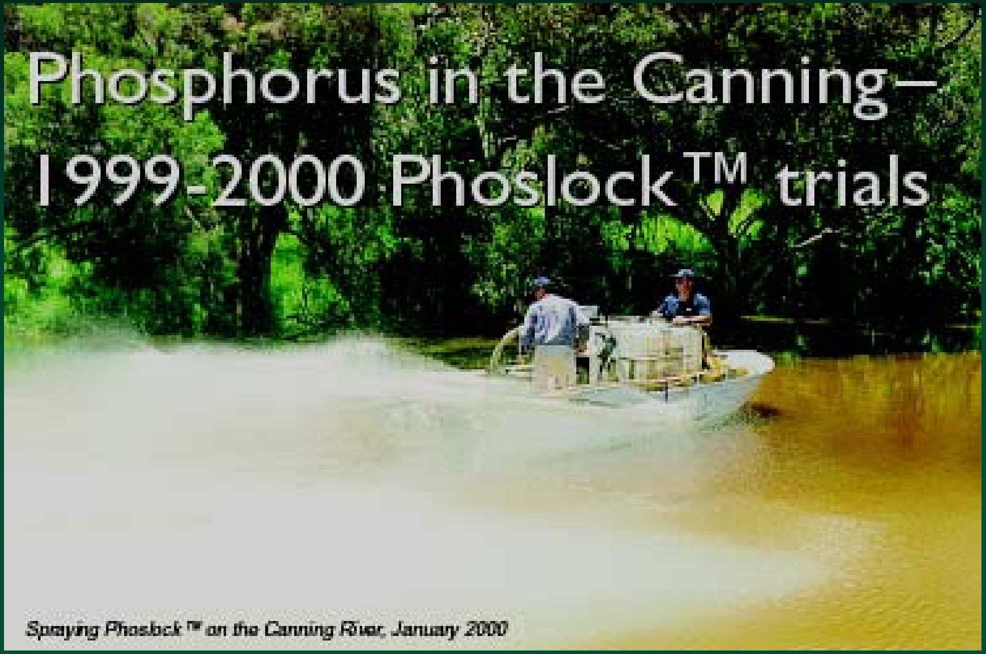
## How phosphorus moves through the environment




Phoslock™ forms a reactive layer on the sediment that binds phosphorus as it is released from the decomposition of organic matter, or transported into the water body from the catchment. This reduces the amount of phosphorus available to algae, and in theory should reduce algal growth.

**from:** ***River Science*****, Issue 17, 2001**

# Phosphorus control in Australian using "Phoslock"




from: *River Science*, Issue 17, 2001

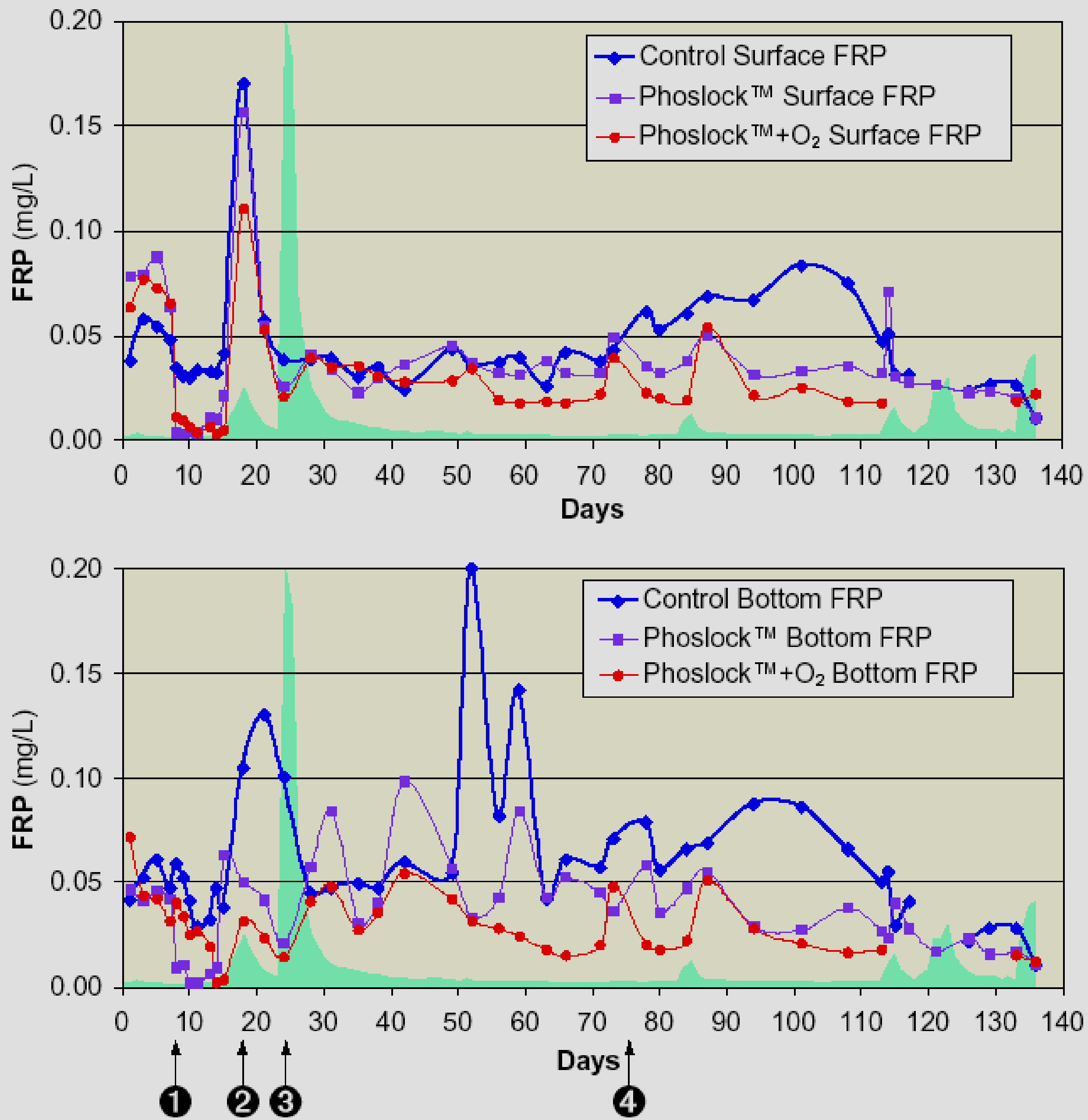



*Figure showing changes in FRP concentrations with time. The green shaded area shows relative flow rates in the Canning River. Point 1 is the application of Phoslock on 5 January 2000. Point 2 is the first rainfall and first flush of nutrients. At point 3 high flow rates flush the trial area. At point 4 FRP concentrations in the bottom water of Phoslock treated areas are consistently less than those of the control area.*

**from: *River Science*, Issue 17, 2001**

## Biological control

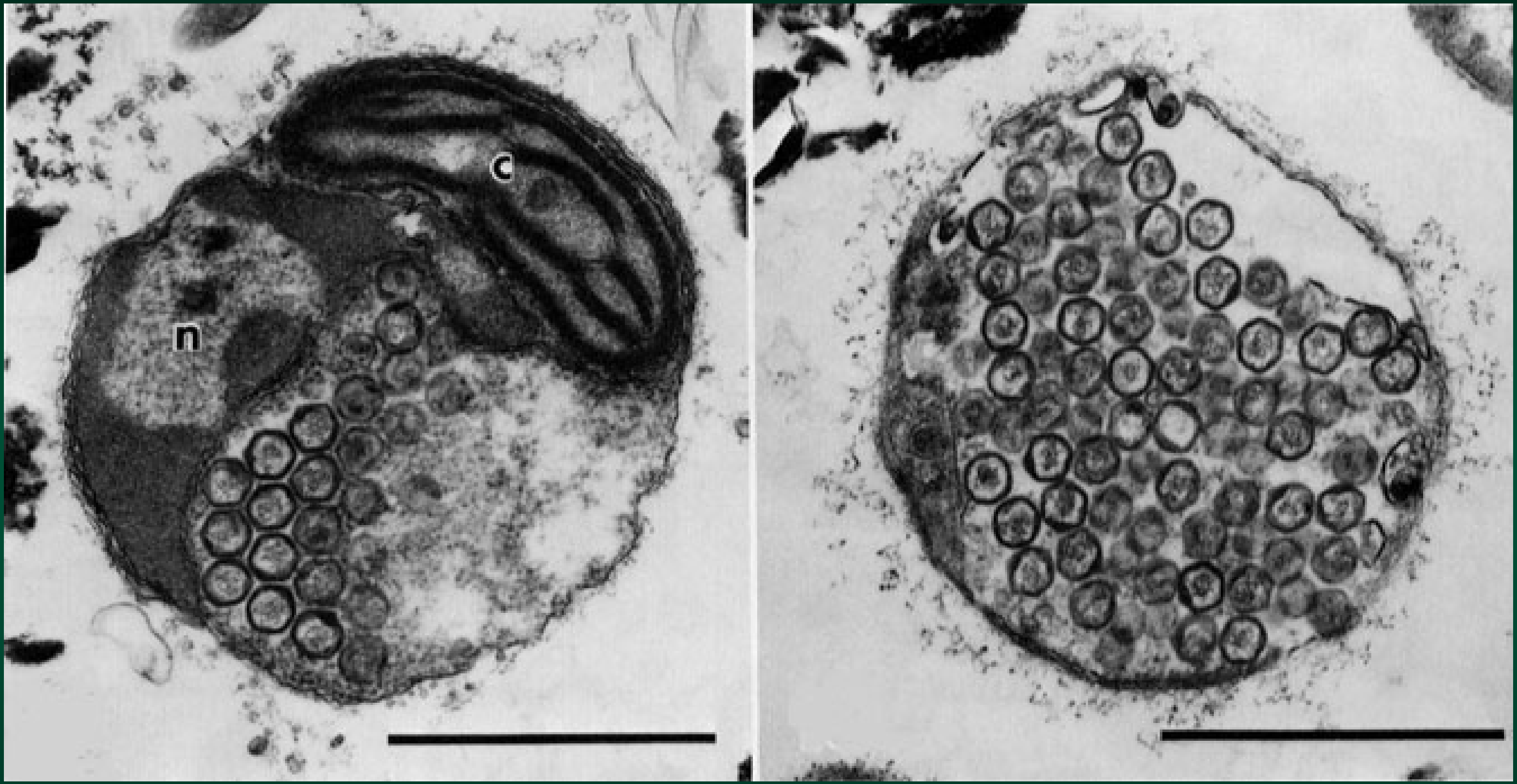
Introduction of non-native predatory or pathogenic species or enhancement of native species.

- Researchers have not yet attempted to use biocontrol in the ocean
- Concerns center on the potential for the introduced species to impact organisms other than the original target species.
- After a long and mixed history on land, biocontrol is receiving increased scrutiny for marine applications, motivated in large part by the proliferation of introduced species.

## Biocontrol of HABs? Is it possible?

Yes - we have host-specific predators, parasites and pathogens for many HAB species

# Biological Control - Viruses




*Aureococcus anophagefferens* virus

**Source: Gastrich et al., 1998, *Phycologia***

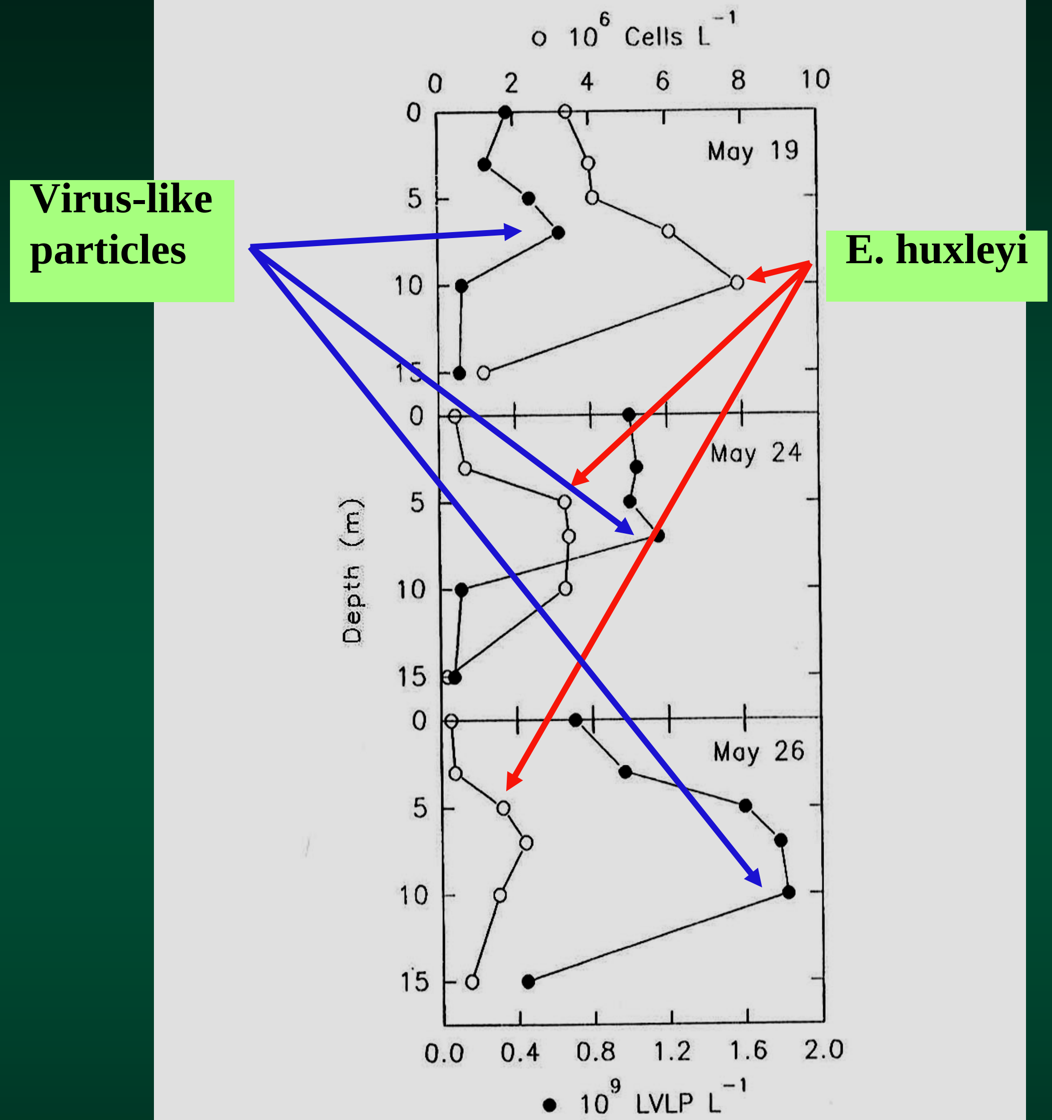



Fig. 2. Dynamics of LVLPs and *E. huxleyi* during one week in May 1993 in Fauskangerpollen, western Norway. The collapse of the *E. huxleyi* bloom corresponded in time and space with an increase in LVLP abundance. Simultaneous changes in other phytoplankton populations were small (for further details see Bratbak et al., 1995).

**Source: Bratbak et al., 1996**

# Viruses for HAB species

| Target species | Agent | Reference |
| --- | --- | --- |
| *Heterosigma akashiwo* | virus HAV01 | Nagasaki et al., 1999 |
| | virus HaNIV | Lawrence et al., 2001 |
| *Heterocapsa circularisquama* | virus HcV | Tarutani et al., 2001 |
| *Aureococcus anophagefferens* | VLP | Gastrich et al., 2002 |
| *Alexandrium catenella* | VLP | Onji et al., 2000 |
| *Gymnodinium mikimotoi* | VLP | Onji et al., 2000 |
| *Tetraselmis sp.* | VLP | Onji et al., 2000 |
| *Lyngbya majuscula* | virus | Hewson et al., 2001 |
| VLP = virus-like particles | | |

**Pros:** **extreme host specificity, rapid proliferation**

**Cons:** **extreme host specificity, general distrust of biocontrol in ocean**

**==>Potentially effective, but not yet tested in field applications**

# Biological control - algicidal bacteria

**Mode of action:**

- direct physical contact, leading to cell lysis
- release of algicidal compounds

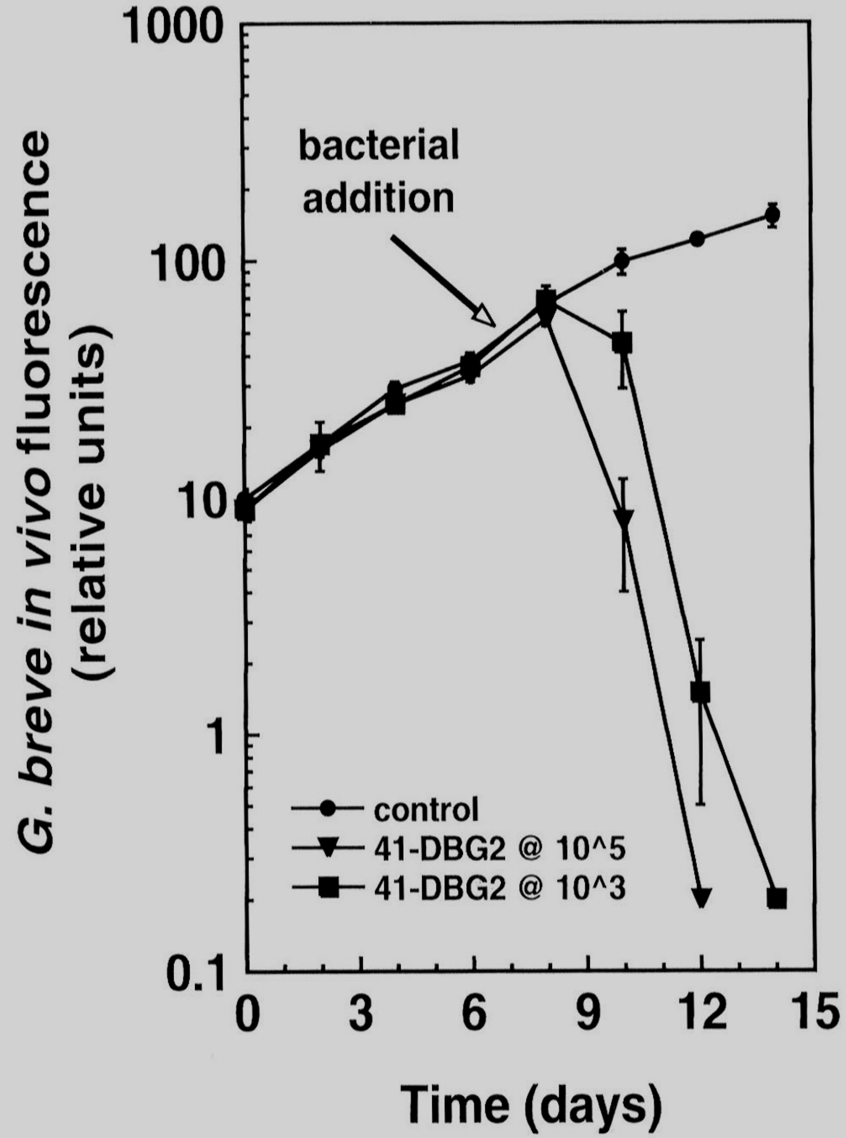



FIG. 1. *Gymnodinium breve* Davis (strain C2). Growth curves of algal cultures as measured by *in vivo* fluorescence, showing response following additions of bacterial strain 41-DBG2 (arrow) at two concentrations (▼ = $10^5$ cells·mL$^{-1}$, ■ = $10^3$ cells·mL$^{-1}$) relative to a no-addition control (●). Values are mean ± SD (n = 3).

**Source: Doucette et al., 1999**

# Biological Control - Bacterial pathogens for HAB species

| Target species | Agent | Reference |
|---|---|---|
| *Heterocapsa circularisquama* | Cytophaga sp AA8-2 | Nagasaki et al., 2000. |
| *Heterosigma akashiwo* | H. akashiwo-killing bacteria (HAKB) | Kim et al., 1998 |
| | H. akashiwo-killing bacteria (HAKB) | Yoshinaga et al., 1998 |
| *Cochlodinium polykrikoides* | Micrococcus sp. LG-1 | Park et al., 1998 |
| *Chattonella ovata* | Altermonas sp. strain S, strain R, Cytophaga sp J18/M01 | Imai 1997 |
| *Chattonella verruculosa* | Altermonas sp. strain S, strain R, Cytophaga sp J18/M01 | Imai 1997 |
| *Karenia mikimotoi* | 28 strains | Yoshinaga et al., 1997 |
| *Karenia brevis* | bacterium 41-DBG2 | Doucette et al., 1999 |

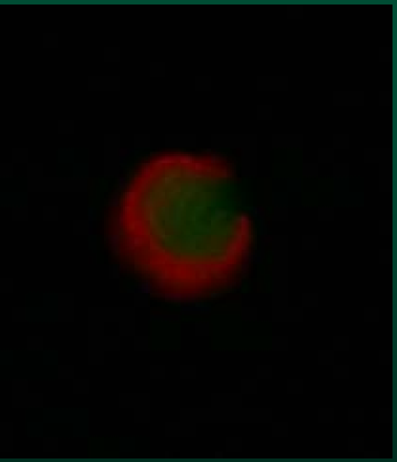
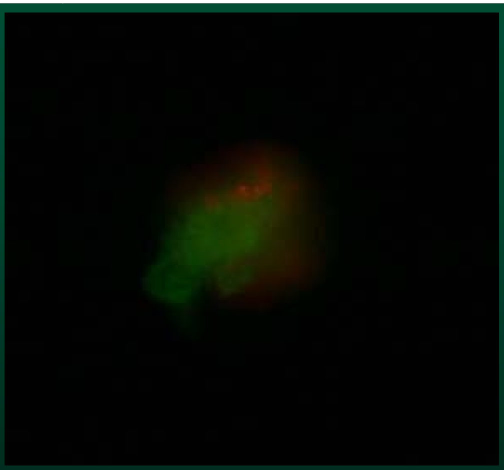
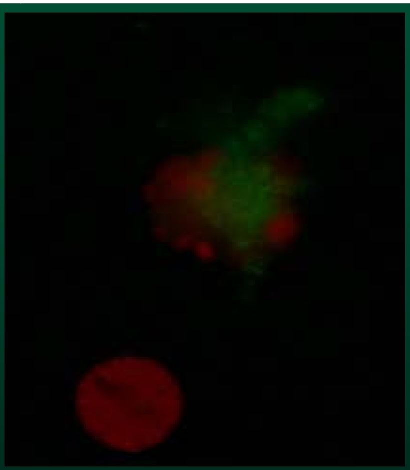
**Pros:** high host specificity, rapid proliferation of pathogen

**Cons:** general distrust of biocontrol in ocean, logistical concerns

**==> Potentially effective, but not yet tested in field applications**

# Biological Control - Parasites

| Target species | Agent | Reference |
|---|---|---|
| *Peridinium balticum* | *Coccidinium duboscqui* | Chatton and Biecheler, 1934 |
| *Dinophysis* sp. | *Parvilucifera infectans* | Noren et al., 1999 |
| *Alexandrium* spp. | *Parvilucifera infectans* | Noren et al., 1999 |
| *Alexandrium catenella* | *Amoebophrya ceratii* | Taylor, 1968 |
| | *Amoebophrya ceratii* | Nishitani et al., 1984 |
| *Alexandrium tamarensis* | *Amoebophrya ceratii* | Jacobson, 1987 |
| *Dinophysis norvegica* | *Amoebophrya ceratii* | Fitz and Nass, 1992 |
| | *Amoebophrya ceratii* | Janson et al., 2000 |
| *Akashiwo sanguinea* | *Amoebophrya ceratii* | Coats and Bockstahler, 1994 |
| *Gyrodinium uncatenum* | *Amoebophrya ceratii* | Coats et al., 1996 |
| *Prorocentrum minimum* | *Amoebophrya sp.* | Maranda, 2001 |

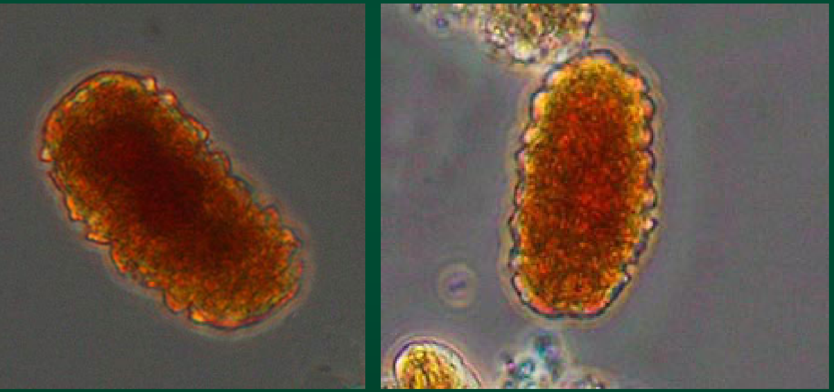
**Pros: high host specificity, rapid proliferation of pathogen**

**Cons: general distrust of biocontrol in ocean, logistical concerns**

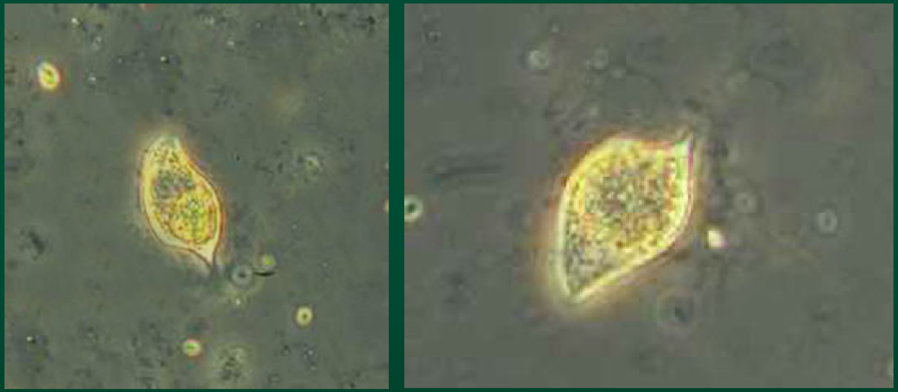
**==> Potentially effective, but not yet tested in field applications**

# Biological Control - Grazers

| Target species | Agent | Reference |
|---|---|---|
| *Karenia brevis* | ciliates | Martin et al., 1973 |
| algal blooms | intact benthic community (San Franscico Bay) | Cloern, 1982 |
| algal blooms | *Acartia clausi* (copepod) and bivalves | Shirota, 1989 |
| *Aureumbra lagunensis* | planktonic grazers | Buskey et al., 1996 |
| *Gymnodinium catenatum* | *Polykrikos kofoidii* (heterotrophic dinoflagellate) | Jeong et al., 2003 |
| *Heterosigma akashiwo* | *Oxyrrhis marina* (heterotrophic dinoflagellate) | Jeong et al., 2003 |



***Polykrikos kofoidii***



***Oxyrrhis marina***

**<u>Pros:</u> moderate specificity, natural predator**

**<u>Cons:</u> slow proliferation, logistical concerns for growth and delivery**

**==> unlikely to be used in practical bloom control efforts**

J. Eukaryot. Microbiol., 50(4), 2003 pp. 274–282


# 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

HAE JIN JEONG,[a] JAE SEONG KIM,[a] YEONG DU YOO,[b] SEONG TAEK KIM,[a] TAE HOON KIM,[a] MYUNG GIL PARK,[c] CHANG HOON LEE,[c] KYEONG AH SEONG,[d] NAM SEON KANG[d] and JAE HYUNG SHIM[e]

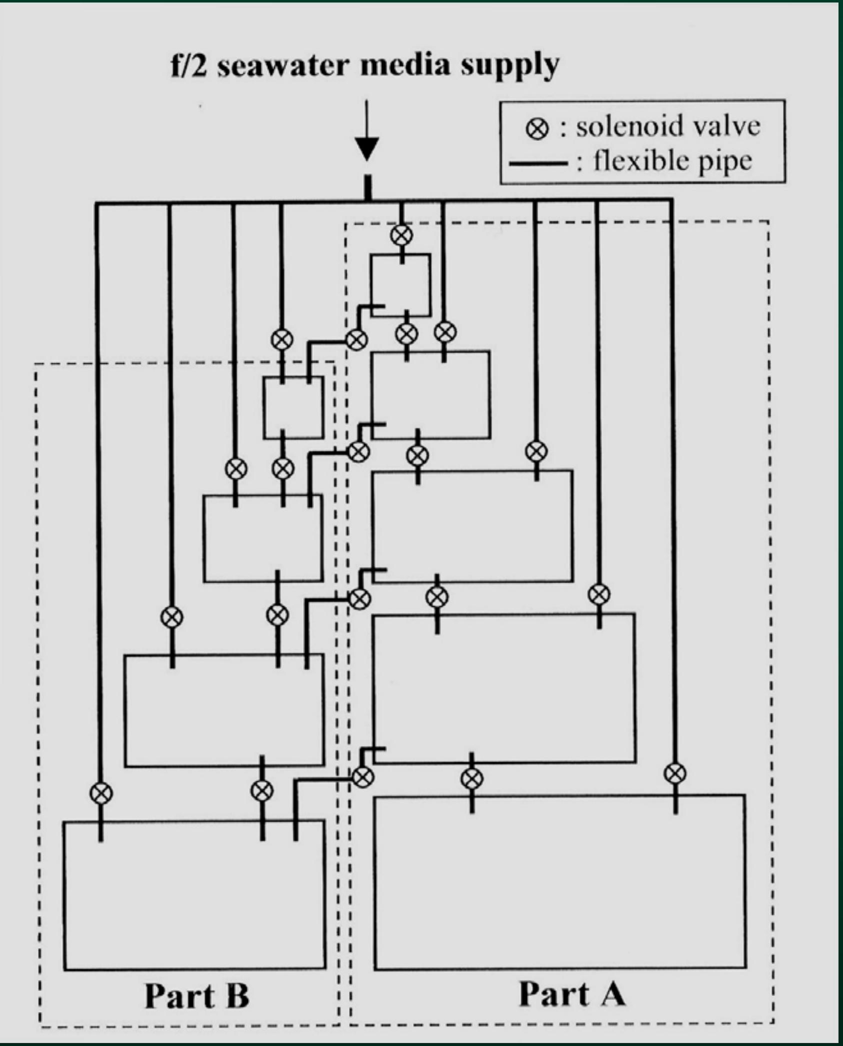
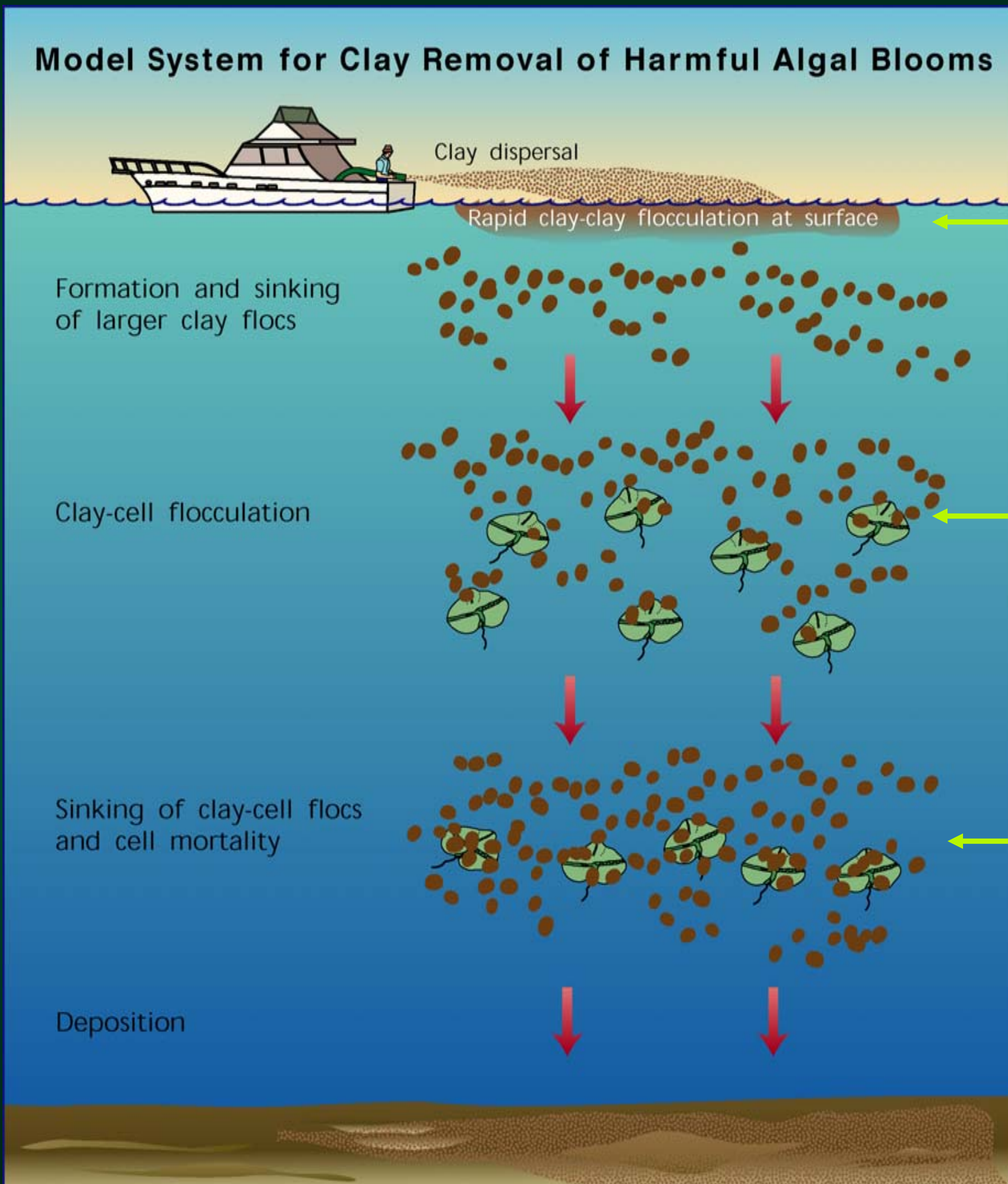
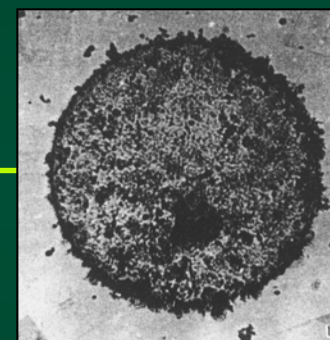



Diagram of an automatic system for growing daily 300 L of *Oxyrrhis marina*

# Clay control of HAB species

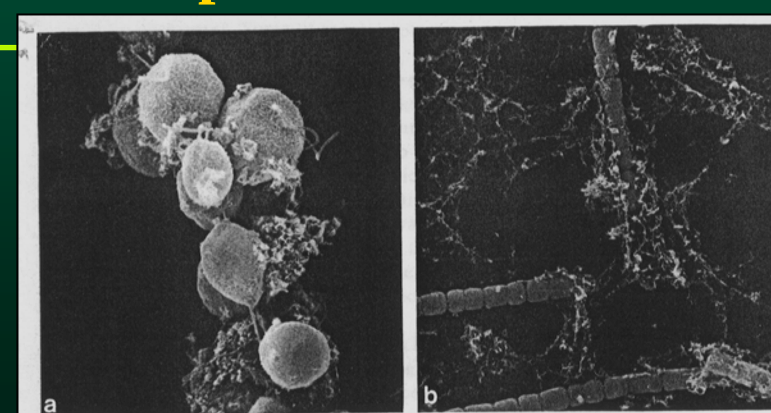



clay minerals



clay/cell flocculation

“sweep floc”



# Clay control research in the United States

How effective are domestic clays at removing U.S. HAB species?

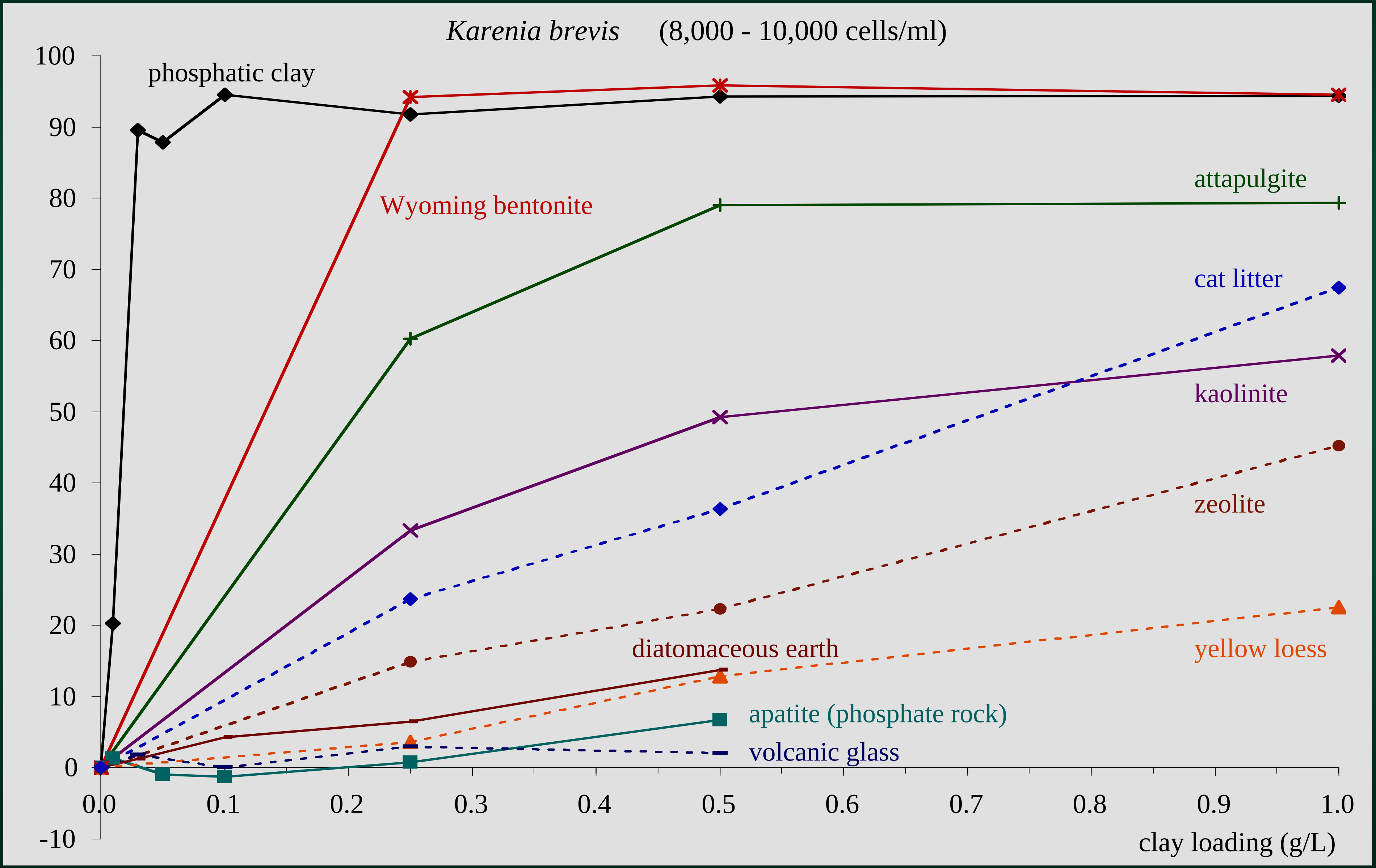
What are the impacts of clay dispersal on water quality and benthos?

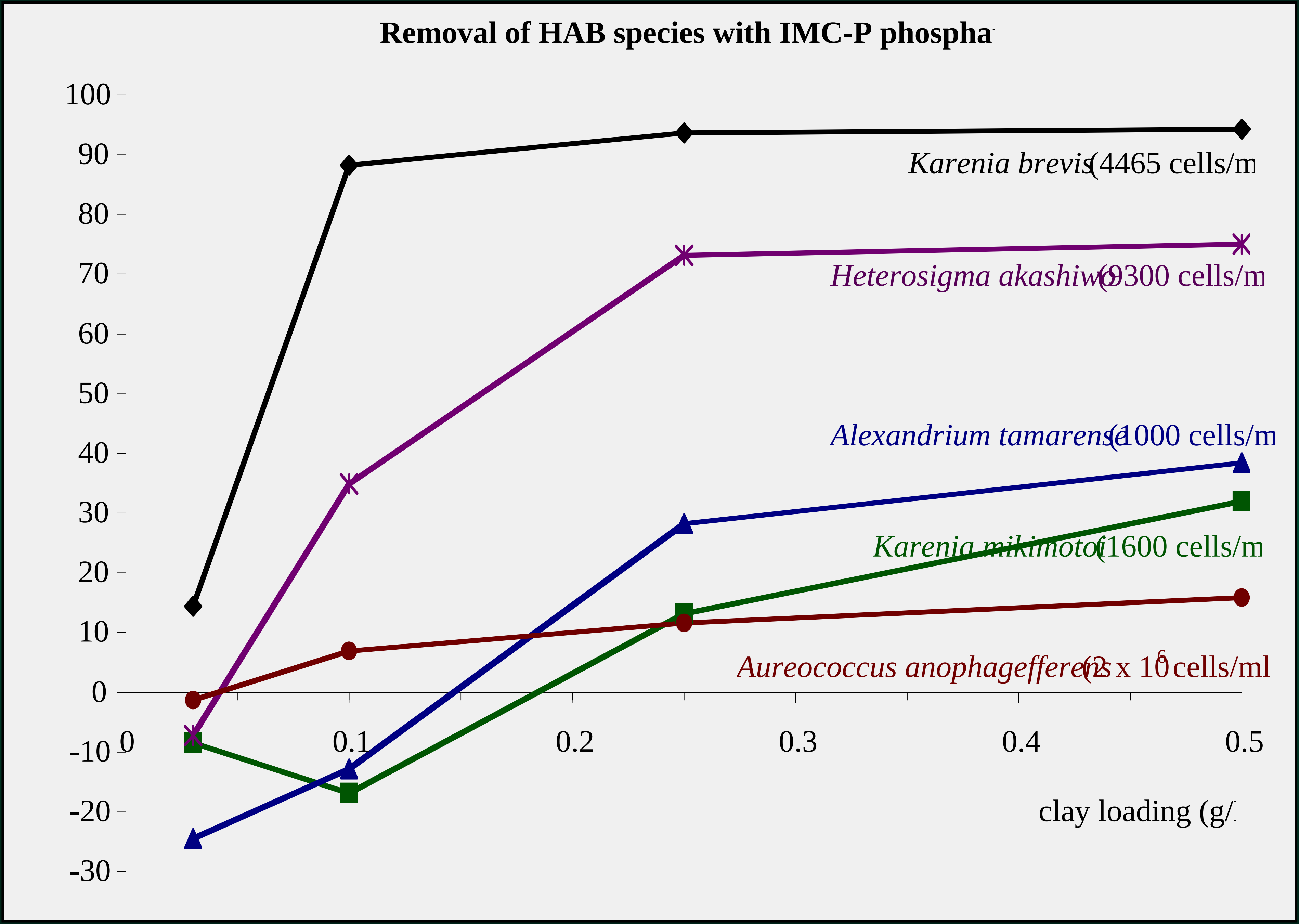
Can we recommend clay control as a means of HAB management?

**<u>Approach:</u>** **laboratory cultures ==> "mesocosms" ==> field trials**

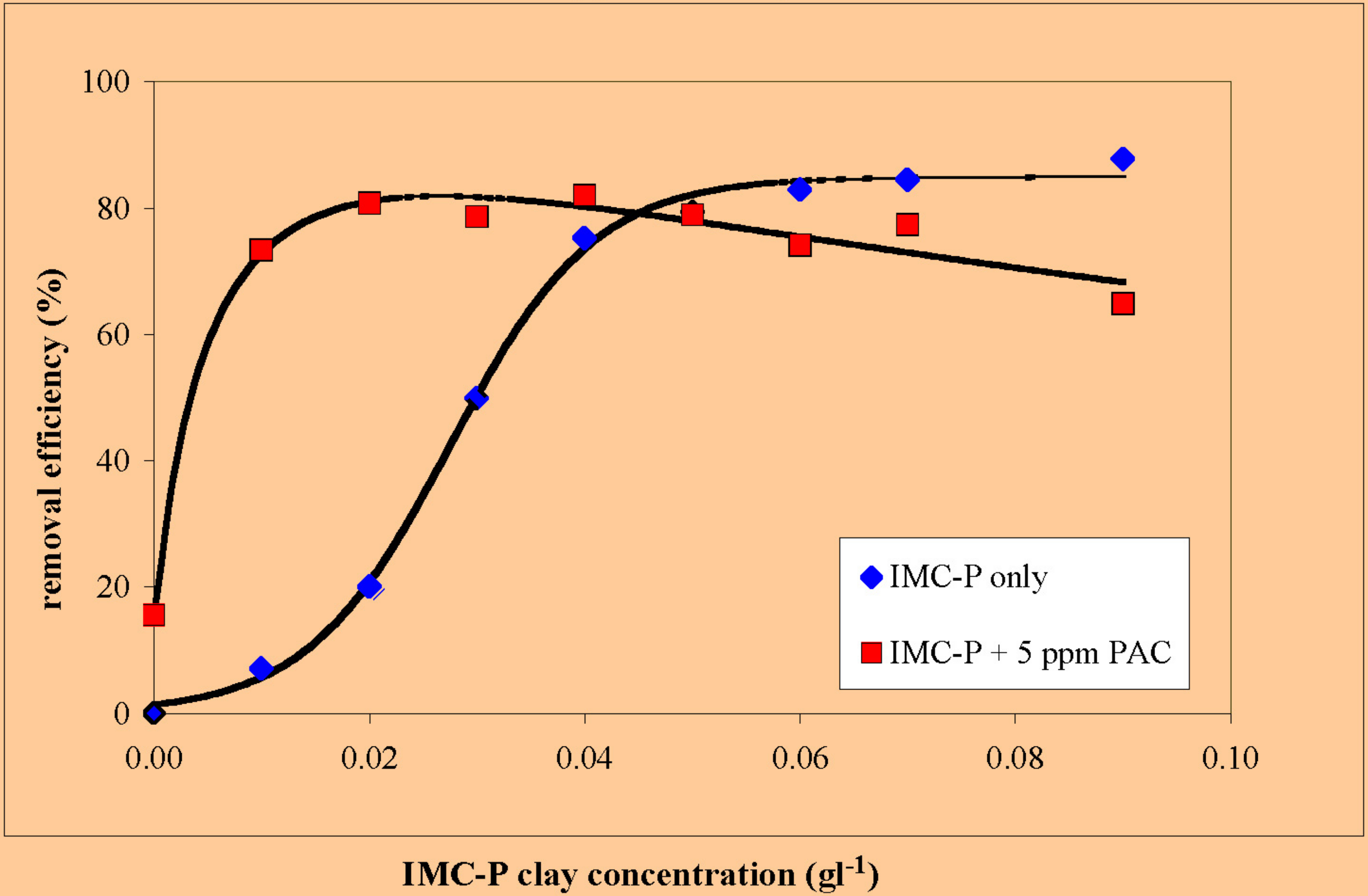
**enclosures**
**limnocorrals**
**flumes**

# Variable removal ability of domestic clay and non-clay minerals




Removal of HAB species with IMC-P phospha
Karenia brevis (4465 cells/m
Heterosigma akashiwo (9300 cells/m
Alexandrium tamarense (1000 cells/m
Karenia mikimotoi (1600 cells/m
Aureococcus anophagefferens (2 x 10^6 cells/ml
clay loading (g/
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
0
0.1
0.2
0.3
0.4
0.5

# Removal efficiency of IMC-P alone and IMC-P2 treated with PAC against *Gymnodinium breve*

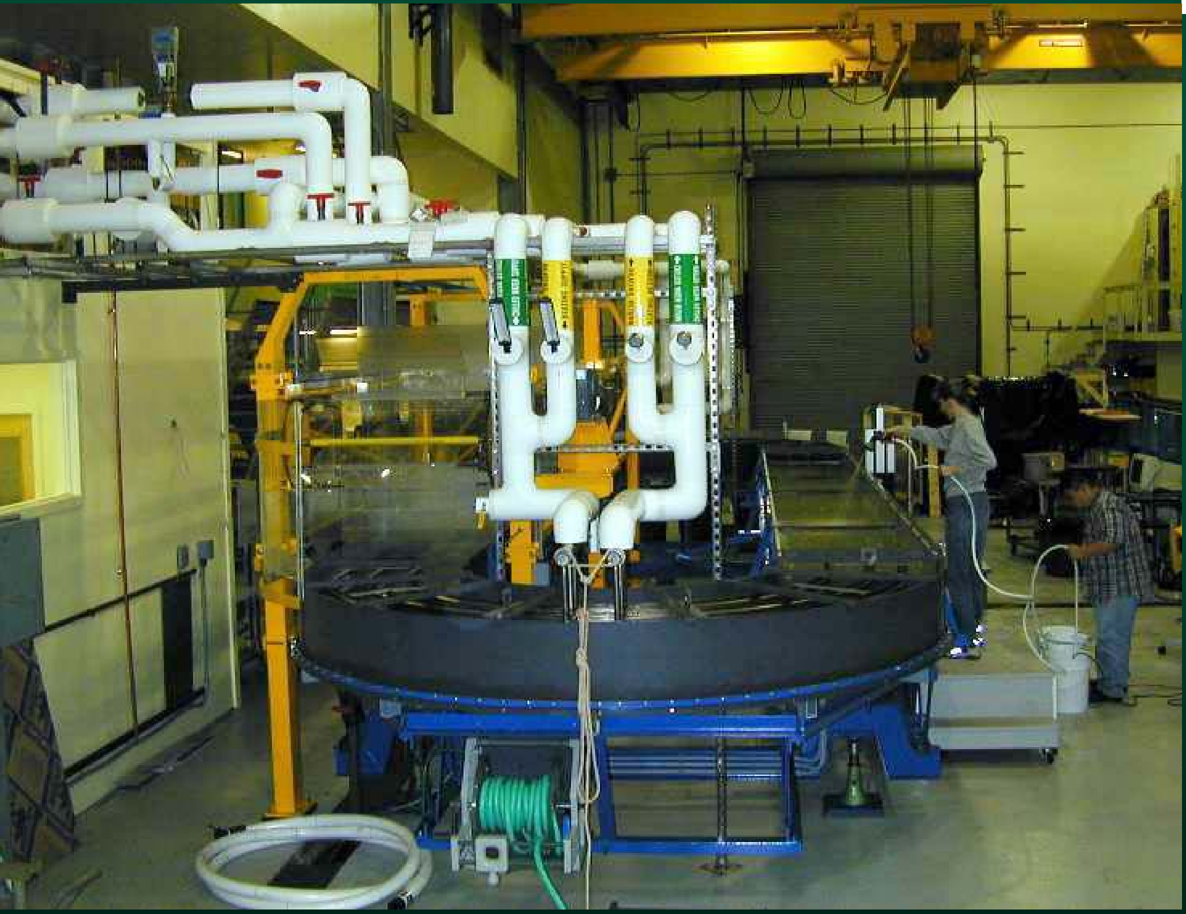



Source: Sengco et al., 2001, Mar. Ecol. Prog. Ser.

# Removal efficiency
## at intermediate scales

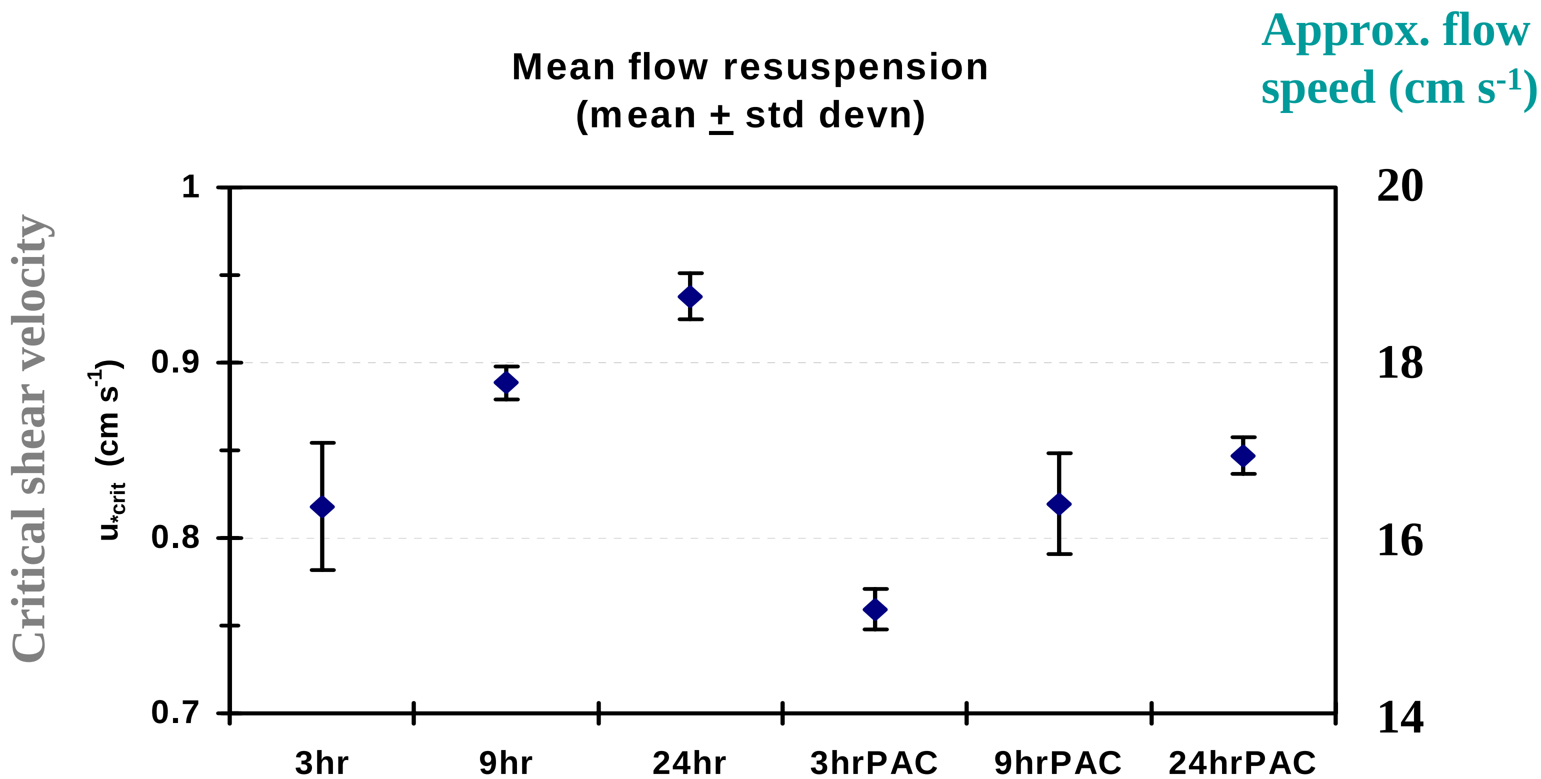


# Flume studies, WHOI



(Beaulieu et al., submitted to *Harmful Algae*)

# Erosion and Resuspension




1) Sedimented flocs are more difficult to resuspend the longer they sit in a layer on the bottom
2) PAC flocculant makes it easier to resuspend the clay/algal flocs
3) Flocs do not settle as rapidly with PAC flocculant

(Beaulieu et al., submitted to *Harmful Algae*)

# Brevetoxin analysis

| | cell concentration (cells/L) | loading (g/L) | PAC (ppm) | toxin removal rel. to con |
|---|---|---|---|---|
| intact | [illegible] $\times 10^{6}$ | [illegible] | | [illegible] |
| intact | [illegible] $\times 10^{6}$ | [illegible] | [illegible] | [illegible] |
| intact | [illegible] $\times 10^{6}$ | [illegible] | [illegible] | [illegible] |
| lysed | [illegible] $\times 10^{6}$ | [illegible] | | [illegible] |
| lysed | [illegible] $\times 10^{6}$ | [illegible] | | [illegible] |
| intact | [illegible] $\times 10^{6}$ | [illegible] | | [illegible] |
| [illegible] | [illegible] $\times 10^{6}$ | [illegible] | [illegible] | [illegible] |

**==> phosphatic clays can remove 68% - 80% dissolved brevetoxins**

**(Pierce et al., submitted to *Harmful Algae*)**

# Impacts - Benthic fauna

Lewis et al., 2003. *Harmful Algae*


**test organisms** — ***Ampelisca abdita*** **(infaunal amphipod)**
***Leptocheirus plumulosus*** **(infaunal amphipod)**
***Palaemonetes pugio*** **(grass shrimp)**

**clay** — **phosphatic clay (0.25 g/L)**

**coagulant** — **polyaluminum chloride (0.50, 5, 50 ppm)**

**HAB organism** — ***Karenia brevis*** **(3.9 to 5.4 x $10^6$ cells/L)**

**main conclusions**

**(1) The use of phosphatic clay and coagulant are not likely to have a detectable toxic effect on the benthos. Field validation needed.**

**(2) Survival of the test species to clay, PAC and *K. brevis* was species-specific. Survival, with one exception, was similar to *K. brevis* alone.**

# Impacts - Benthic fauna

**Archambault et al., *in press*. *Marine Biology***

| | |
|---|---|
| test organism | *Mercenaria mercenaria* |
| clay | phosphatic clay (0.25 g/L) |
| organism | *Heterocapsa triquetra* |

*M. mercenaria*, notata strain

**RESULTS: Sedimented clay/cell floc (non-toxic)**

- -No mortality occurred in any of the trials
- -Oxygen levels remained >85% saturation.
- -Significant growth in shell length and soft tissue occurred in all trials
- -Clams quickly recovered siphon contact with the overlying water column

**RESULTS: Suspended clay/cell floc (14 days)**

- -A highly significant growth effect (~90% reduction in shell and tissue growth) *with suspended clay* compared to no-clay controls.
- -Repeated clay applications in the field are likely more detrimental to clams under flow conditions leading to prolonged *in situ* resuspension of clay than under conditions that promote rapid sedimentation.

# What is the status of clay control for marine HABs?

- Most results suggest that clay flocculation is a viable strategy for certain types of HABs in certain locations. Cells, and some dissolved toxins, can be removed effectively from the water column

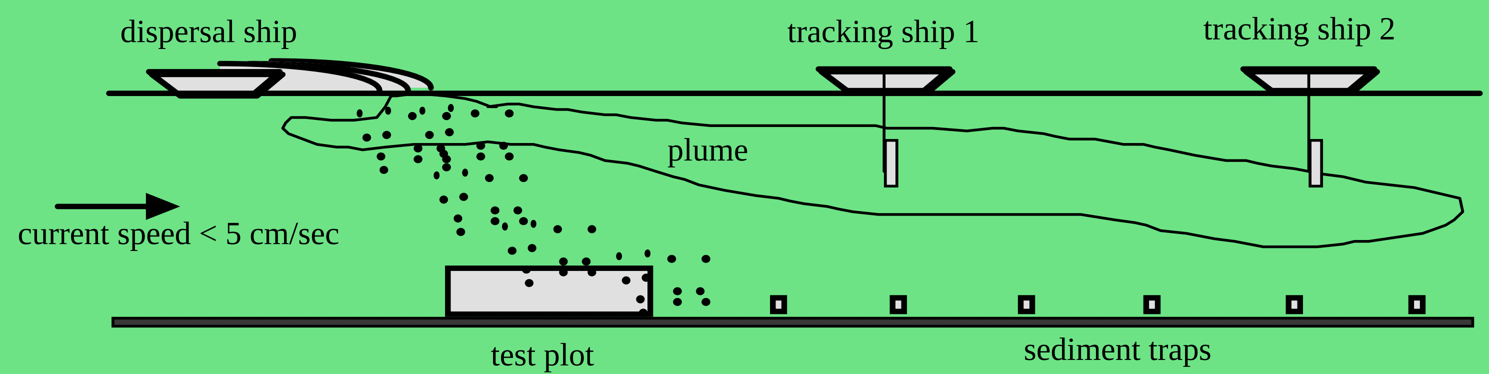
- More impact studies are still needed, especially on the fate of algal toxins and organic matter enrichment of the sediments

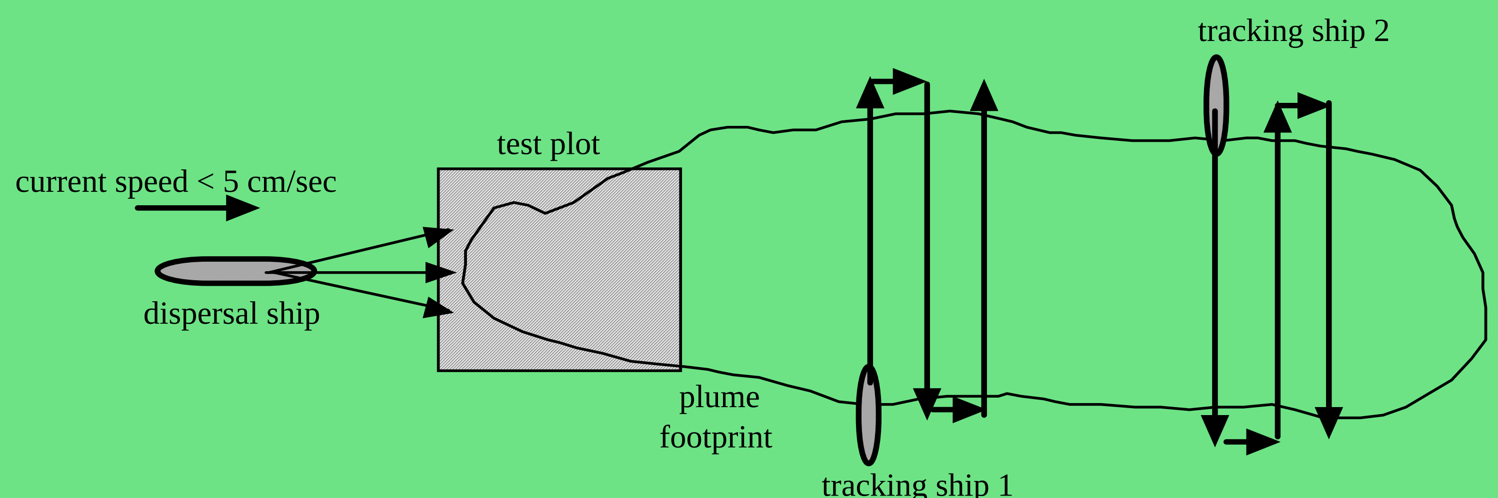
- Need to resolve whether PAC or other flocculants should be used in the field
  PRO: enhance cell removal, minimize toxin/nutrient release
  CON: increase erosion, decrease settling, unknown impacts

- Logistical challenges and economic costs generally unknown

# Future directions:

Cell removal, settling, and viability in flow - more flume studies
Removal, degradation and bioavailability of brevetoxins on clay
Impact of flocs on other bivalves and benthic fauna
Pilot-scale treatment of a *Karenia* bloom in unbounded waters




Anderson et al., unpublished data

# Experiments on removal of *Prymnesium parvum* with clay

## Kalmar, Sweden

**Hagstrom and Graneli, submitted to *Harmful Algae***

When the cells reached exponential phase (NP sufficient), and in stationary phase (N or P deficient), the cultures were placed in 30 ml flasks (in triplicate).

A slurry of clay in seawater was then dispersed to the surface

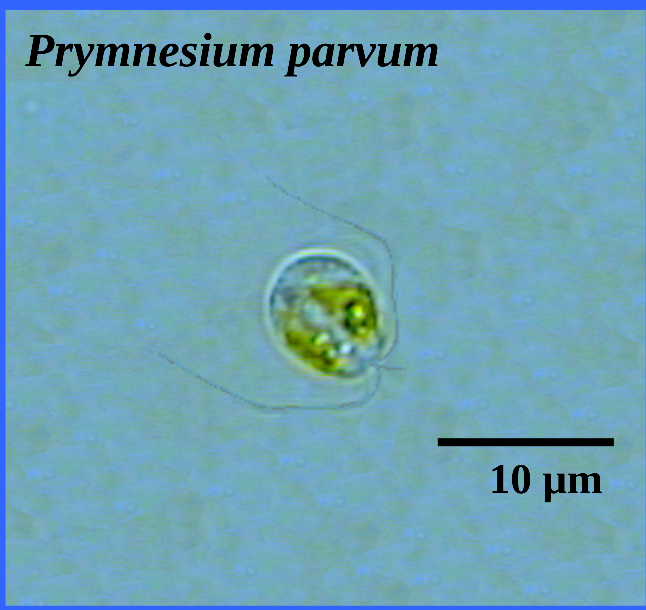
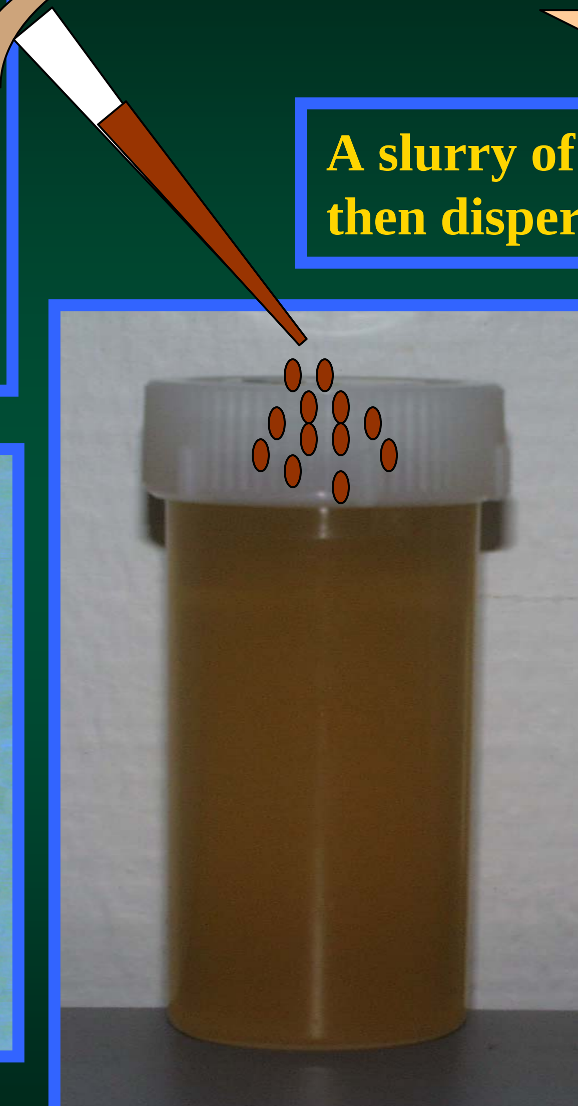
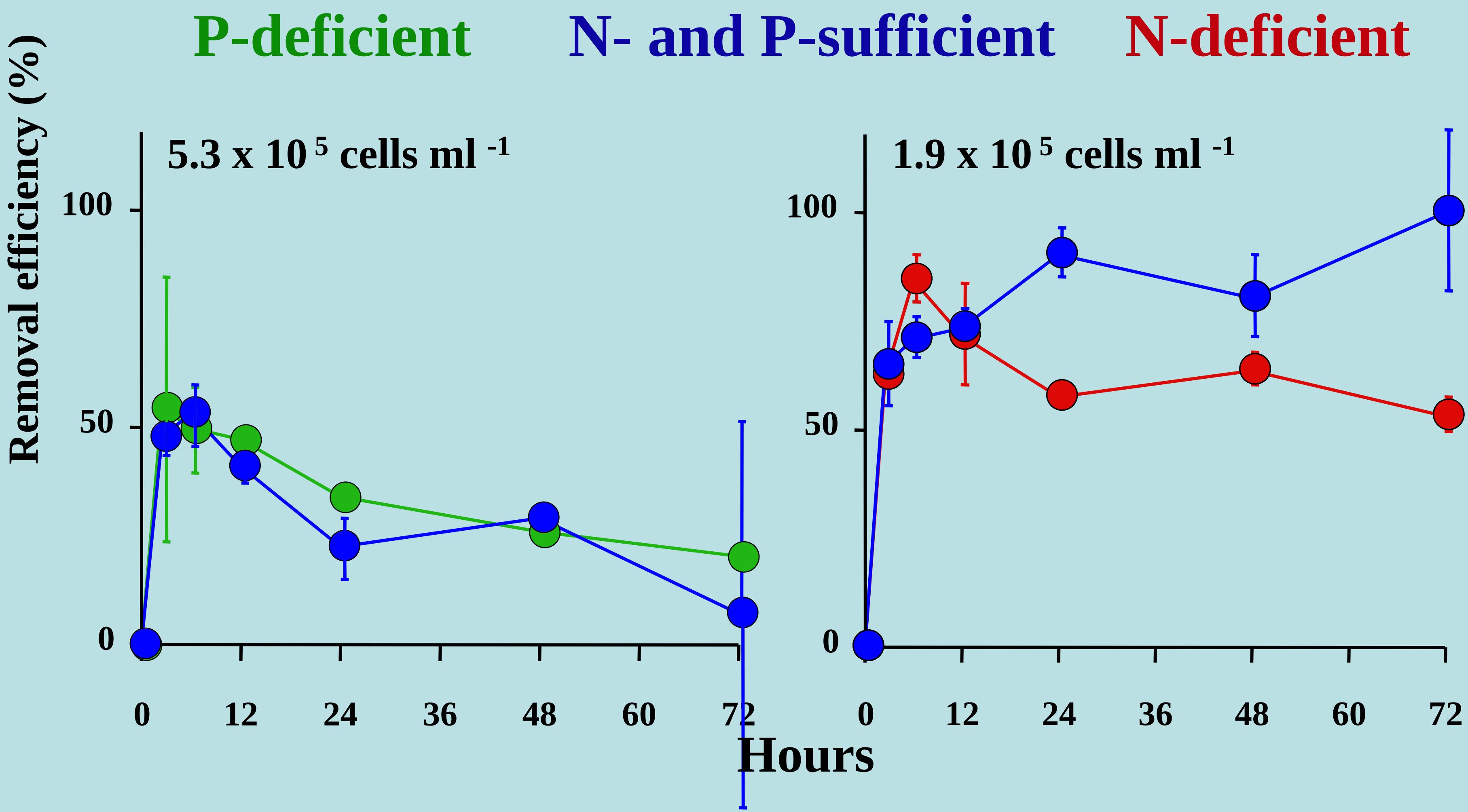



Photo C. Esplund



# Florida Phosphatic clay

## 4 g/L phosphatic clay + 5 ppm PAC




Hagstrom and Graneli, submitted to *Harmful Algae*

# Conclusions
# Kalmar Experiments

- Phosphatic clay can, in a few hours, remove 100% of the *Prymnesium parvum* (grown with sufficient nutrients) using 4 g/L of clay and 5 ppm polyaluminum chloride

- Lower RE's for nutrient-deficient cells

- The method may be promising for bloom mitigation, but the clay loadings required are very high. (But, there is an explanation for this).

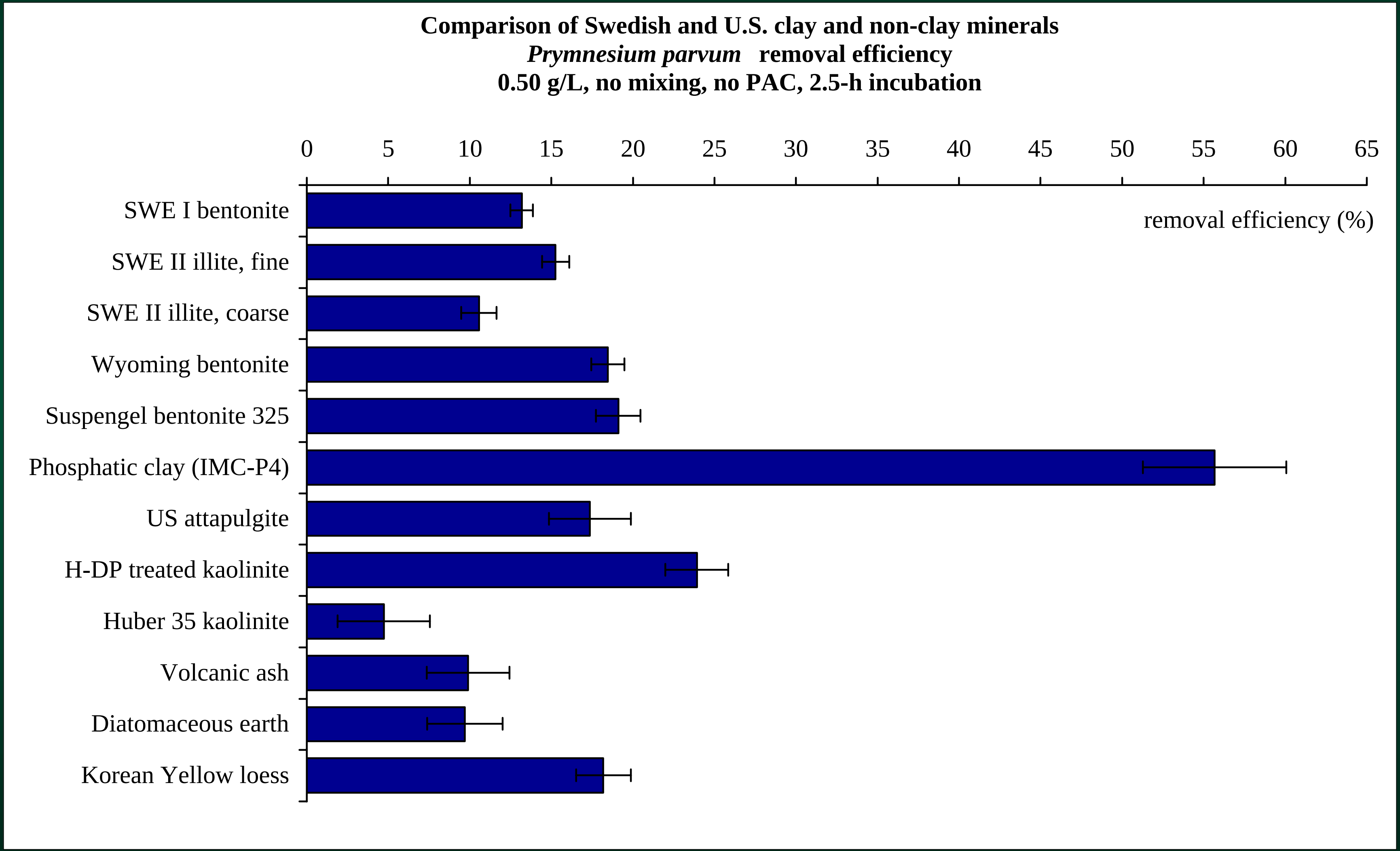
- In the Baltic Sea, expect low RE as algae are N deficient

**Clay Control Experiments**
**Tvarminne Zoological Station, Finland**

***Prymnesium parvum*** **and Swedish clays**

# Experiments at Woods Hole (in collaboration with J. Hagström)

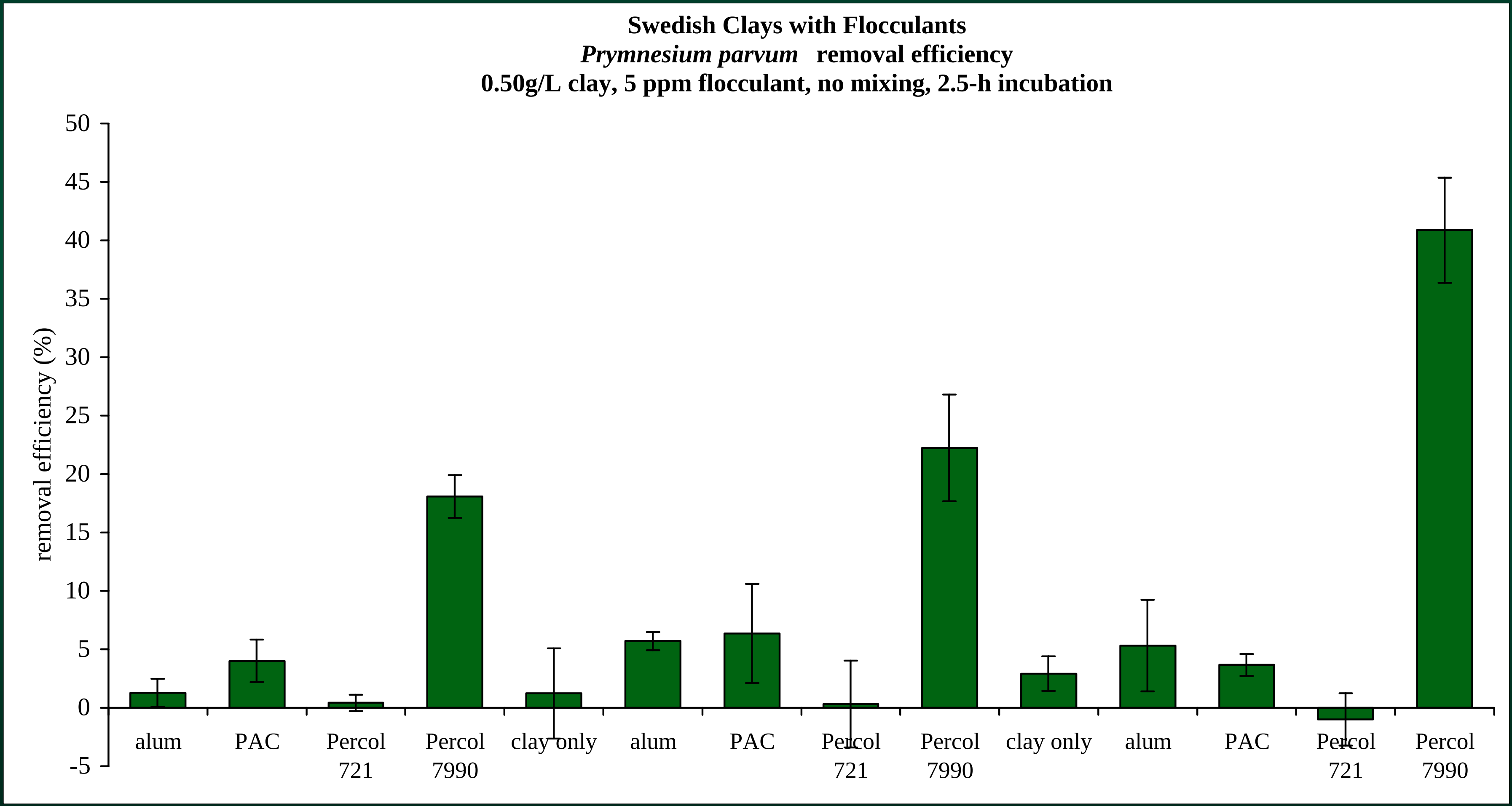
## Extended clay screening (clay only - no flocculants)




**Source: Hagström, unpublished data**

# Experiments at Woods Hole (data from J. Hagström)

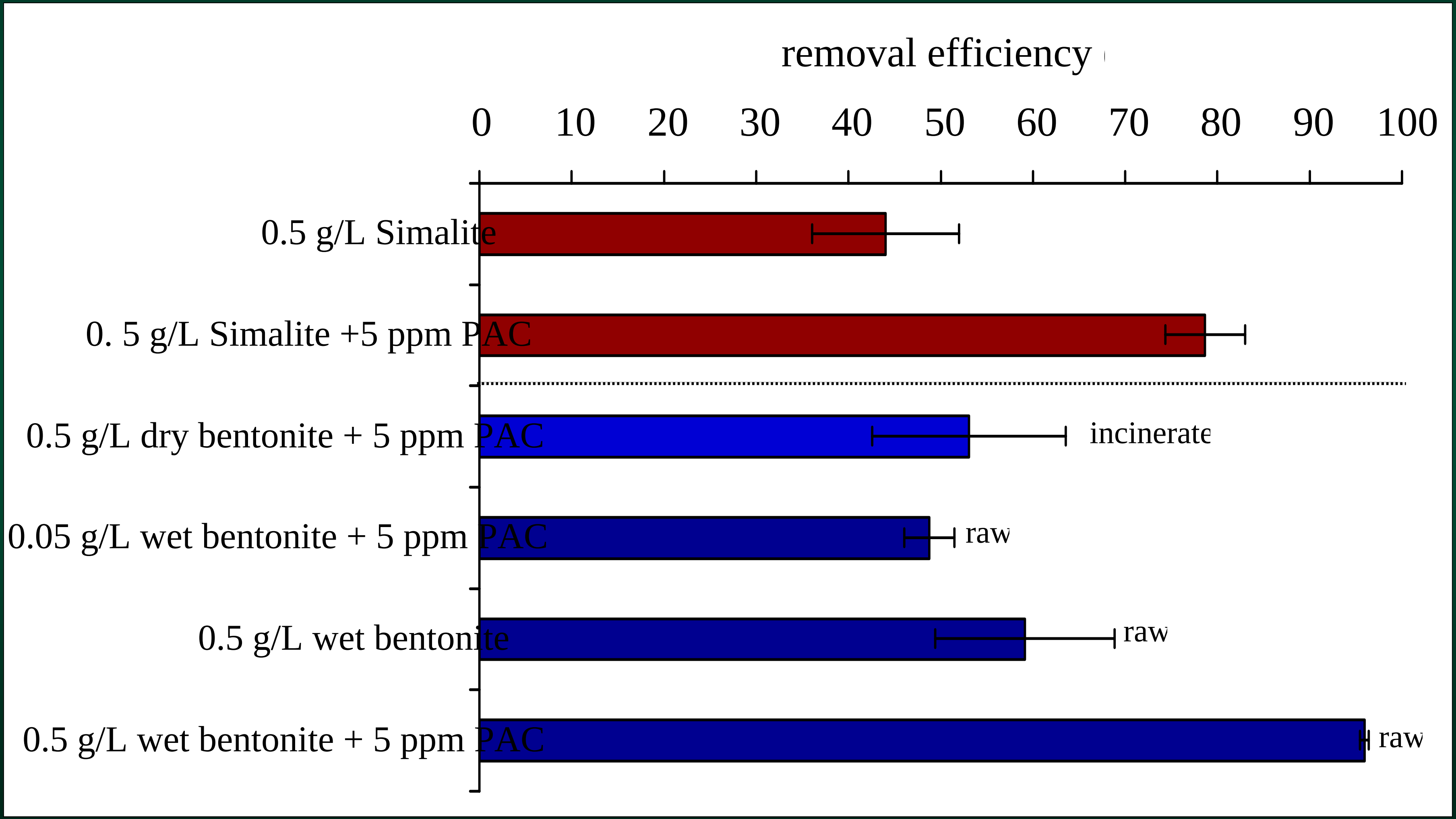
## Alternative flocculants (no clay)




Source: Hagström, unpublished data

# Recent work in Kalmar (data from J. Hagström)

## Un-incinerated (raw) vs. incinerated Swedish clays (with and without flocculants




**Source: Hagström, unpublished data**

# Conclusions - general

1) Preventive strategies should be pursued to keep blooms from happening, but these will take decades to implement
2) Bloom control research is not well advanced for marine HABs
3) Biological control options are possible in theory, but are far from the application stage
4) Chemical control is also possible, but is not likely due to broad lethality and other environmental concerns
5) Clay flocculation is promising for certain HABs (or certain HAB toxins) in certain locations or situations
6) More research is clearly needed

# Conclusions - control of Prymnesium

1) **Consider barley straw and other simple bloom suppression methods in small reservoirs and hatchery ponds**
2) **Consider Phoslock treatments, if phosphorous is shown to be a controlling parameter (but will this increase toxicity?)**
3) **Consider testing local clays against *Prymnesium parvum* - begin freshwater removal efficiency studies  Low salinity (ionic strength) directly influences flocculation rates, reducing cell removal.  Flocculants will likely be needed.**
4) **Although particle aggregates form with flocculants,  floc density may be too low for good settling and cell retention (cell escape, lack of floc settling).**
5) **Explore methods to increase interparticle collisions for clay to work better with *Prymnesium***
6) **Can clays remove *Prymnesium* toxins?**