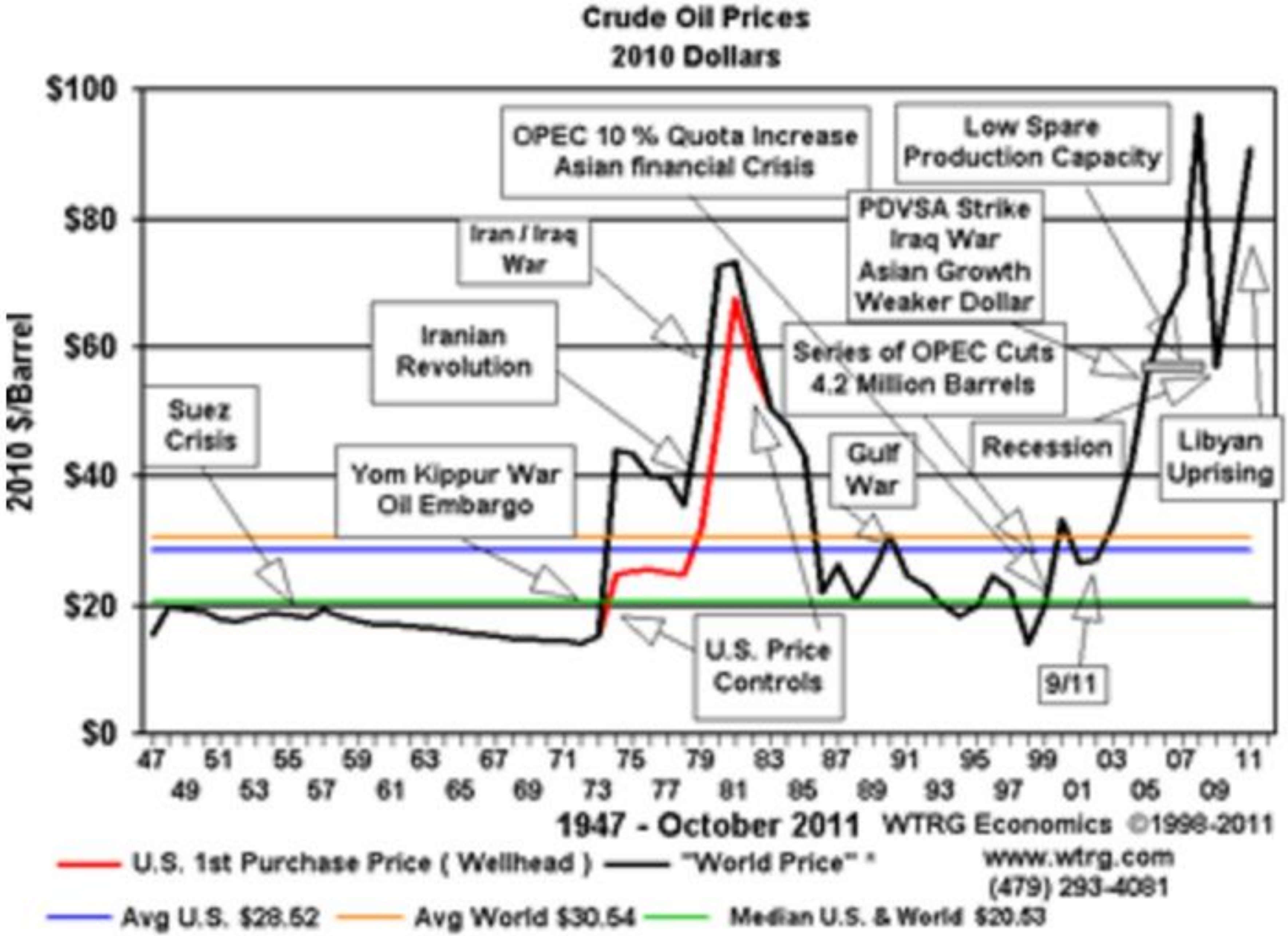
February 11, 2016
Washington DC.

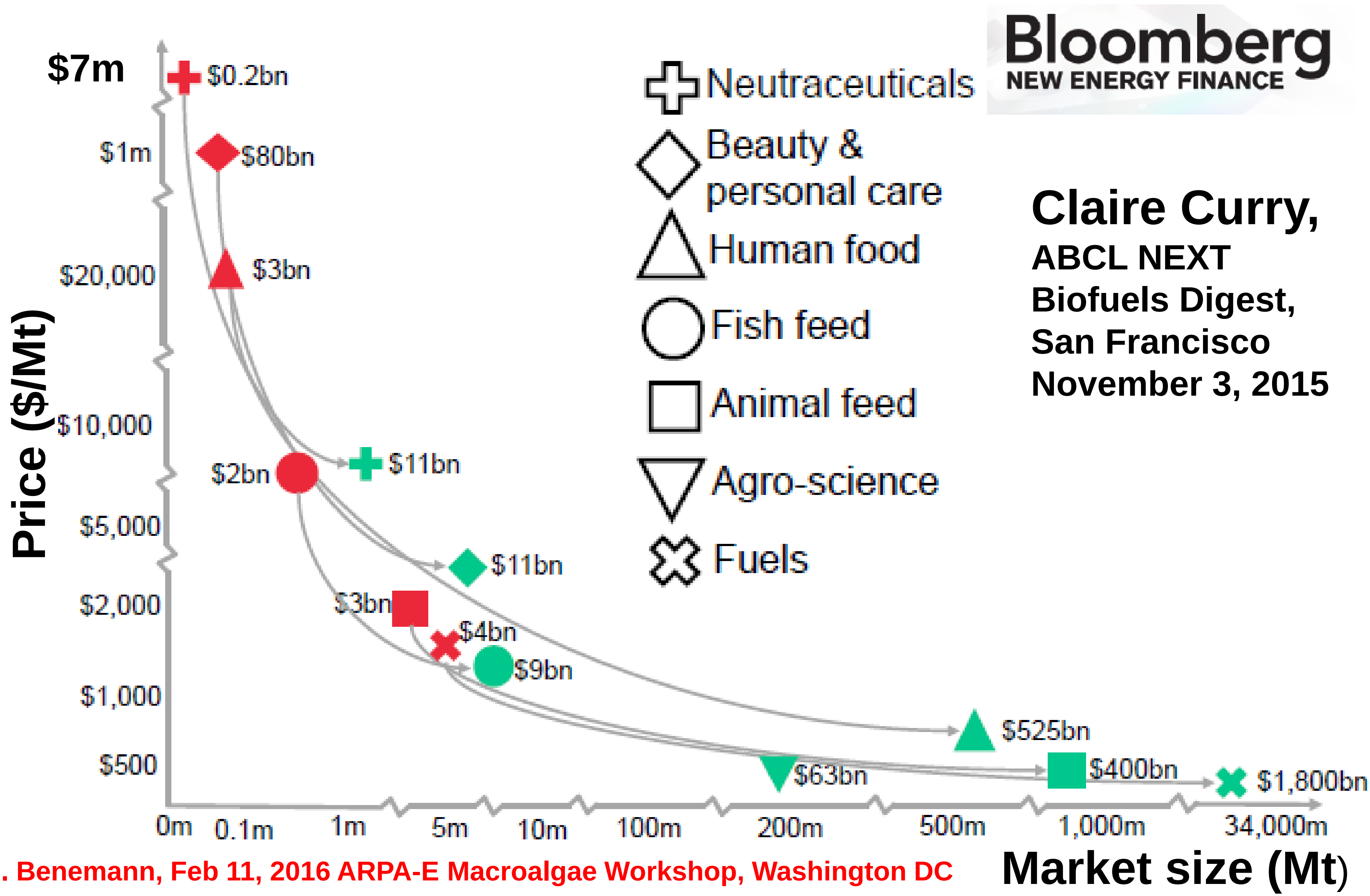
History of US Department of Energy macroalgae projects – major conclusions

John Benemann
MicroBio Engineering, Inc.,
San Luis Obispo, CA,

Crude Oil Prices 1947 - October 2011



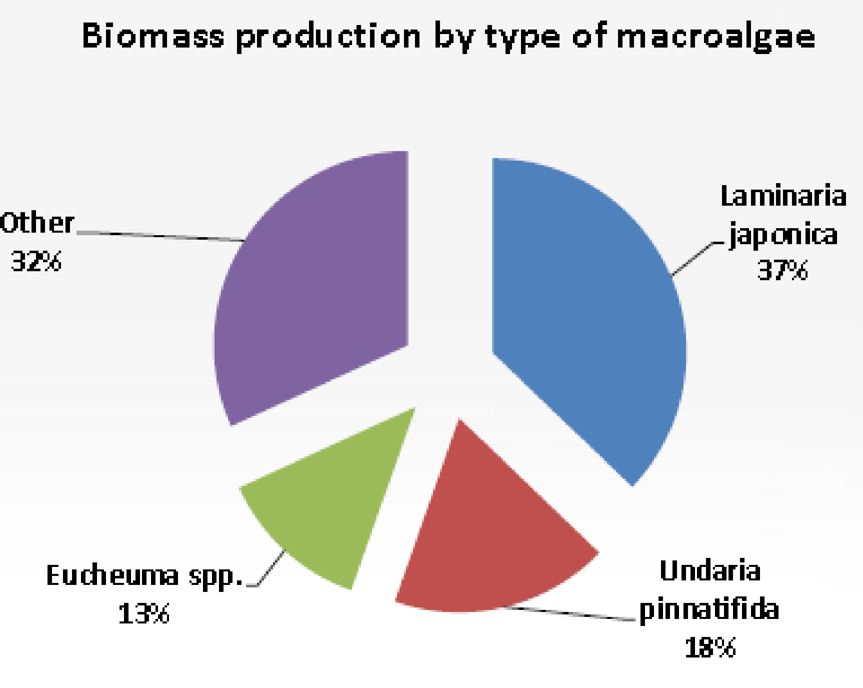
MARKET SIZE FOR MAIN ALGAE CHEMICAL AND FUEL PRODUCTS ($/TONNE, TONNES, $BN MARKET SIZE), 2015

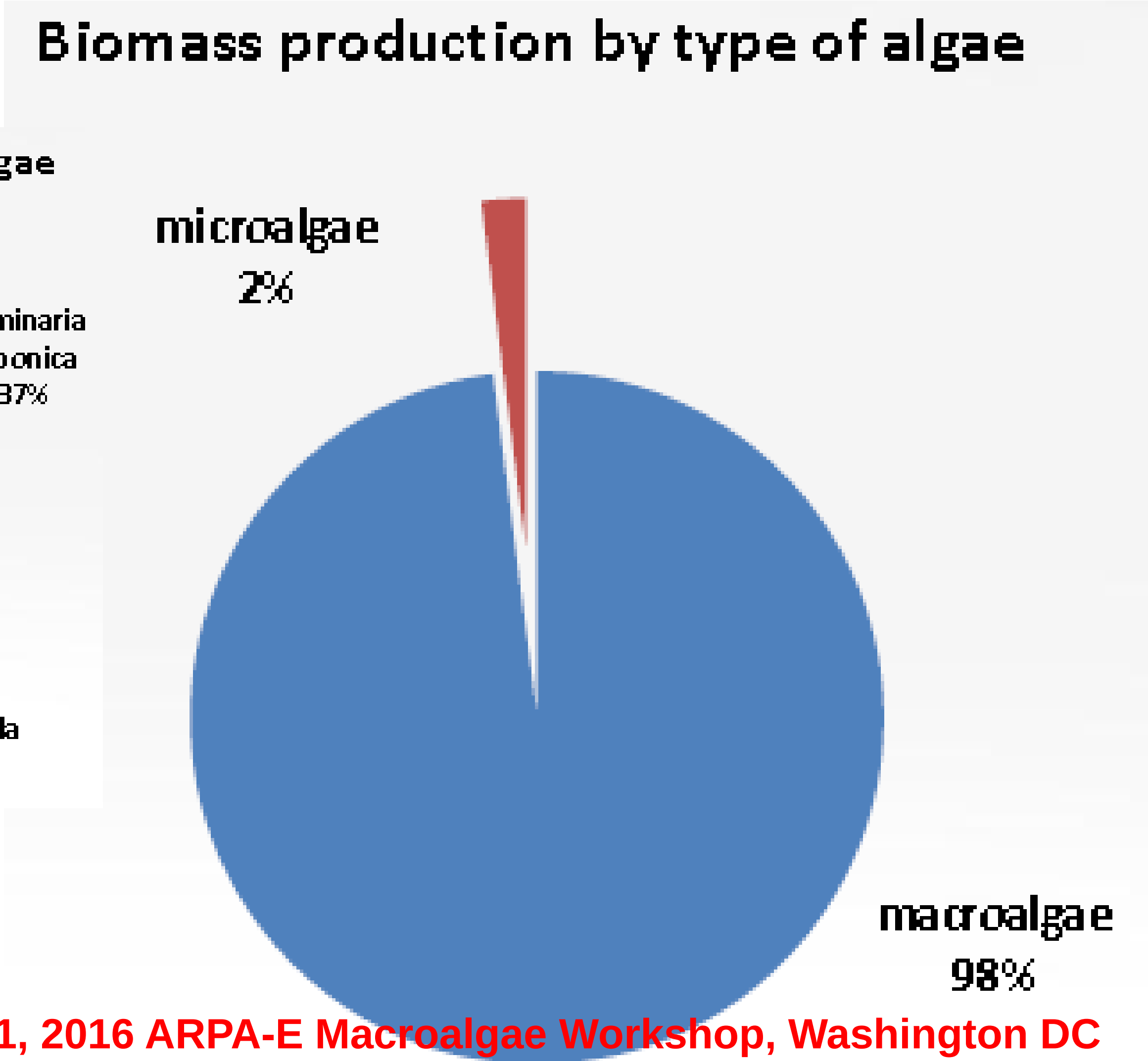


Claire Curry,
ABCL NEXT
Biofuels Digest,
San Francisco
November 3, 2015

Two Types of Algae (non vascular plants): Microalgae (unicellular, colonial) and Macroalgae (Seaweeds)

Seaweeds produced commercially: *Laminaria japonica, Porphyra spp.., Undaria pinnatifida, Eucheuma spp.*, and *Gracilaria*





Seaweed aquaculture is a traditional technology

Xincun, China *Kappaphycus* sp. cooperative farms

Seaweed Culture: Porphyra sp.

J. Benemann, Feb 11, 2016 ARPA-E Macroalgae Workshop, Washington DC

Laminaria japonica

Canadian Kelp Resources, Bamfield BC

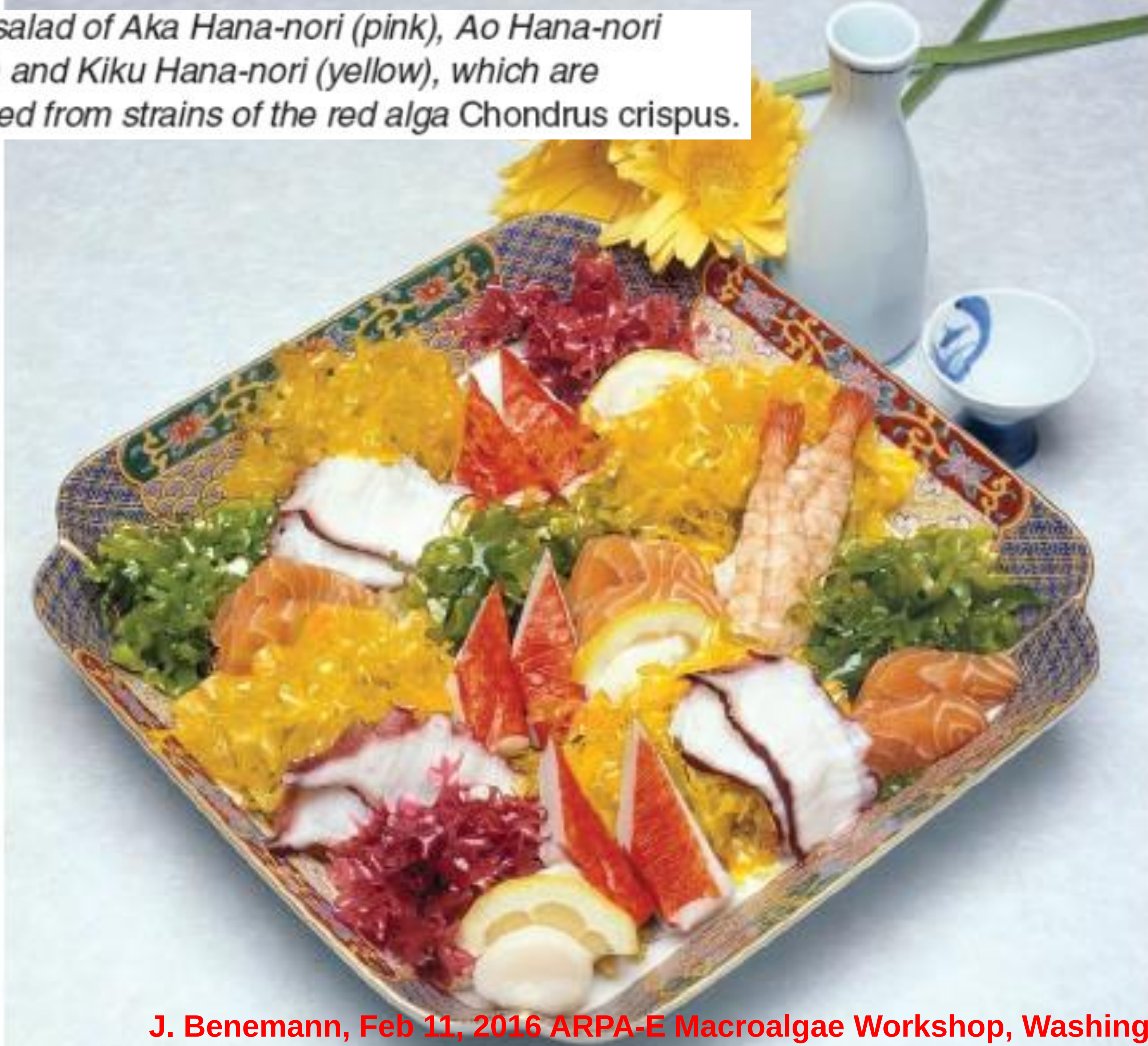
0.28ha Site, 5 tons of *Alaria marginata* , *Laminaria sacccharina* and *Macrocystis integrifolia*

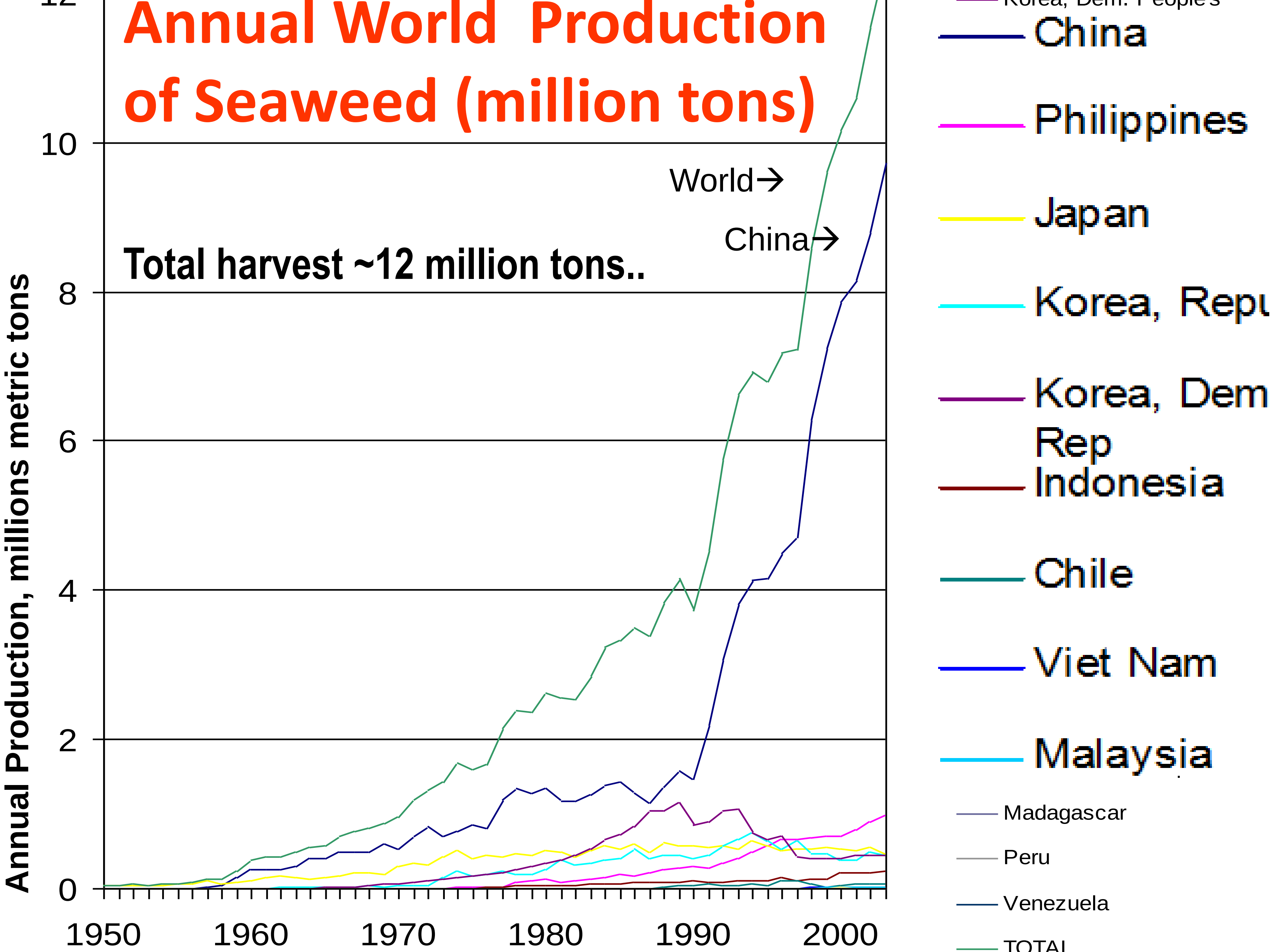
Acadian Seaplants Ltd., Nova Scotia
(only large on-shore commercial seaweed farm in world)

Haga Farm, South Africa, abalone culture system (left) - effluents cleaned by seaweed raceway ponds

Small-scale edible seaweed - abalone producer

Mixed salad of Aka Hana-nori (pink), Ao Hana-nori (green) and Kiku Hana-nori (yellow), which are produced from strains of the red alga Chondrus crispus.





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Markets for Seaweed products (McHugh 2003)

Product	Value (US$)
Human food (nori, aonori, kombu, wakame, etc)	$5 billion
Algal hydrocolloids	
• Agar (food ingredient, pharmaceutical, biological/ microbiological)	$132 million
• Alginate (textile printing, food additive, pharmaceutical, medical)	$213 million
• Carrageenan (food additive, pet food, toothpaste)	$240 million
Other uses of seaweeds	
• Fertilisers and conditioners	$5 million
• Animal feed	$5 million
• Macroalgal biofuels	Negligible
Total	**$5.5-6 billion**

Stinking mats of seaweed (*Sargassum*) piling up on Caribbean beaches

Puerto Rico , August 8 2015

Cancun, Mexico, Aug 8 2015

Qingdao beaches are covered in algae, 15/7/2015

People in Qingdao have grown accustomed to their beaches looking more like verdant meadows every July

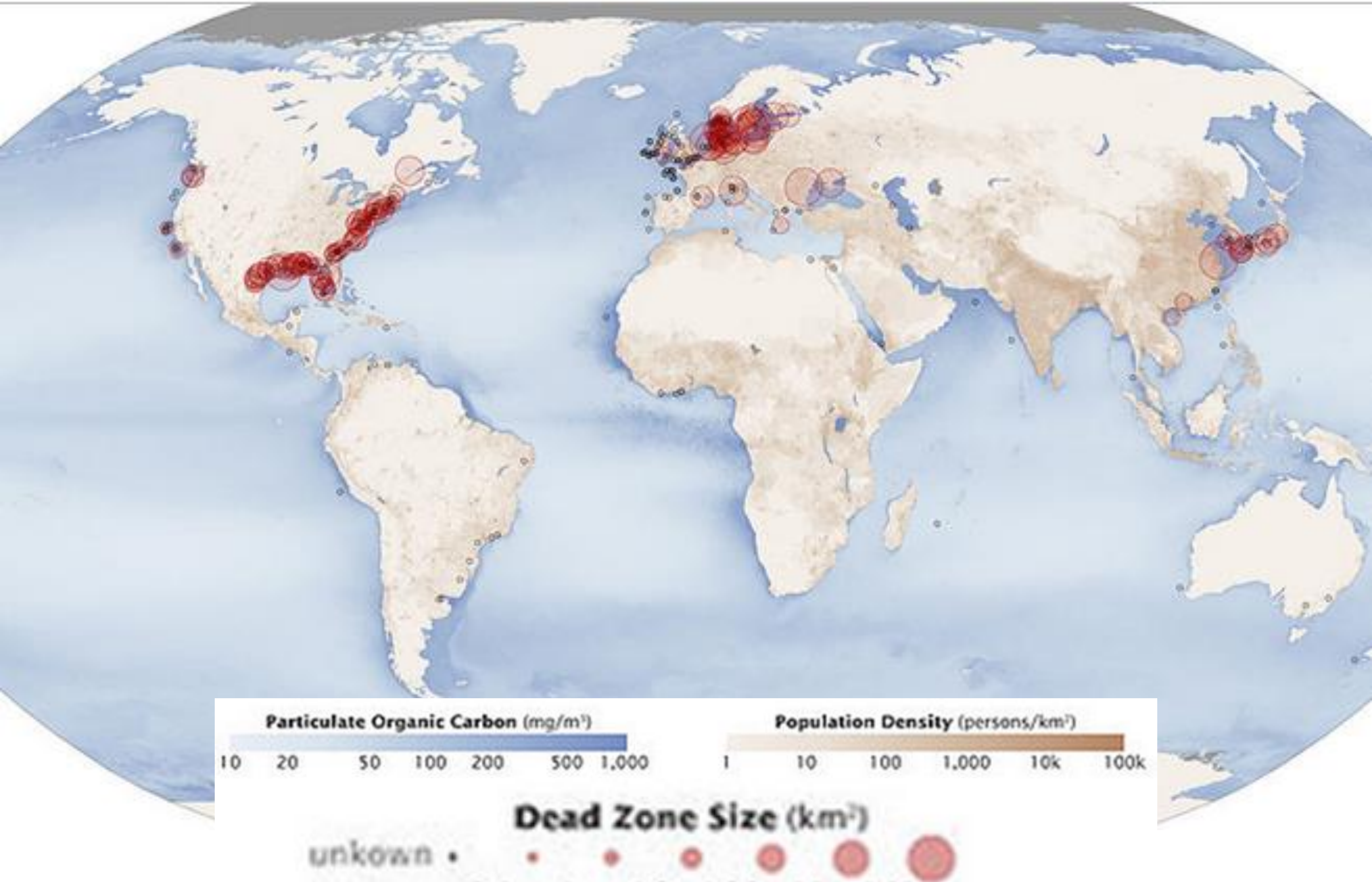
June 27, 2015: A fisherman removes some of the algae clogging a beach in Qingdao

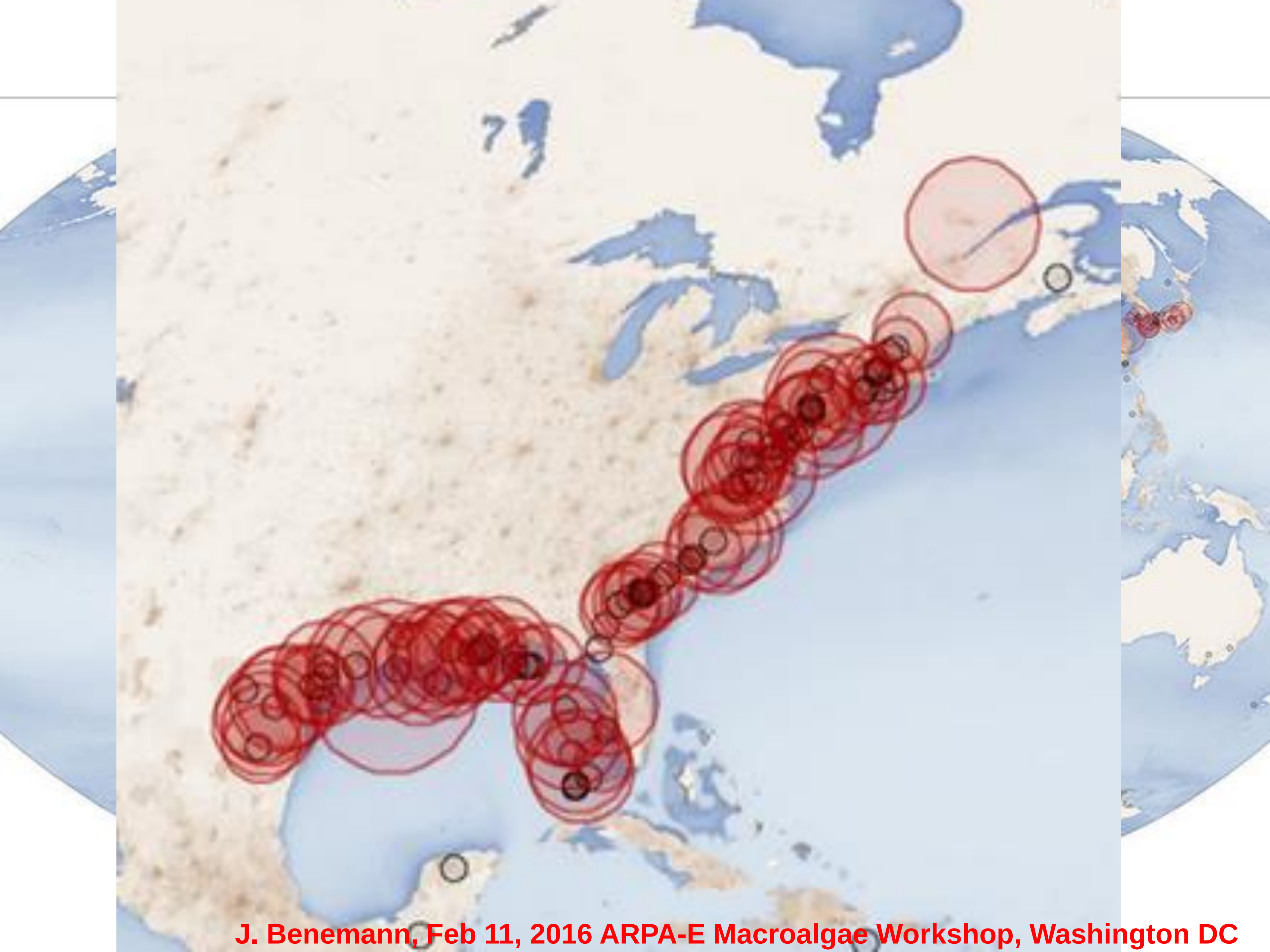
ALGAE WORLD NEWS

Tian, info@algaeworld.org

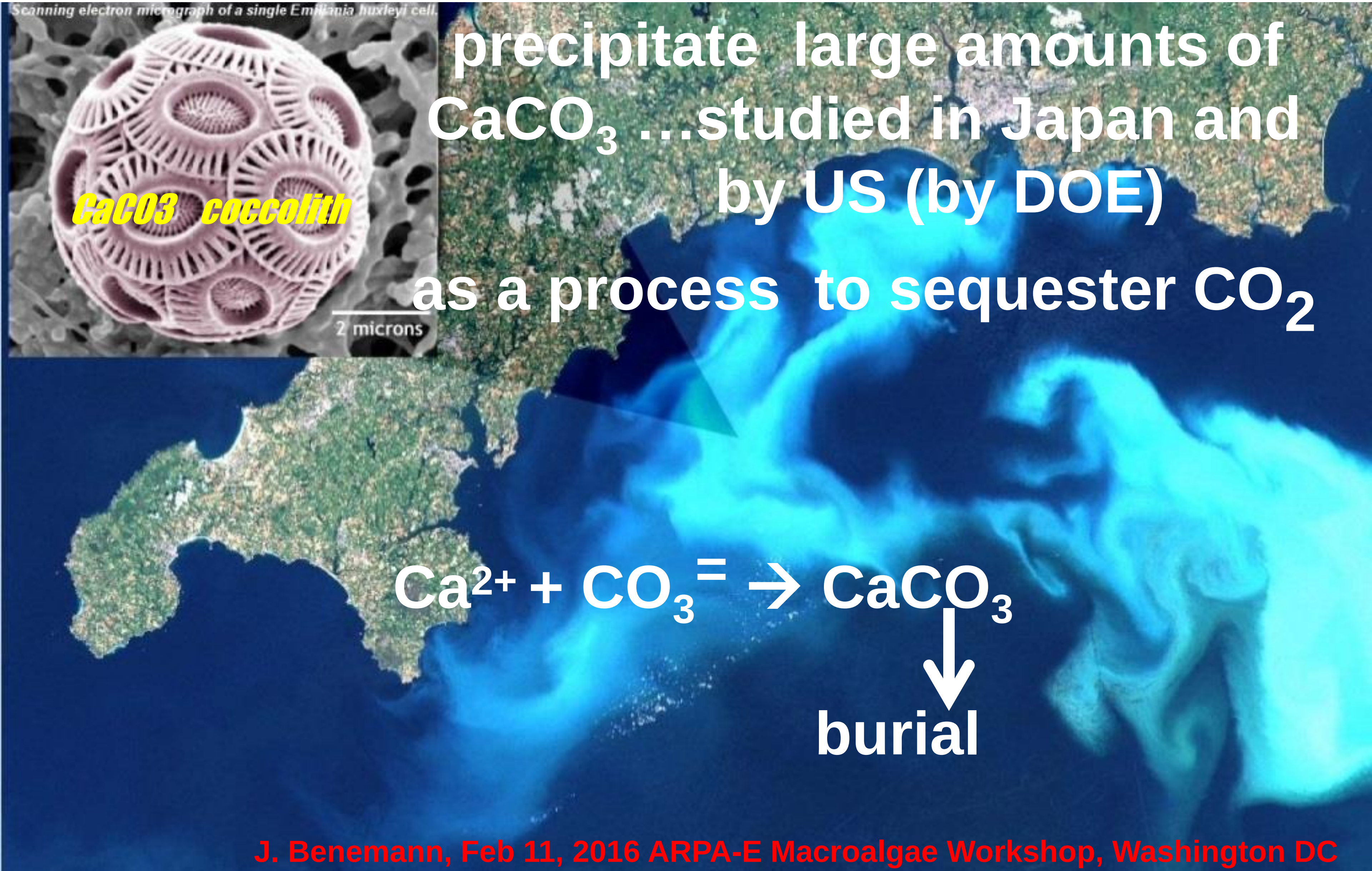
Vast algal blooms in northern Europe's Baltic Sea fuel annual aquatic dead zones, with O_2 levels too low to support animal life

Coastal ‘Dead Zones’ a world-wide problem





Blooms of *Emiliania huxleyi* (haptophytes) cause "whitening" events in the N. Atlantic Ocean



precipitate large amounts of $CaCO_3$ …studied in Japan and by US (by DOE)

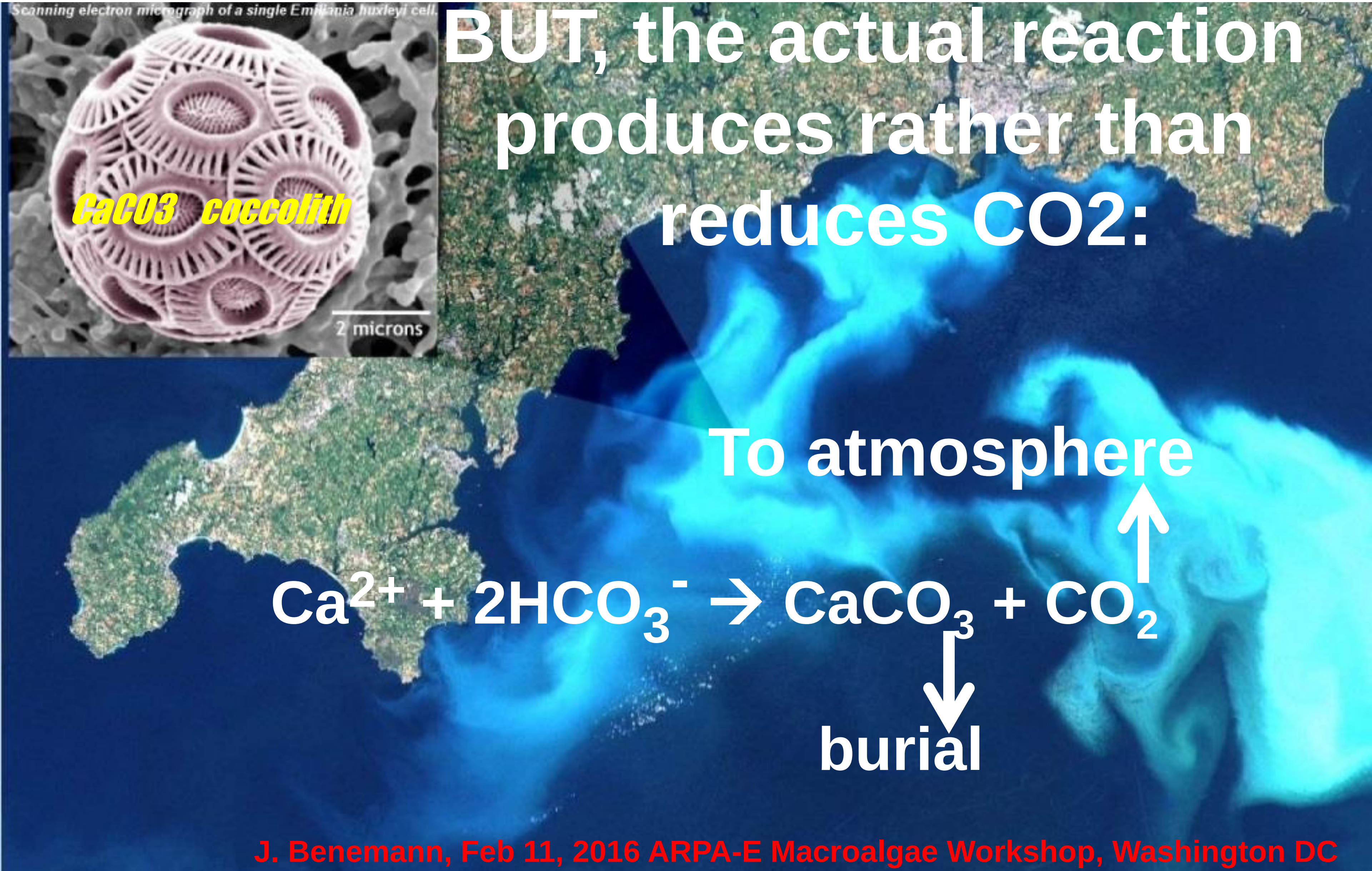
as a process to sequester CO_2

$$Ca^{2+} + CO_3^{=} \rightarrow CaCO_3$$

↓

burial

Blooms of *Emiliania huxleyi* (haptophytes) cause "whitening" events in the N. Atlantic Ocean



Dec. 4, 1997: US Department of Energy (DOE), Japan NEDO (New Energy and Industrial Technology Development Organization), and Norwegian Research Council (NRC) enter into a *Project Agreement for*

International Collaboration on CO2 Ocean Sequestration

… initial field experiment to inject liquid CO2 at depth of ~900 m to study plume dynamics, dissolution, biological impacts, etc.

The Natural Energy Laboratory of Hawaii, on the big island near the town of Kona was selected for conducting the experiment …

Problems arose in obtaining permits for the Hawaii experiment…

Ended up studying effect of natural volcanic CO2 vent in Hawaii…

Moved CO2 experiment to Norway, Norwegian parliament nixed it.

DOE shifted to an exclusively land-based CCS Program …

Seaweeds for War: California's WWI Kelp Industry (Peter Neushul, 1989)

Over 1 million tons of *Macrocystis pyrifera* harvested and converted ~10 million gallons of acetone (+ butanol, potash) at the Hercules Plant in Chula Vista (San Diego) during WW! from 1916-1919 (produced for British Navy, needed for cordite manufacturing)

http://www.scribd.com/doc/16595766/Seaweed-Feasibility-Final-Report#scribd

"Techno-Economic Feasibility Analysis of Offshore Seaweed Farming for Bioenergy and Biobased Products"

Roesjadi, Coppinger, Huesemann, Forster and Benemann, March 2008, PNNL (Pacific Northwest National Laboratory)

California Kelp (*Macrocystis pyrifera*)

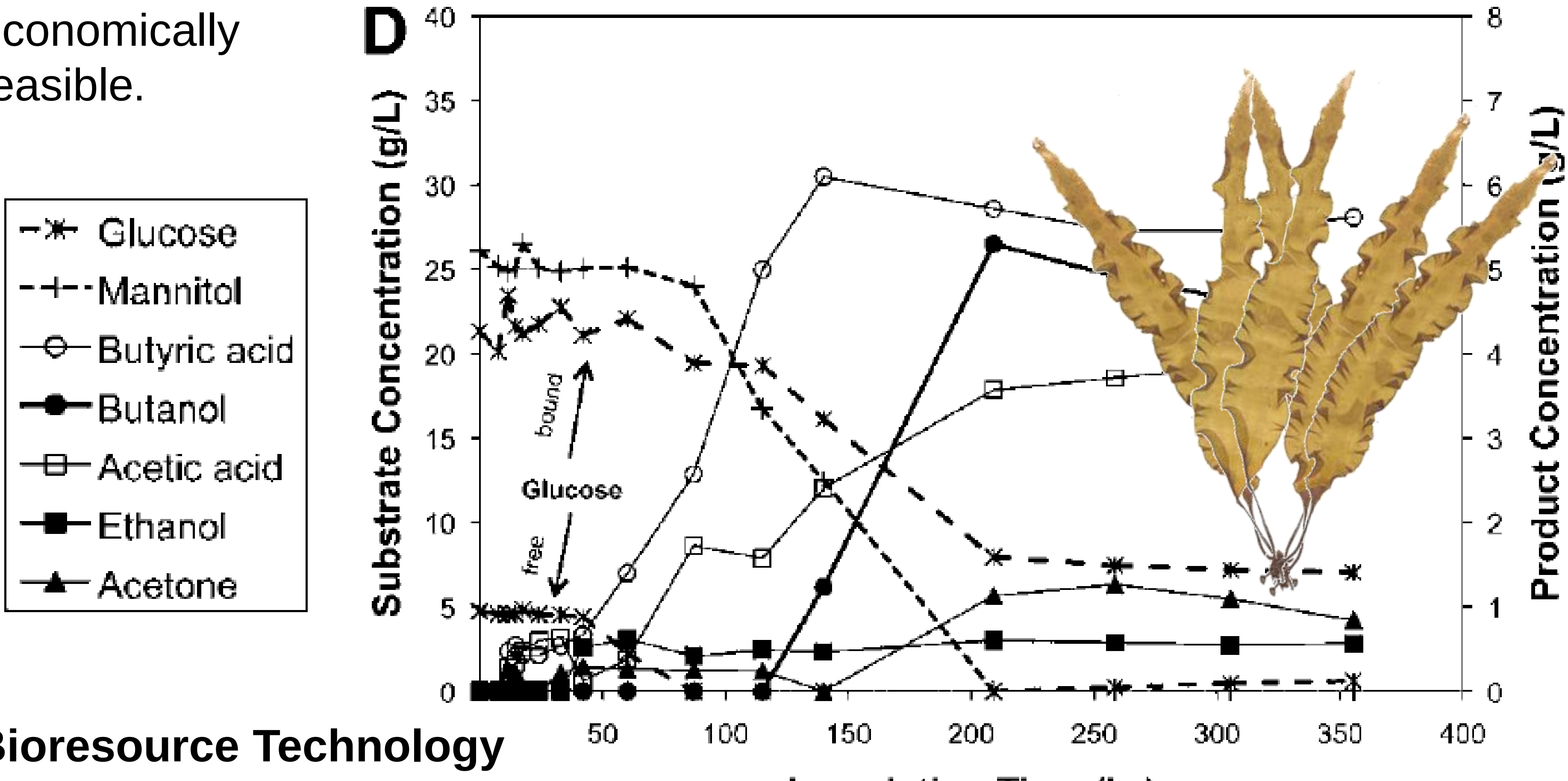
Acetone-butanol fermentation of marine macroalgae

Michael H. Huesemann *, Li-Jung Kuo, Lindsay Urquhart, Gary A. Gill, Guri Roesijadi

Pacific Northwest National Laboratory, Marine Sciences Laboratory, 1529 West Sequim Bay Road, Sequim, WA 98382, USA

Fermentation of kelp [*Saccharina* sp.],extract… Butanol and total solvent yields were 0.12 g/g and 0.16 g/g, respectively, significant improvements still needed to make industrial-scale acetone-butanol fermentations of seaweeds economically feasible.

.

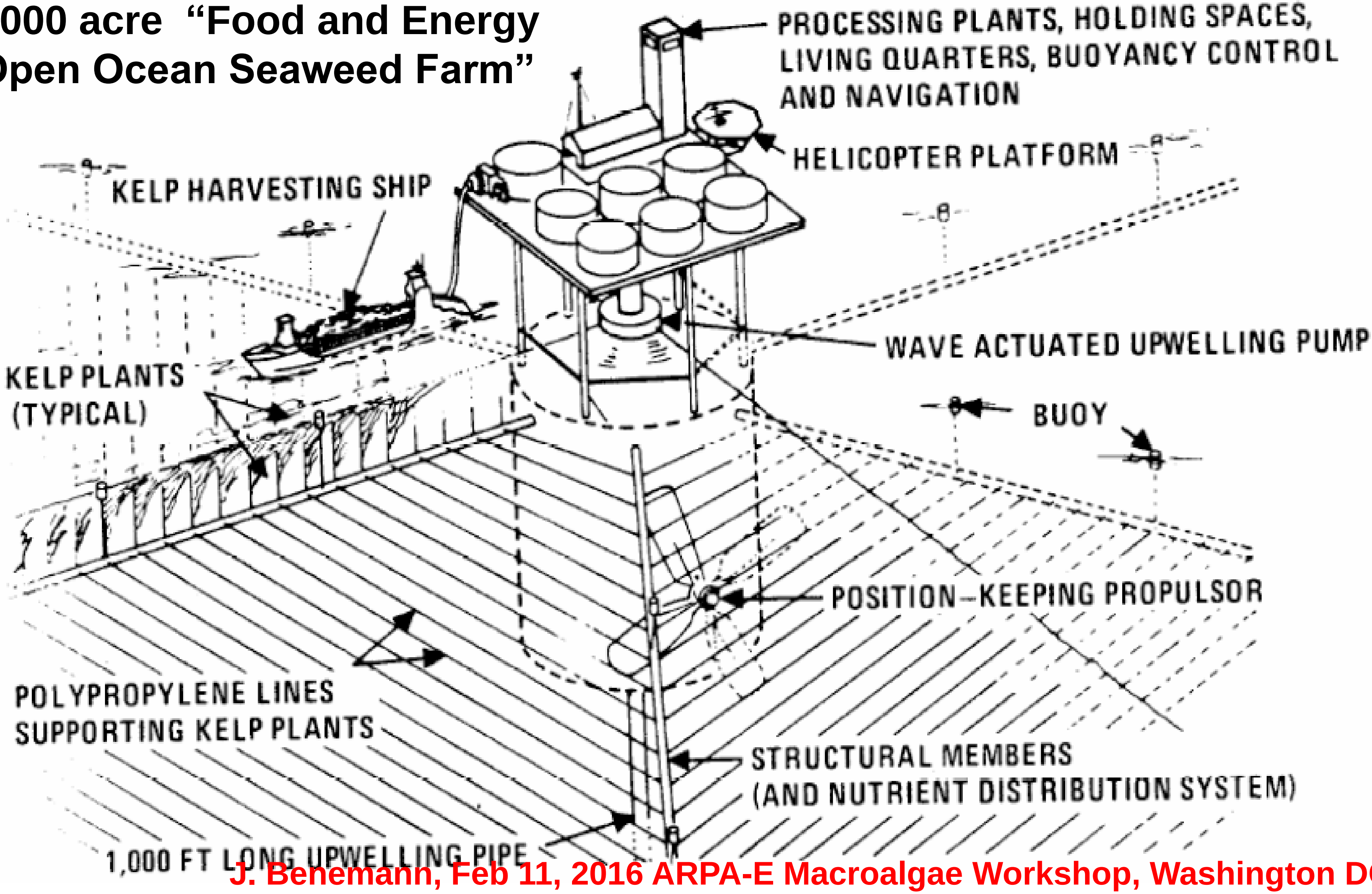


Bioresource Technology

Conceptual "Ocean Energy Farm" (1975)

In December 1974 the American Gas Association funded a $20 million R&D project on giant kelp for methane production

1000 acre "Food and Energy Open Ocean Seaweed Farm"



Ocean Food and Energy Farm Project

(publiations by some of the main participants in project)

Wilcox, Howard A., 1975. "The Ocean Food and Energy Farm Project", Proceedings of American Association for Advancement of Science, Jan., 1975.

North, Wheeler J., 1975. Evaluating Oceanic Farming of Seaweeds as Sources of Organics and Energy. NSF/RANN/SE/GI-43881/PR/75/4 California Institute of Technology, 1975.

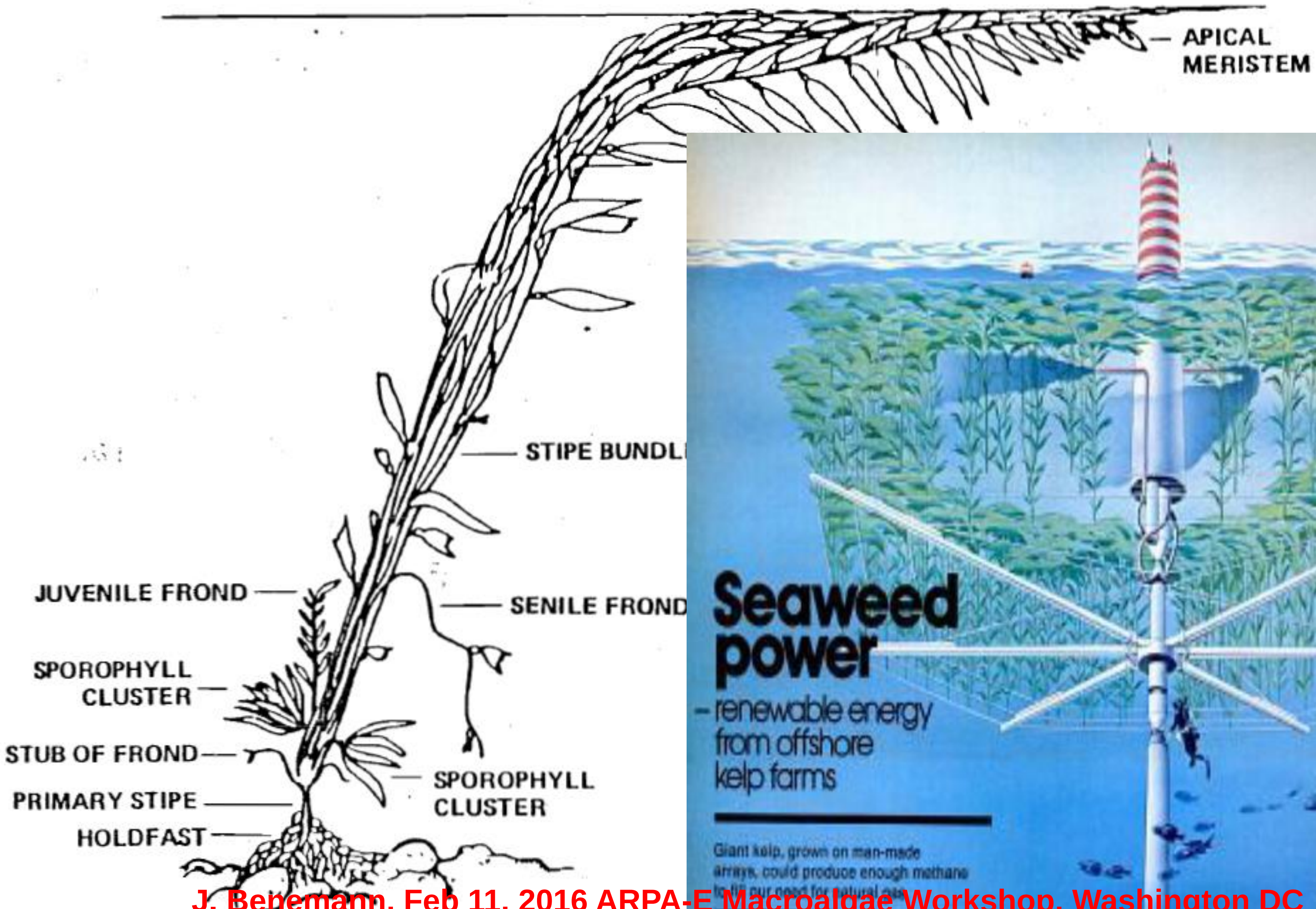
Flowers, A.B. and A.J. Bryce 1977, "Energy Conversion from Marine Biomass presented at IXth International Seaweed Symposium, Santa Barbara, CA., August 1977.

Bryce, A. J. 1978 "A Review of the Energy from Marine Biomass Program", Proceedings of Symposium on Energy from Biomass and Wastes, Washington, D. C., August.

Tompkins, A. N., 1978, "Energy from Marine Biomass Project - Program Review", General Electric Co., Re-Entry and Environmental Systems Division, Philadelphia, PA.

Ashare, E., et al., 1978, Cost Analysis of Aquatic Biomass Systems-Final Report, by Dynatech R/D Company for U.S. Dept. of Energy, Fuels from Biomass Branch.

Adult *Macrocystis pyrifera* Plant



Start of energy crisis early 1970s Wheeler North meets Howard A. Wilcox, then with the Navy.

Prof. Wheeler North 1922 -2002, Cal Tech

Wilcox idea: giant seaweed food & energy farms

Initial study funded by navy, build structure at San Clemente Island. But difficulties in growing kelp

Second structure, use airlift of cold bottom water for nutrients (NSF RANN grant). Then hexagon-module. AGA (American Gas Association) funded

Ab Flowers of AGA departs Wilcox from project.

Wheeler North continues. General Electric put in charge of marine biomass program. New module with curtains 1978 off Laguna Beach. North: module “a biological zoo”. Storm destroys plants.

Project funded by DOE. Program Manager in 1978 contracts Dynatech to write report critical of Ocean Farms. AGA has PM departed from DOE, which then funds project (overall current $ ~50 million?).

But then gas prices deregulated, and AGA no longer interested

DYNATECH R/D COMPANY

COST ANALYSIS OF AQUATIC BIOMASS SYSTEMS

- Final Report -

July 25, 1978

Prepared by:

Edward Ashare
Don C. Augenstein
A. Carl Sharon
Ralph L. Wentworth
Elizabeth H. Wilson
Donald L. Wise

Supportive Work by:

Thomas Hruby, Woods Hole Oceanographic Institution
J.D. Nyhart, Massachusetts Institute of Technology
John R. Benemann, CSO International Inc.
Peter Persoff, CSO International, Inc.

Prepared for:

The United States Department of Energy Fuels from Biomass Branch
Under Contract No. EG-77-C-01-4000

SAN-2165-1

ENERGY FROM MARINE BIOMASS

Final Report

By
Alan N. Tompkins

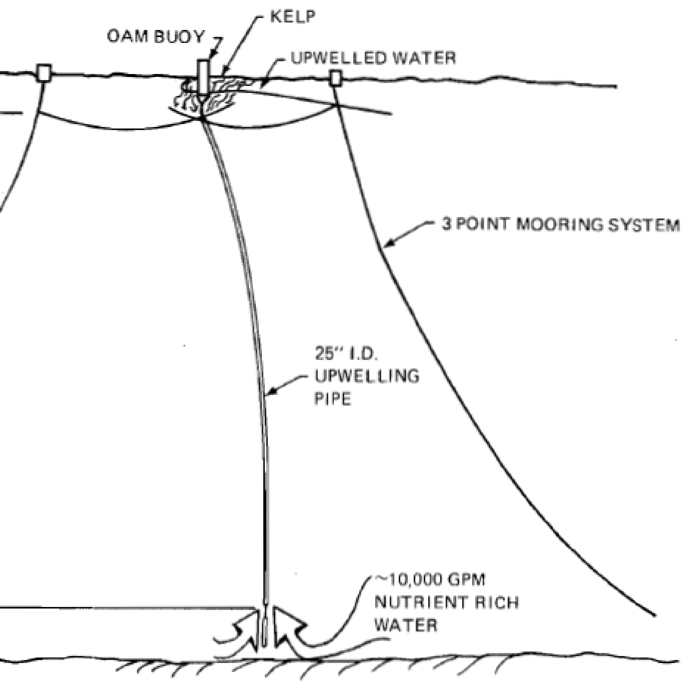
U.S. Department of Energy

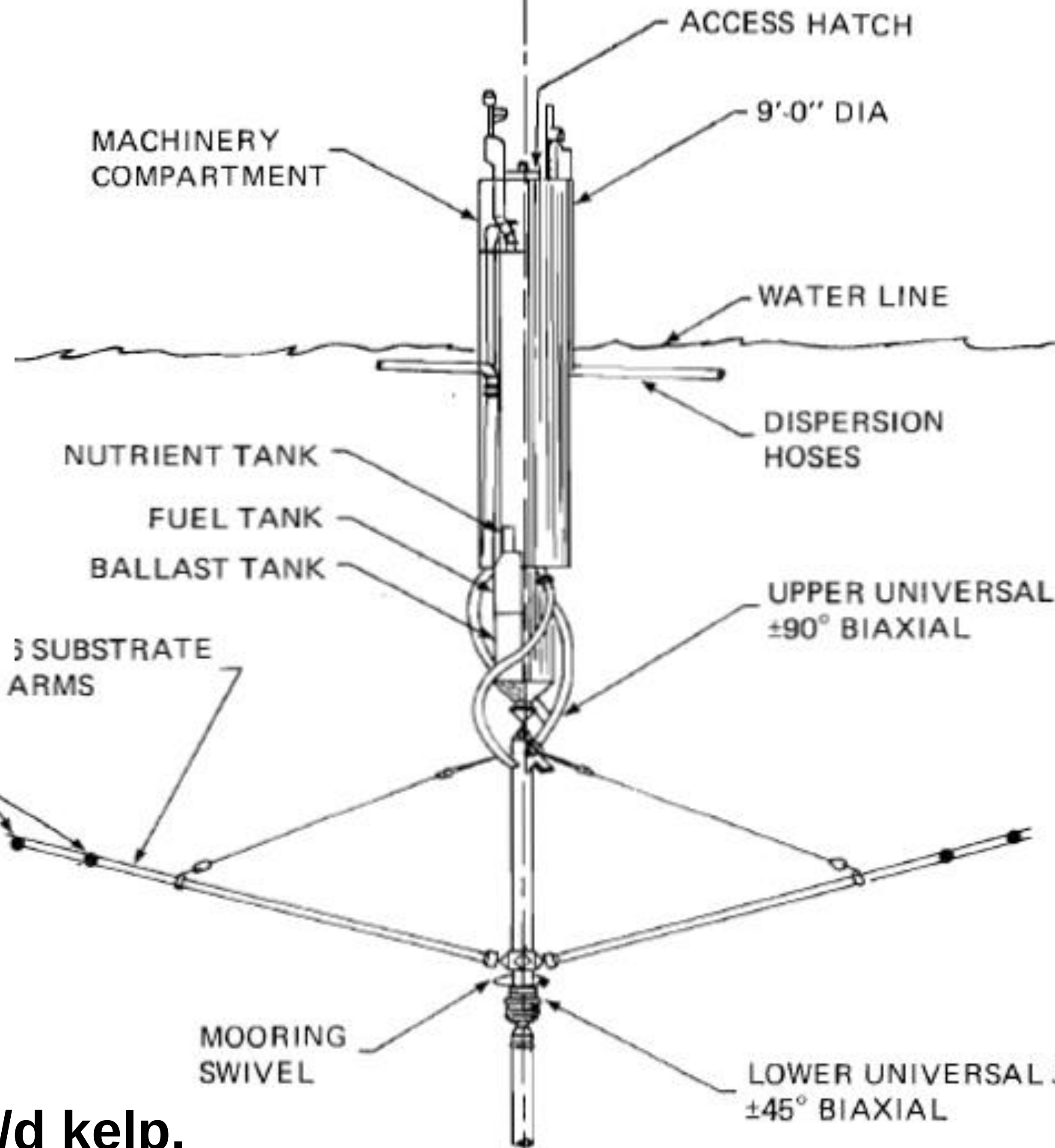
Solar Energy

March 20, 1979

Work Performed Under Contract No. ET-78-F-03-2165

General Electric Company
Re-entry & Environmental Systems Division
Philadelphia, Pennsylvania





Farm area for 1000 t/d kelp,
Source: A. Bryce, 1978

Seaweed Productivities (afdw, Benemann, 1980)

Genus/Species	State	Comments	Productivity[1] g/m²/d	Productivity[1] T/HA/yr
Macrocystis pyrifera	California	Average of four studies based on field measurements	4.5	17
" "	"	Average of four studies based on physiological measurements	17	63
Gracilaria tikvahiae	Florida	On-shore system, fertilized	11.2	41
Iridaea cordate	Washington	near shore	26[2]	35[2]
" "	"	Semi-closed culture in tanks	10.8-11.9	20
Gigartina exasperata	"	"		16

Kelp Area Required to stabilize atmospheric CO_2

North (1990): assumes upwelled water with C:N ratio of 7:1 vs. 21:1 in kelp - thus 2/3rd of CO2 supplied from atmosphere

Anthropogenic CO_2 production = $5X10^9$ tons C/yr (Booth, 1988)

Environmental uptake of anthro. CO_2 = $2X10^9$ tons/yr

Anthro. CO_2 remaining in atm. = $3X10^9$ tons/yr

$$\frac{3X10^9\ T/yr\ X\ 2000\ lbs/T\ X\ 1000\ g/kg}{2.2lbs/kg} = 2.73\ X\ 10^{15}\ g\ C/yr$$

$$\frac{2.73\ X\ 10^{15}\ g\ C/yr}{365\ d/yr} = 0.75\ X\ 10^{13}\ g\ C/day$$ as anthro. CO_2 output

Assume kelp productivity = 3 g $C/m^2/d$, of which 2 g $C/m^2/d$ represents CO_2 removal from the atmosphere *

Kelp area required = K_a = $\frac{0.75\ X\ 10^{13}\ g\ C/d}{}$ = $3.8\ X\ 10^{12}\ m^2$

to stabilize atmospheric CO_2 thus need ~ 1 billion acres

Proc. Natl. Acad. Sci.
Vol. 84, pp. 1314–1318,
March 1987

Wave energy and intertidal productivity

EGBERT G. LEIGH, JR.* et al.

Sea palm *Postelsia palmaeformis* can produce (in a good year) > 10 kg dry biomass /m2-yr (extrapolated to >100 mt/ha-yr or >1,500 GJ/ha-yr – however, such extrapolations are problematic…)

1982 Marine Biomass Program Annual Report (General Electric Co.)

…four harvests at the Goleta near-shore test facility determined harvestable kelp yield of 15 afdw t/ac-yr maybe achievable in commercial production. …

individual plants projected to 3 x this yield…

can reliably establish and maintain plants on near-shore substrates…

continuous year-round fertilization not required…

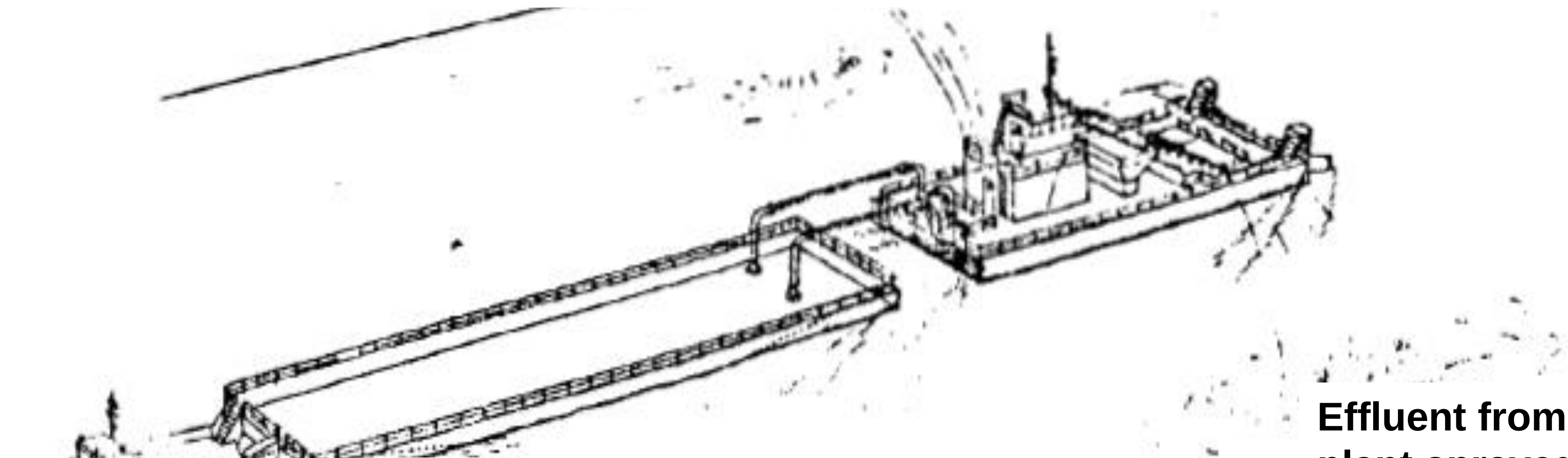
ECONOMIC AND SYSTEMS ASSESSMENT OF THE CONCEPT OF NEARSHORE KELP FARMING FOR METHANE PRODUCTION

APR 1983

PARSONS (RALPH M.) CO. PASADENA, CA

…given current technical status and costs, marine biomass could play a significant role as a long-term gas supply option

Need genetic selection for higher biomass yields at greater planting densities and improved cultivation practices



Harvester cuts at sub 1” size and pumps kelp to barge.

Effluent from digester plant sprayed at same rate as harvester cuts

David Chynoweth (1982)
Review of Biomethane from Marine Biomass

Marine biomass offers highest potential technically for bioenergy

Growth rates exceed by far those of terrestrial based plants

Major limiting factor /challenge /cost in ocean farming is nutrients

Upwelling nutrients too costly. Recycling nutrients is best option.

Main technical challenge: grow macroalgae in open ocean.
"Numerous attempts to do so have been unsuccessful"

Anaerobic digestions demonstrate with high yields and rates

Costs reduced with near-shore rather vs. open ocean farms

Major Conclusions from US DOE Macroalgae Projects

Seaweed biology, productivity major issues

Need open ocean production system concepts

Near-shore systems have limited potential
(on-shore systems not considered herein)

Commodities not congruent with specialties

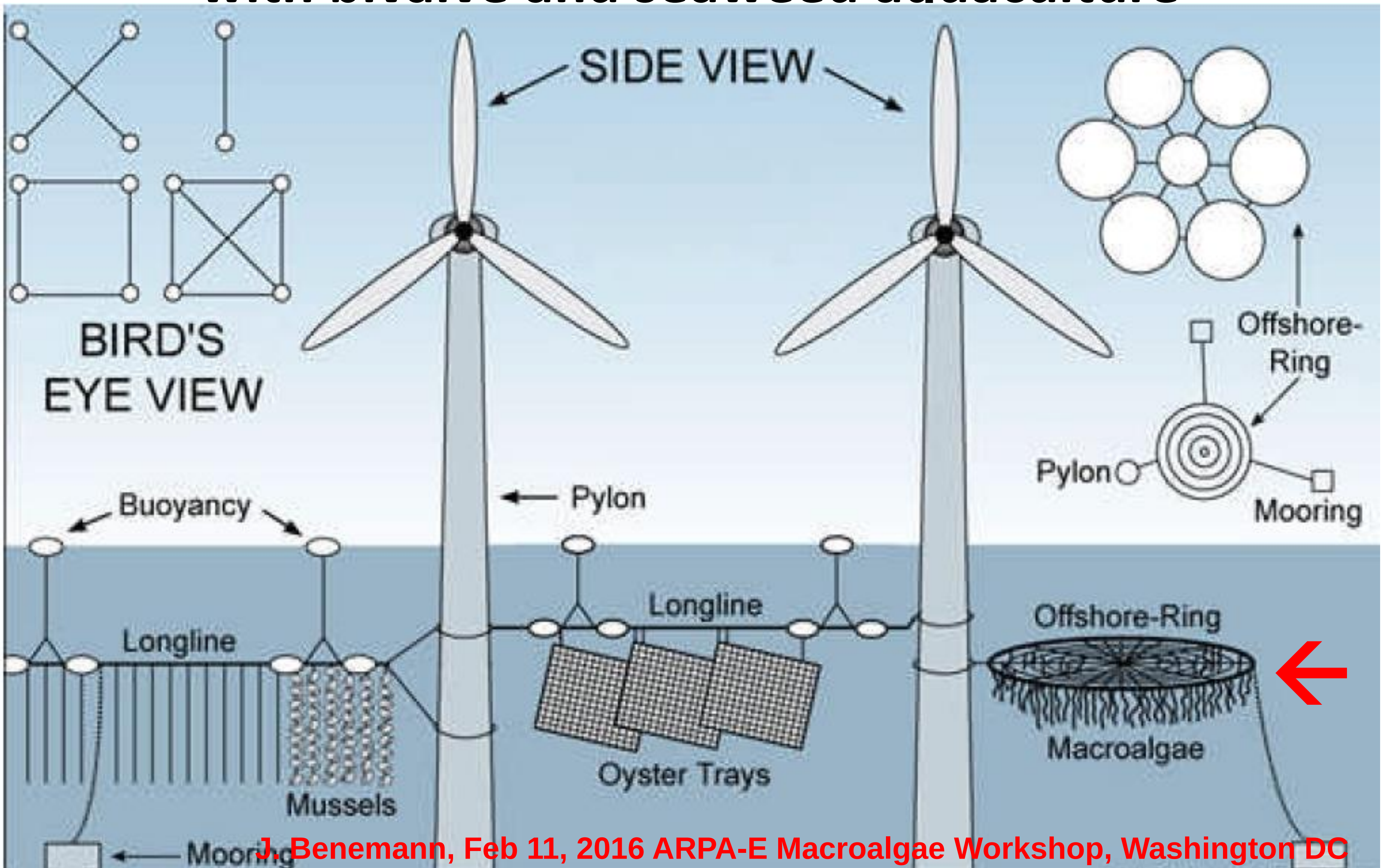
ARPA-E program address fuels/ commodities

Goal to determine if it is plausibly achievable

Start with deep dive Ocean Farm Project review

Debased politics drives out sound science

Many Seaweed Projects ongoing Worldwide – For example here in Europe, combining offshore wind with bivalve and seaweed aquaculture



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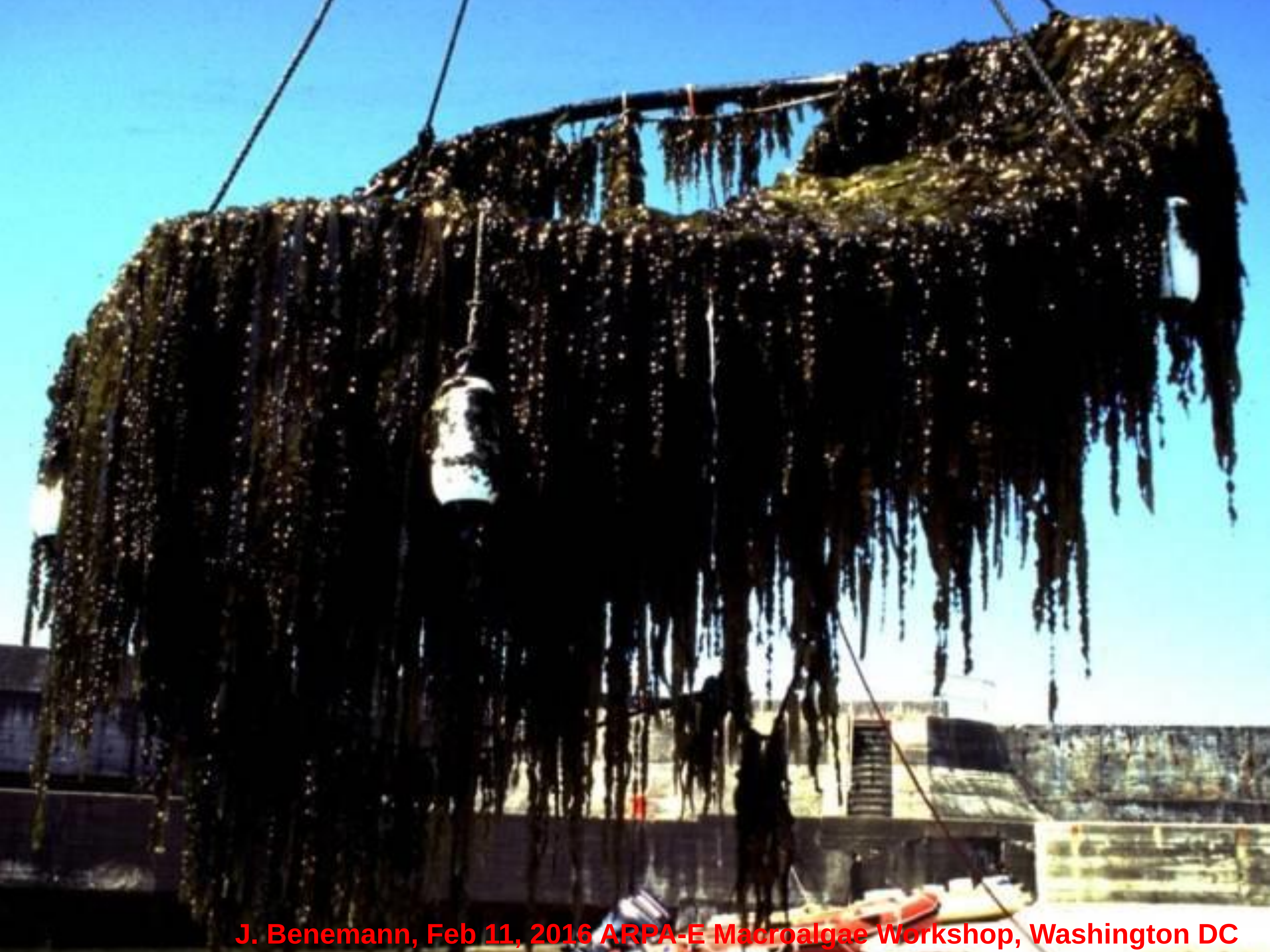

22-23 September 2015

Seagriculture

4th international seaweed conference

IMARES WAGENINGEN UR

ALFRED-WEGENER-INSTITUT HELMHOLTZ-ZENTRUM FÜR POLAR- UND MEERESFORSCHUNG

Cargill

OCEAN HARVEST TECHNOLOGY

CNRS UPMC INSU Station Biologique Roscoff

Smel Synergie Mer et Littoral Recherche & développement

NOORDZEE BOERDERIJ

for a better life olmix Group

THANK YOU, ANY QUESTIONS?

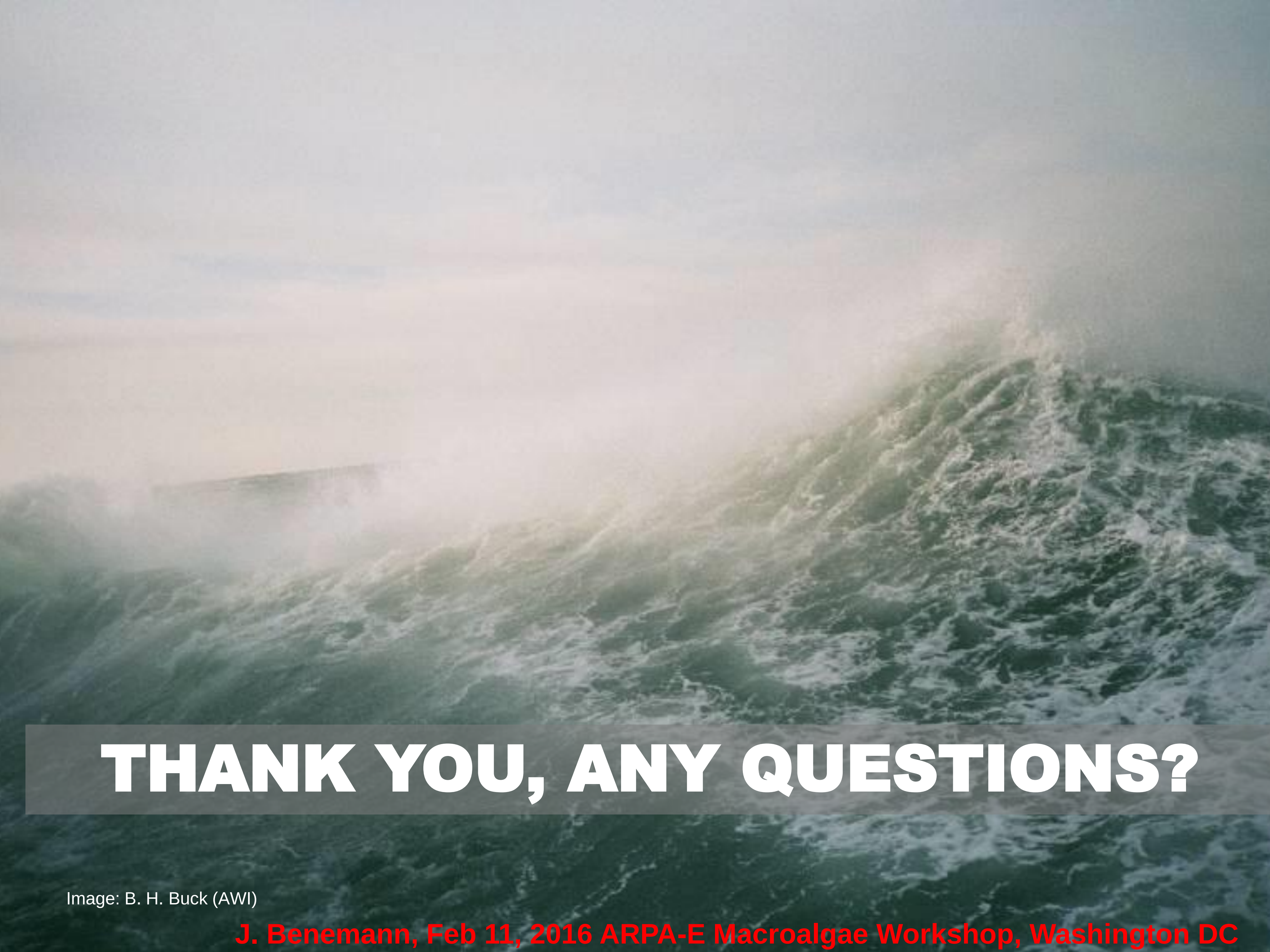

Image: B. H. Buck (AWI)