A New Agenda for Addressing the Impacts and Management of Coastal Invasions

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Consequences of Biological Invasions

- Biological invasions are “non-native species” moved beyond their normal range limits due to human activities
- Biological invasions are the second most important threat to global biodiversity, behind habitat loss (Chapin 2000, Sala 2000)
- In the U.S., 10% of all plants and animals are introduced (OTA 1993)
- Introduced species are a significant risk factor for > 40% of listed threatened and endangered species in the U.S. (Wilcove et al. 1998)

Invasions and Natural Range Expansions

- Movement of species beyond their normal range is naturally occurring process (range expansion)
- For marine/estuarine species, human activities have increased the rate of introduction by ~10^6
- Increase above natural rates is similar to human mediated increase in extinction rates

The Extent of Invasions in Coastal Systems

- Coastal bays and estuaries are among most heavily invaded aquatic habitats
- There are ~500 spp. of introduced species in coastal U.S. waters
- There is a new species introduced into San Francisco Bay every 14 weeks (Cohen and Carlton 1995)

Economic Consequences of Biological Invasions

- Invasive species cost the world's economy hundreds of billions per year (IUCN)
- In the U.S., invasive species cost $128 billion per year (Pimentel et al. 2000)
- Zebra mussels in the Great Lakes cost >$100 million per year in U.S. (Michigan Sea Grant)

Outline

- Ecological impacts of introduced species
  - Effects from populations to ecosystems
  - Specific example of *Spartina* cordgrass in San Francisco Bay, CA, USA
- Economic impacts of introduced species
  - Summary of examples of estimated impacts
  - Formal analysis of economic impacts of European green crab in U.S.
- A new agenda for invasive species research
  - Focusing science to assist invasive species management

Outline

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Table 1. Examples of studies of ecological and evolutionary consequences of invasions in coastal systems

Category	Area of study	Invading taxa	Refs
Ecological consequences	Single-species impacts	*Ilyanassa obsoleta* (snail)	16
		Littorina littorea (snail)	17,26,27
		Batillaria attramentaria (snail)	18,19
		Membranipora membranacea (bryozoan)	20
	Multiple-species impacts	*Musculista senhousia* (mussel)	21,22
		Carcinus maenas (crab)	23–25
	Multiple trophic-level impacts	*Carcinus maenas*	25,29
	Ecosystem-level impacts	*Potamocorbula amurensis* (clam)	30,31
		Pseudodiaptomus inopinus (copepod)	54
	Recipient community impacts	*Musculista senhousia*	32,33
		Codium fragile (alga)	34
		Various	35
	Geographical spread	Various	37
	Pathogens and disease spread	*Vibrio cholerae*, others	38
Evolutionary consequences	Invasion pathways	*Carcinus maenas*	39
		Eurytemora affinis	15,51
	Cryptic species	*Carcinus aestuarii* (crab)	40
		Mytilus galloprovincialis (mussel)	41,42
		Botrylloides sp. (tunicate)	56
	Hybridization with natives	*Spartina alterniflora* (marsh grass)	45,46
	Plasticity in native species	*Carcinus maenas*	47,48
	Population differentiation	*Botrylloides* sp.	49,56
		Potamocorbula amurensis	50
		Eurytemora affinis (copepod)	52
	Physiological adaptation	*Eurytemora affinis*	15,51

Examples of Invasion Consequences

Grosholz , E. 2002. Trends Ecol. Evol.

Estuarine-Wide Ecosystem Impacts

- In 1986, *Corbula (=Potamocorbula) amurensis* first found in San Francisco Bay, California
- Densities of thousands per m^2, filter entire water column every three days (Kimmerer et al 1994)
- Clams can remove 8% of all copepod nauplii (larvae) per day
- Three native copepods and phytoplankton abundances dropped 50-90% (Alpine and Cloern 1992)

Ecosystem Impacts

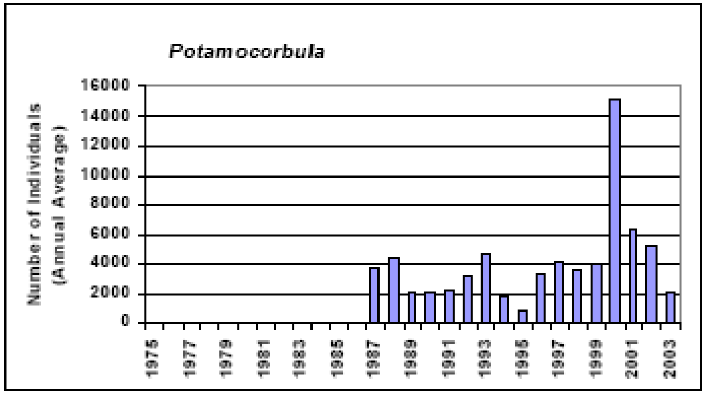


Figure 6: The Amur or overbite clam, Potamocorbula invaded the estuary in 1986. The number of individuals per sample has remained at high levels despite subsequent high flow events. Benthic data courtesy of Department of Water Resources Environmental Monitoring Program.

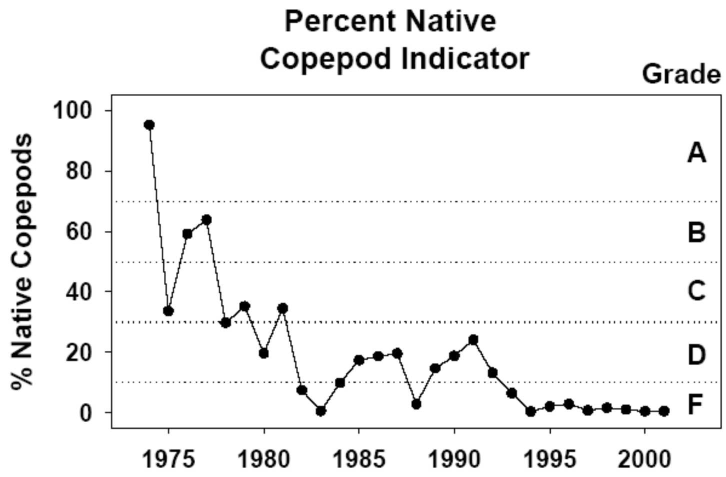


Figure 10: The Percent Native Copepod Indicator measures the percent of copepod individuals in Suisun Bay that are non-native. In 2001, native copepod individuals were less than 1% of the mean of 1974-1979 values (56%). Data source: California Department of Fish and Game, *Neomysis* and Zooplankton survey.

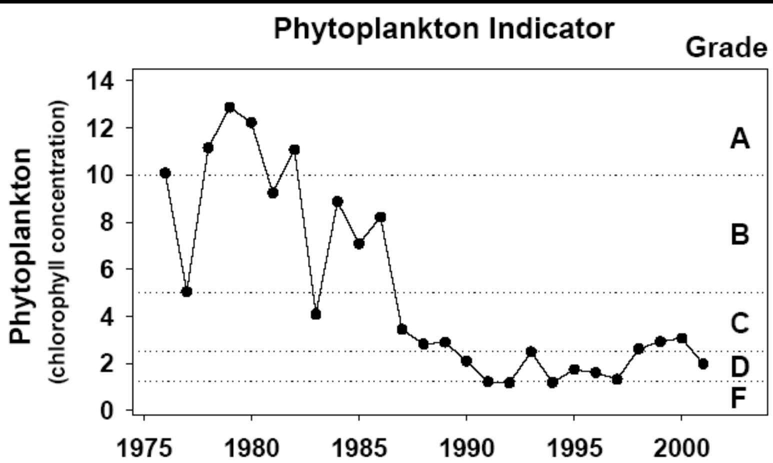


Figure 5. Phytoplankton Indicator from 1976-2001 as determined from chlorophyll measurements taken by the California Department of Fish and Game, concurrent with the *Neomysis* Zooplankton Survey. Average annual chlorophyll levels were 10.27 ug/l from 1976-1980 compared to 2.38 ug/l from 1997-2001. This represents a five-fold decrease in chlorophyll.

New Invaders Accelerating Older Invasions

- Hundreds of species have accumulated in coastal waters worldwide
- Currently most are benign invasions with little impact
- New invasions can change the habitat facilitating other invasions
- Positive feedback among invasions could result in extensive ecosystem degradation (invasional meltdown?)

Invasion of European Green Crab

Carcinus maenas

Indirect Effects Produce Positive Feedbacks Among Invaders

- Introduced *Gemma gemma* was benign invasion in Bodega Harbor, California USA with restricted distribution for >40 years
- European green crabs invaded system in 1994
  - Reduced density of native *Nutricola* by >90% (but not *Gemma*) within two years
- Indirect effects of green crab invasion
  - Invasion of *Gemma* rapidly accelerated throughout Bodega Harbor

Risk to Coastal Systems

- A new mechanism for positive feedbacks among invaders
- New invasions can accelerate older introductions via positive feedbacks
- Even if few new invasions occur, initially benign invasions can become new management problems

Grosholz 2005. Proceedings of the National Academy of Sciences

Risks to Fisheries and Offshore Systems

- Nearshore bays and coastal habitats are more invaded than deeper subtidal and offshore habitats
- However, these habitats are already being negatively impacted by a small but significant number of invasions

Invasions of Gelatinous Zooplankton

- Offshore areas are subject to invasion by gelatinous zooplankton
- The spotted jelly *Phyllorhiza punctata* has caused significant problems for shrimp fishers in the Gulf of Mexico by fouling nets ($10 million in losses, Purcell et al. 2007)
- Data suggests ctenophores *Mnemiopsis leidyi* contributed to the collapse of fisheries in Black and Caspian seas (Daskalov et al. 2007)

Invasive Tunicates and Offshore Fisheries

- Invasive fouling species are increasingly becoming problems in deeper, offshore areas
- *Didemnum* sp. is established in benthic habitats (to 81 m) in important fishing areas including Stellwagen, Tillies and George's Bank (Bullard et al. 2007)
- Up to 50-90% cover in some areas (Bullard et al. 2007)

Undaria in Argentina

- *Undaria pinnatifida* grows abundantly in the Golfo Nuevo, adjacent to Puerto Madryn, Argentina
- It seasonally senesces and accumulates in large mats with significant negative impacts on benthic communities and fisheries (Cassas et al. 2004)

Invasive Algae in the Mediterranean



- Invasive *Caulerpa taxifolia* rapidly covered thousands of hectares of the northern Mediterranean in the 1980-90s
- Grow to depth of 100 m impacting native species (overgrowth, Ceccherelli et al. 2002) and local fisheries (Meinesz 1999)
- Subsequent invasion by *C. racemosa* is adding to impacts (Piazzi et al. 2005)

Plant Invasions in Coastal Systems

- Introduced plants can strongly influence food webs (ecosystem engineers)
  - Change primary producers
  - Alter physical environment (light penetration, water flow)
  - Provide habitat or trophic support for other species including invaders
- Alter biogeochemical processes
  - Detrital inputs
  - Nutrient availability
  - Carbon and nitrogen storage, cycling

Invasive Salt Marsh Cordgrass in San Francisco Bay, CA, USA


Spartina Invading Open Mudflat

Shorebirds Avoiding *Spartina*

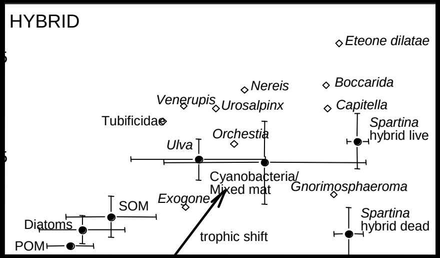
Invasion of Hybrid *Spartina* in San Francisco Bay

- *Spartina alterniflora* was intentionally introduced from the eastern U.S. (native) in 1975 by US Army Corp of Engineers for marsh restoration
- It hybridized with native *Spartina foliosa* (locally extinct at some sites) and spread quickly
- Hybrid *Spartina* has greater tidal range (higher and lower) than native plants
- Invades unvegetated mudflats (focus today) and upper marsh displacing native plants

Impacts of *Spartina* Invasion

Migratory Shorebirds

Resident Canada Geese



Food Web Structure

Other Invasions

Invertebrate Communities

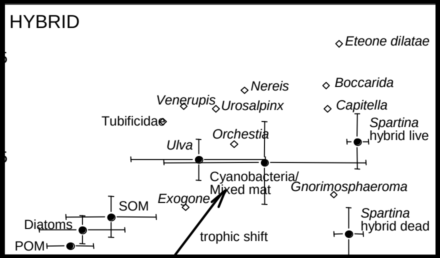
Sediment Biogeochemistry

System Metabolism

Impacts of *Spartina* Invasion

Migratory Shorebirds

Resident Canada Geese



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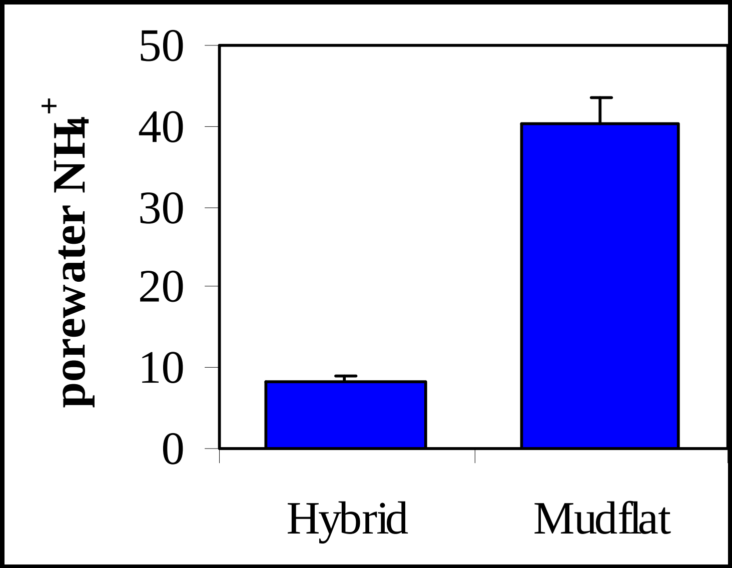
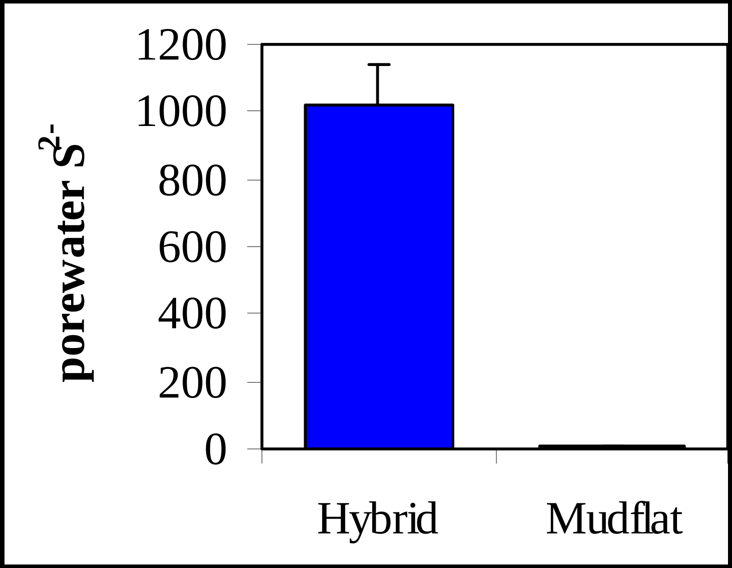
Physical Changes Following *Spartina* Invasion

	Habitat				
	Tidal flat		Hybrid-Invaded		
	Mean	1 SE	Mean	1 SE	P
Relative water circulation					
Gypsum weight loss (g d^{-1})					
April	13.4	0.9	6.7	0.7	< 0.0001
May	9.9	0.3	4.4	0.4	< 0.001
June	20.1	1.1	8.9	0.9	< 0.0001
Mean pooled	14.5	0.9	6.6	0.5	< 0.0001
Water flow (cm s^{-1})	3.3	0.8	0.8	0.1	0.007
Deposition rates					
Sediment deposition (mg cm^{-2} d^{-1})	14.2	2.9	20.4	1.1	0.005
Fine particle deposition (<63 µm) (mg cm^{-2}	1.8	0.6	9.3	1.3	0.0001
Organic matter deposition (mg cm^{-2} d^{-1})	0.4	0.1	3.2	0.2	< 0.0001

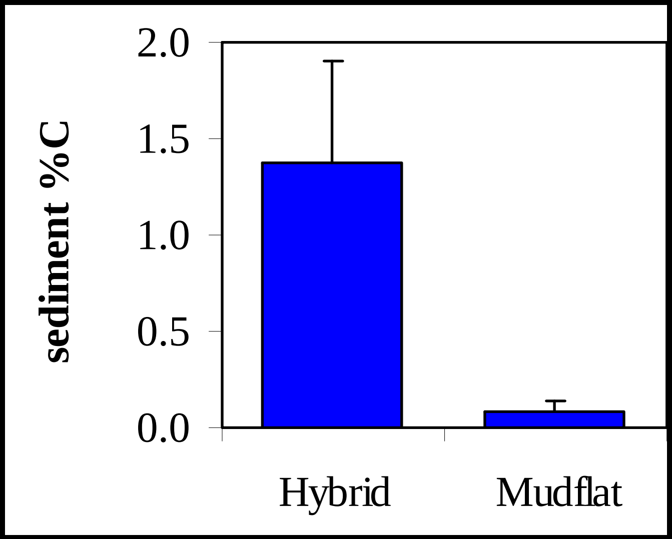
Neira, Grosholz, Levin and Blake. 2006. Ecological Applications.

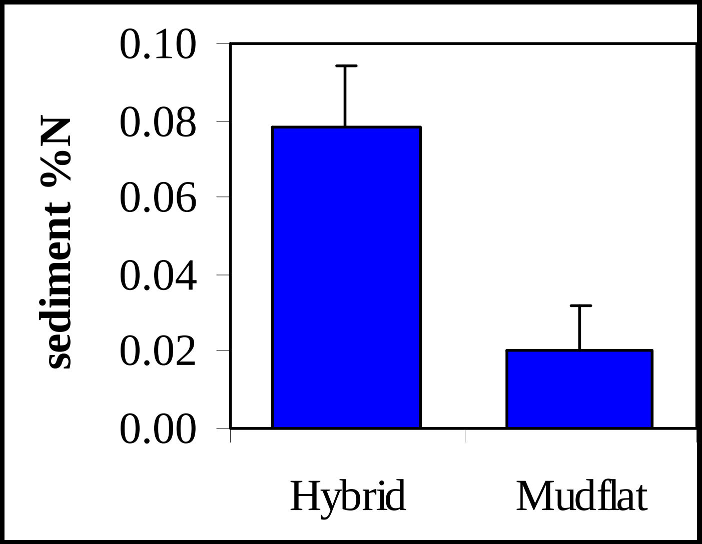
Sediment Porewater

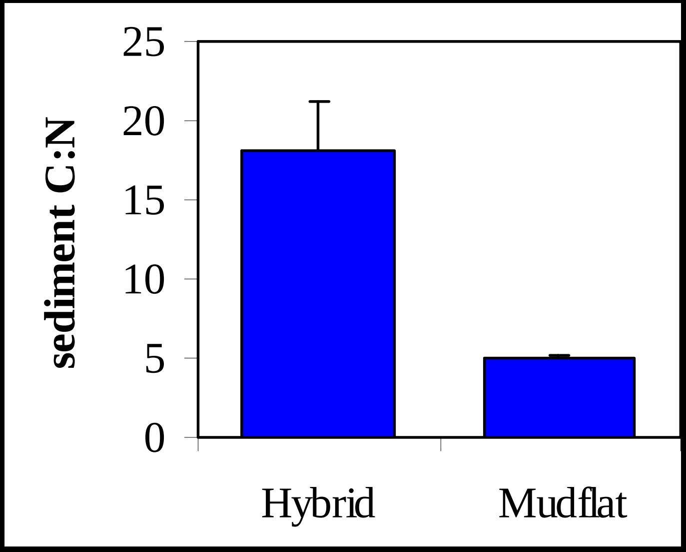




Sediment Organic C and N



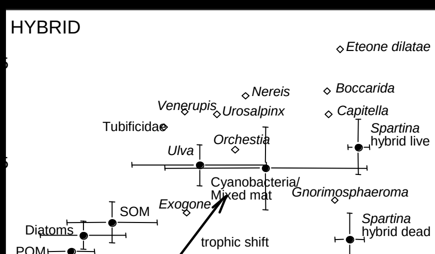




Impacts of *Spartina* Invasion

Migratory Shorebirds

Resident Canada Geese



Food Web Structure

Other Invasions

Invertebrate Communities

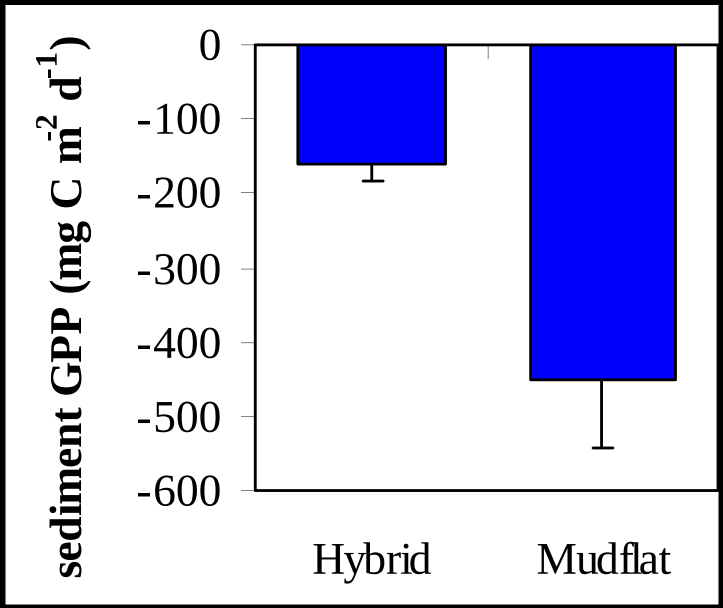
Sediment Biogeochemistry

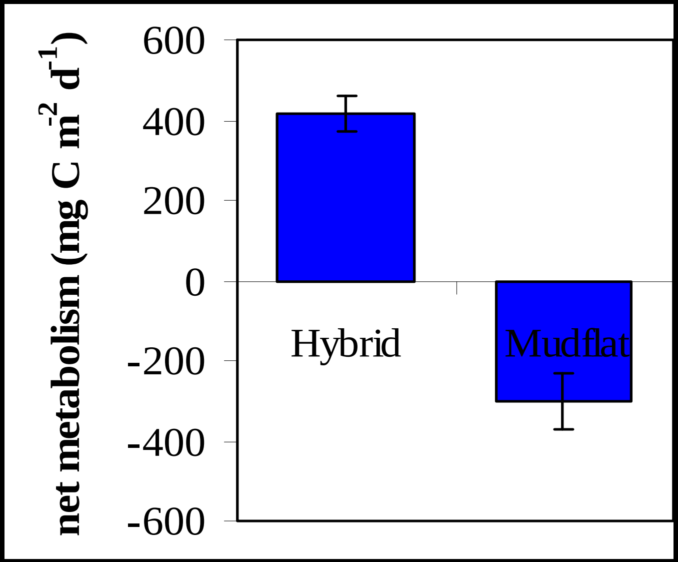
System Metabolism

System Metabolism

- **Measure CO_2 flux over time in chambers**
- **Compare estimates in light (photosynthesis) with dark measurements (respiration)**

System Metabolism





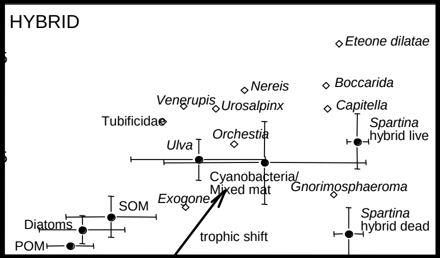
Microalgal production greater in mudflat

Sediments only (no vascular plant PP)
Switch from autotrophic mudflat to heterotrophic hybrid meadow

Impacts of *Spartina* Invasion

Migratory Shorebirds

Resident Canada Geese



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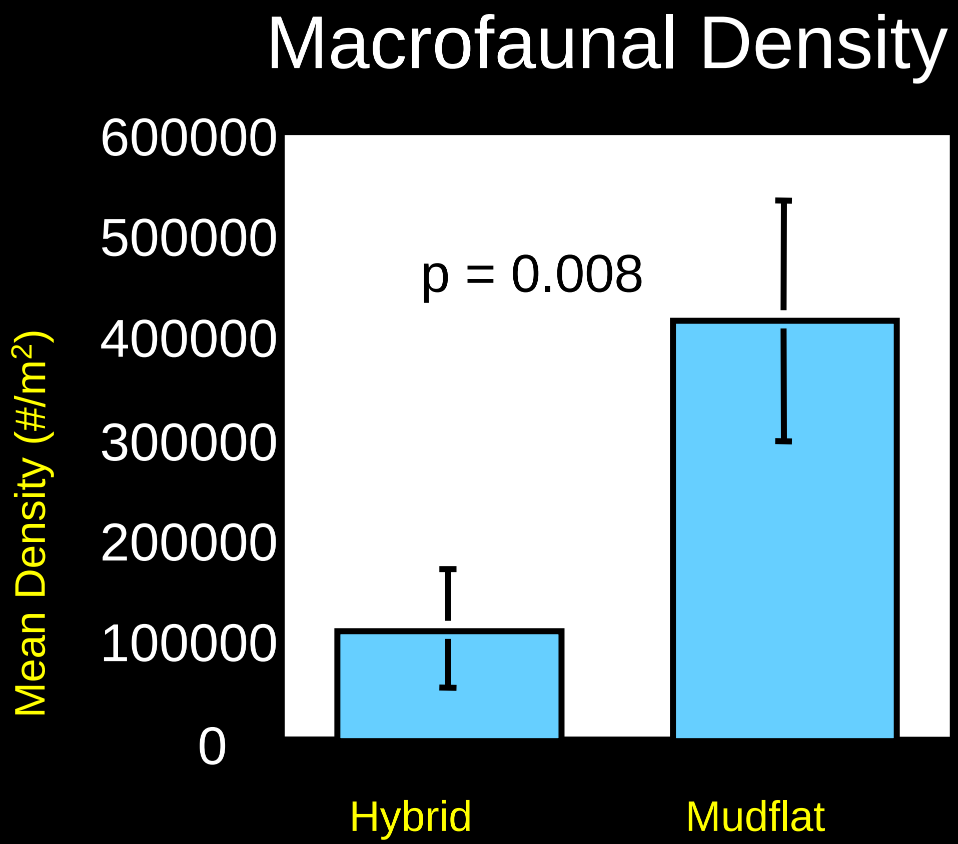
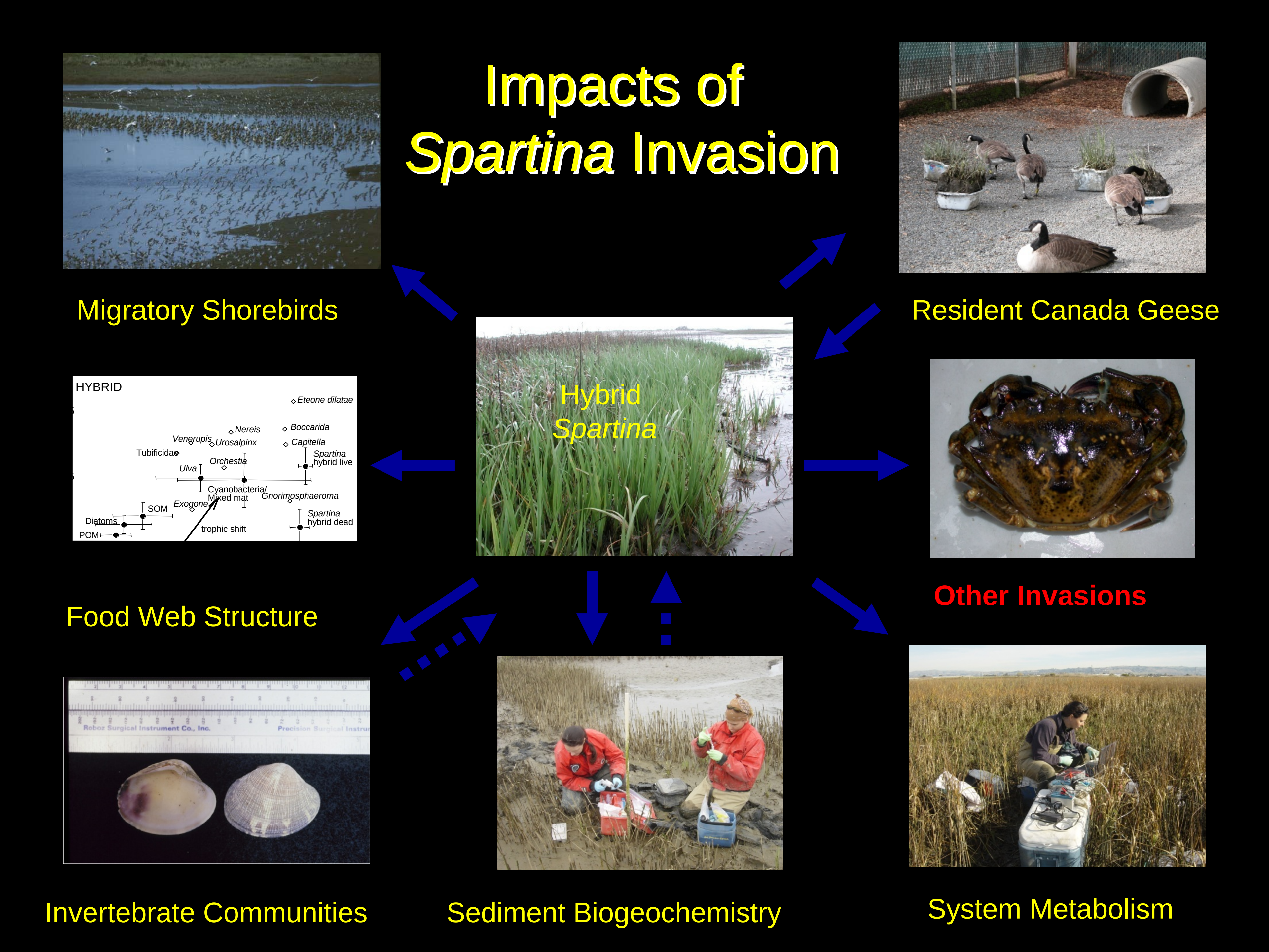
Invertebrate Density

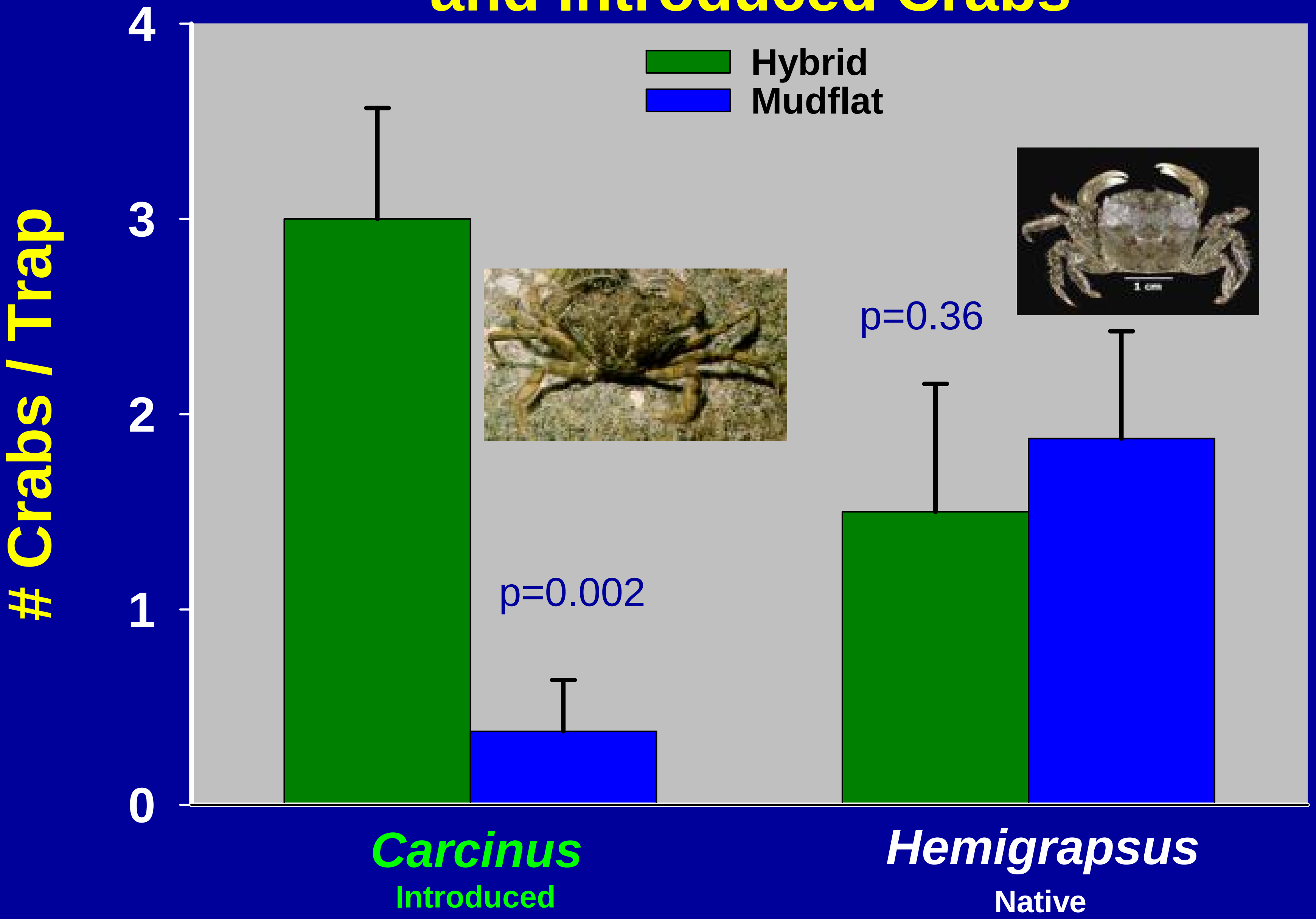


Neira, Levin, and Grosholz. 2005. Mar. Ecol. Prog. Ser.

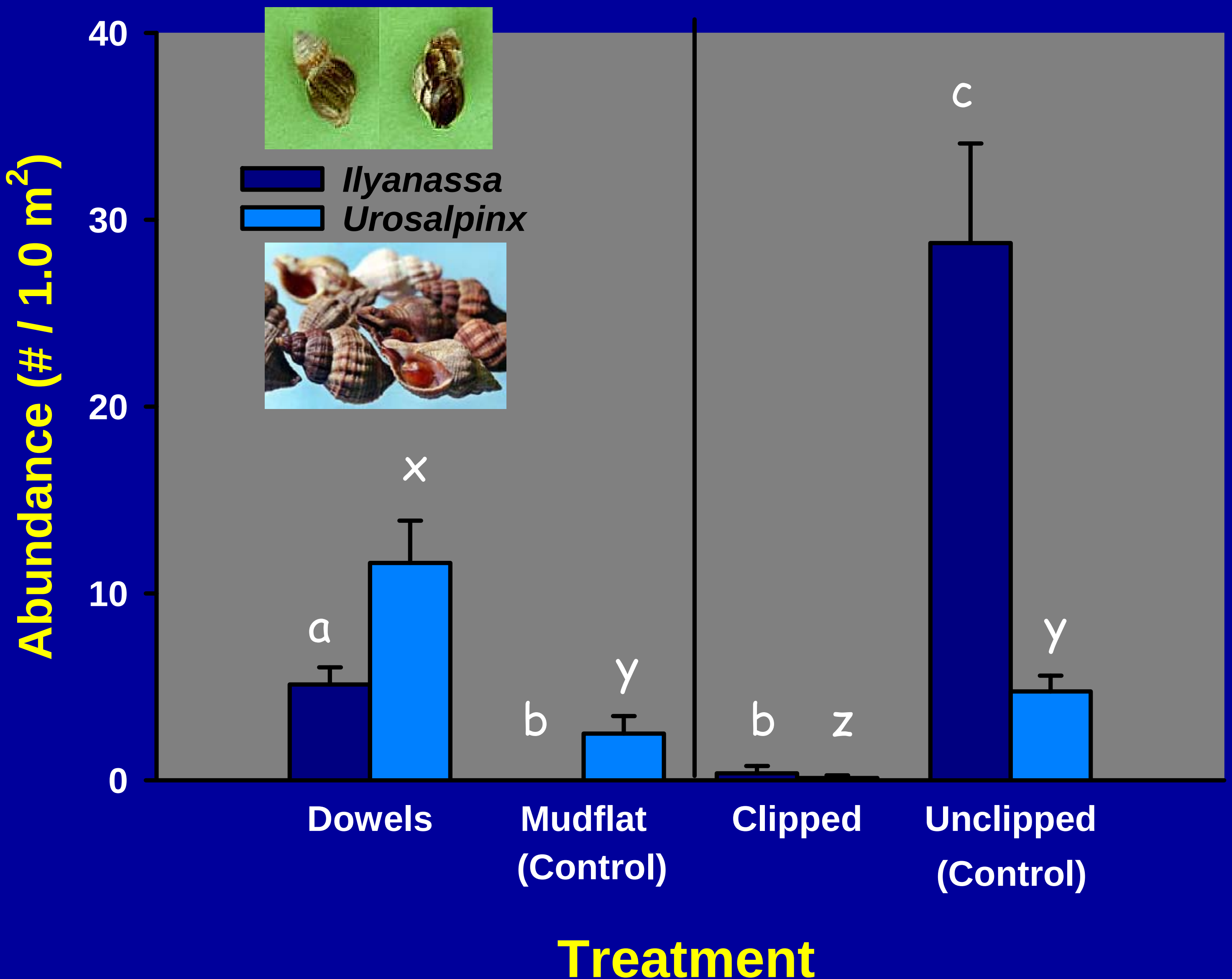


Impacts of
Spartina Invasion
Migratory Shorebirds
Resident Canada Geese
HYBRID
Eteone dilatae
Nereis
Boccarida
Venerupis
Urosalpinx
Capitella
Tubificidae
Orchestia
Spartina hybrid live
Ulva
Cyanobacteria/ Mixed mat
Gnorimosphaeroma
SOM
Exogone
Diatoms
POM
trophic shift
Spartina hybrid dead
Hybrid *Spartina*
Other Invasions
Food Web Structure
Roboz Surgical Instrument Co., Inc.
Invertebrate Communities
Sediment Biogeochemistry
System Metabolism

Relative Abundance of Native and Introduced Crabs



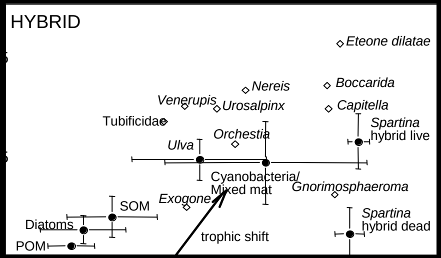
Abundance of Introduced Atlantic Gastropods



Impacts of *Spartina* Invasion

Migratory Shorebirds

Resident Canada Geese



Food Web Structure

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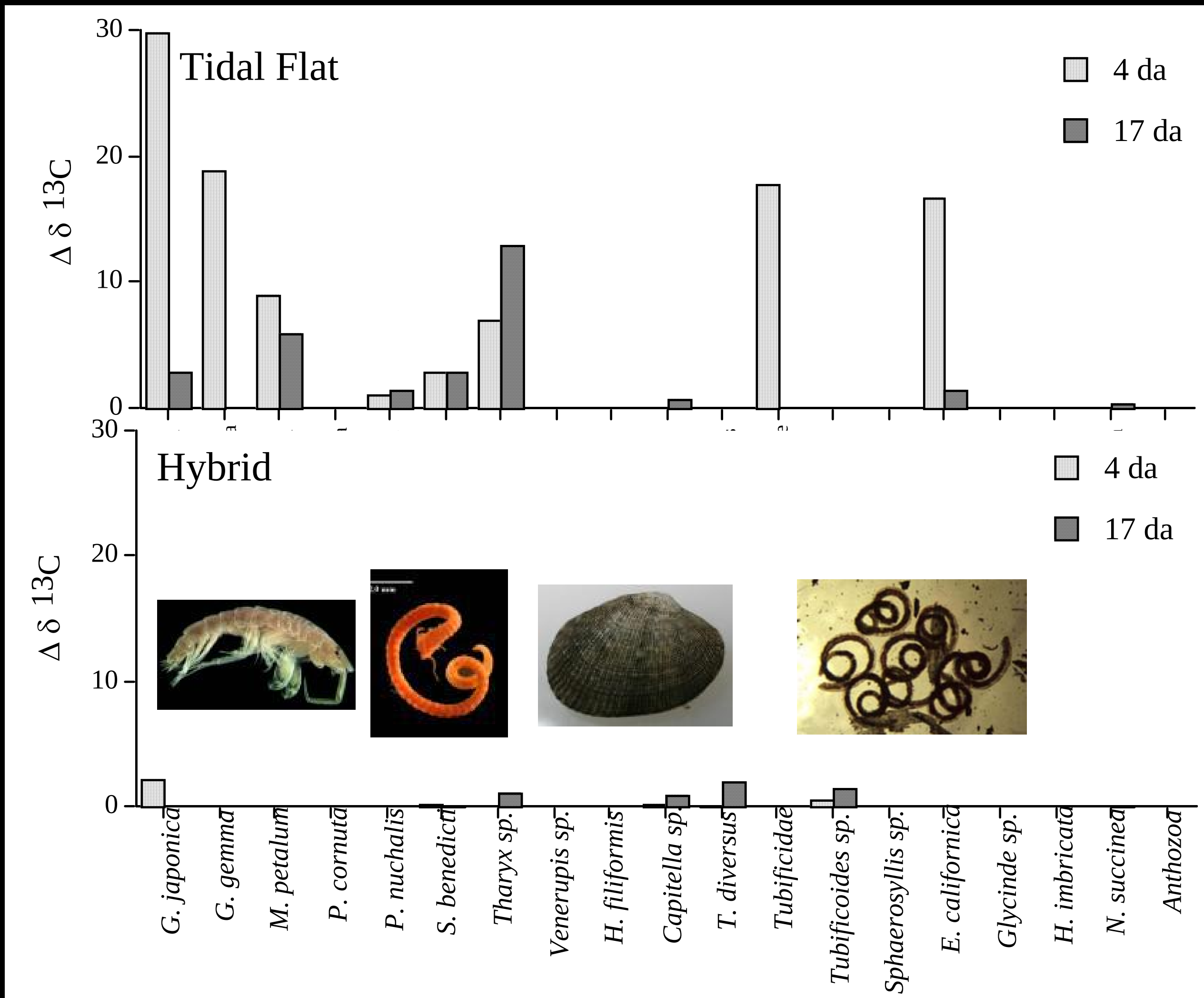
Food Web Changes Using Stable Isotope Tracers

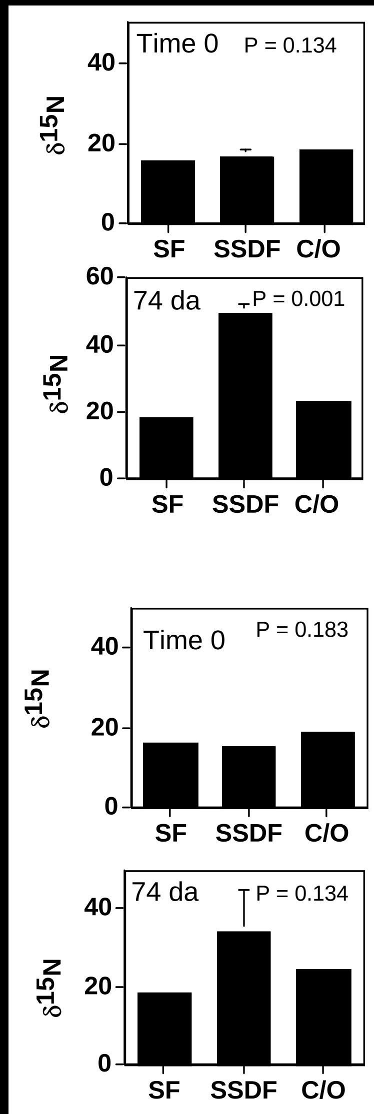
- ^{15}N labeled ammonium nitrate to label *Spartina* detritus
- ^{13}C labeled sodium bicarbonate to label microalgae
- Spray ^{13}C bicarbonate on surface (uptake by microalgae)
- Place ^{15}N detritus in surface sediments and in below ground litter bags

^{13}C Uptake



Levin, Neira and Grosholz. 2006. Ecology.

^{15}N Uptake



Hybrid Area

Tidal Mudflat

Levin, Neira and Grosholz. 2006. Ecology

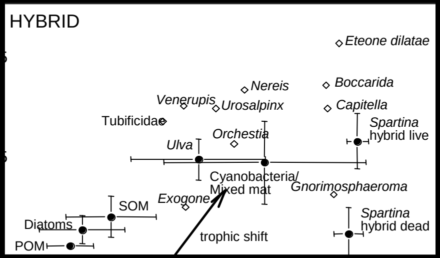
Food Web Effects

- Microalgae consumed more by surface feeders and *Spartina* detritus more by subsurface feeders
- Invaded areas have much higher densities of subsurface feeders and lower densities of surface feeders
- *Spartina* has shifted the system from a largely primary production based system to a largely detrital based system

Impacts of *Spartina* Invasion

Migratory Shorebirds

Resident Canada Geese



Food Web Structure

Other Invasions

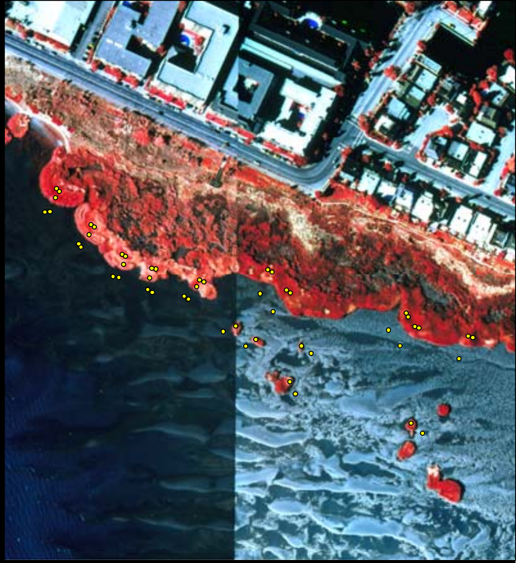
Invertebrate Communities

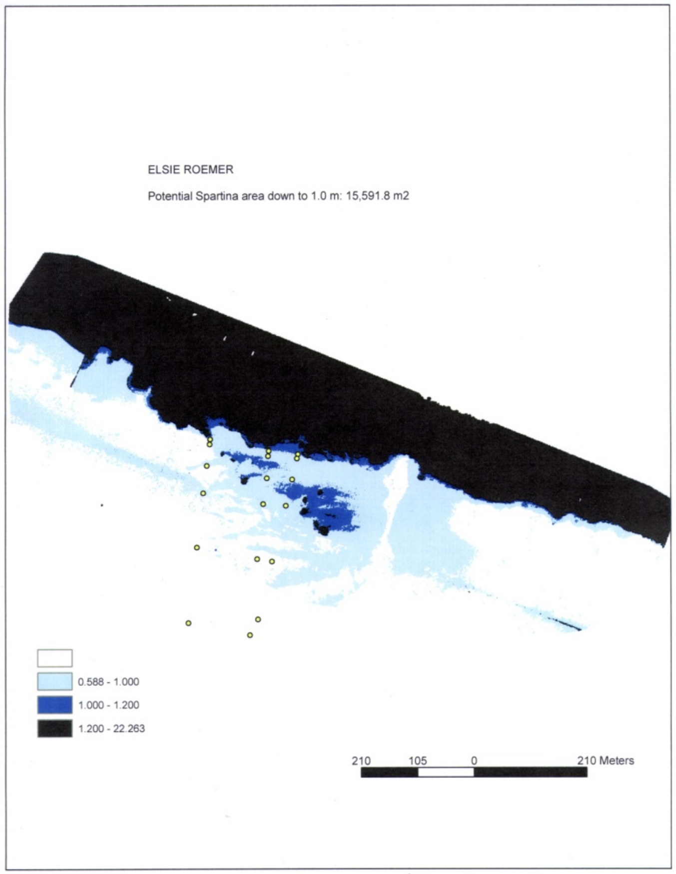
Sediment Biogeochemistry

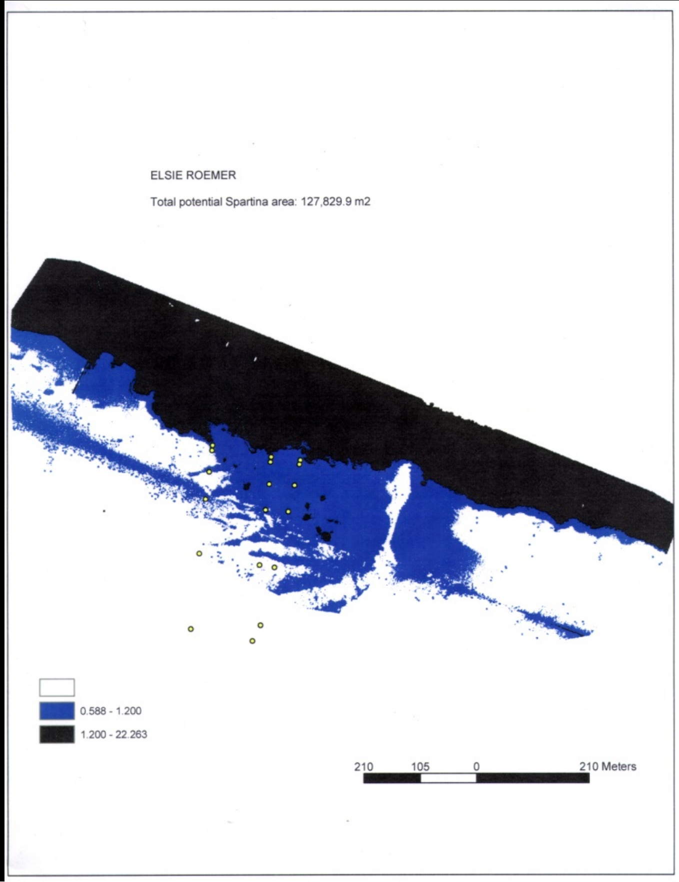
System Metabolism

What are the Consequences of Hybrid *Spartina* Invasion for Shorebirds?

Quantifying *Spartina* Spread with Tidal Elevation Estimated from LIDAR







Estimate Increase in Area Invaded

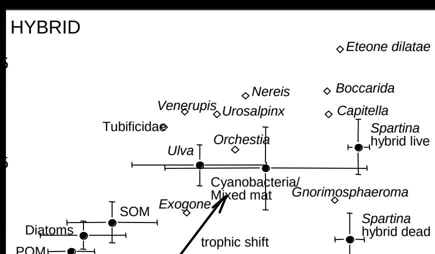
Shorebird Impacts

- Invertebrate biomass declines with tidal height
- Time available for foraging by shorebirds declines with tidal height
- *Spartina* colonizes upper intertidal areas leaving areas with longer inundation period and fewer invertebrates

Impacts of *Spartina* Invasion

Migratory Shorebirds

Grazing Canada Geese



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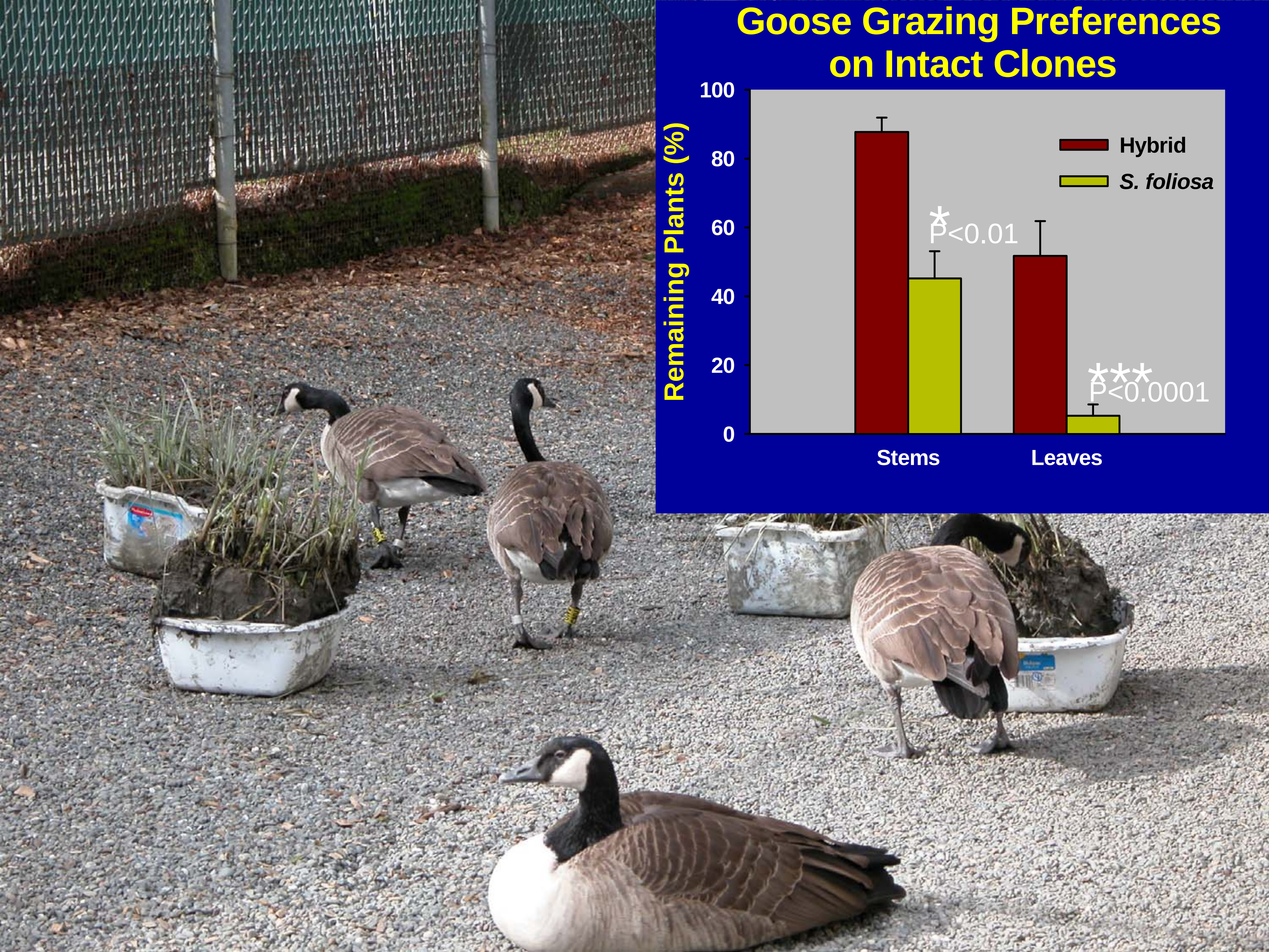
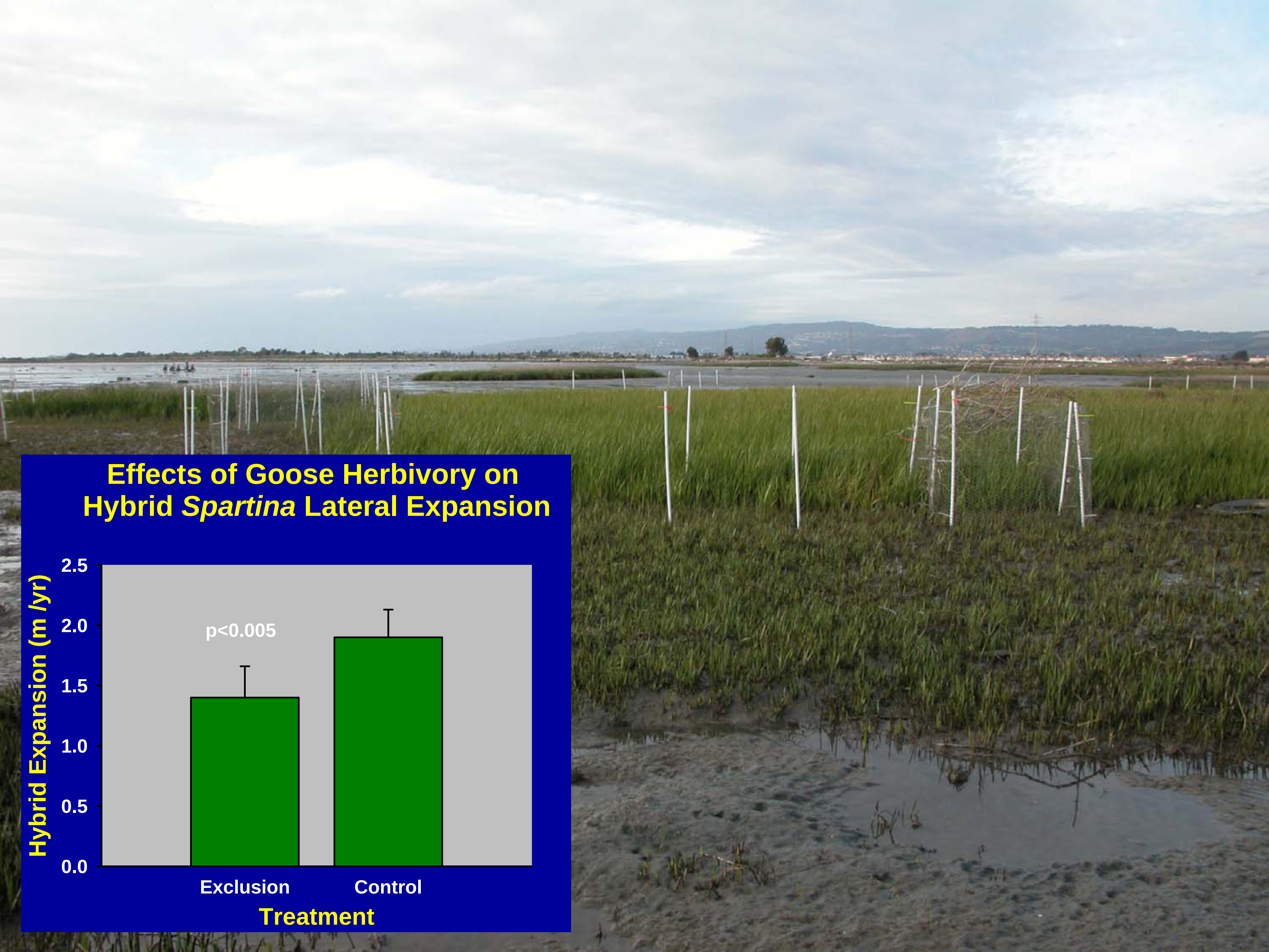


Goose Grazing Preferences on Intact Clones
Remaining Plants (%)
100
80
60
40
20
0
Hybrid
S. foliosa
*
P<0.01
***
P<0.0001
Stems
Leaves

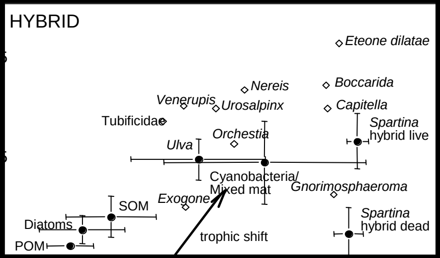


Effects of Goose Herbivory on
Hybrid *Spartina* Lateral Expansion
Hybrid Expansion (m /yr)
2.5
2.0
1.5
1.0
0.5
0.0
p<0.005
Exclusion
Control
Treatment

Impacts of *Spartina* Invasion

Migratory Shorebirds

Resident Canada Geese



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- A new agenda for invasive species research
  - Focusing science to assist invasive species management

Examples of Economic Impacts of Marine Invasions

Estuaries and Coasts: J CERF (2008) 31:3–20

Table 1 Examples of economic impacts of introduced estuarine and marine species

Introduced Species	Economic Impact	Estimated Cost	Reference
Seaweeds			
Caulerpa taxifolia killer algae	Eradication	>US$6M (6 year)	Authors
Codium fragile v. *tomentosoides* oyster thief, deadman's fingers	Cultured oyster mortality, kelp valuation	C$1,500,000 /yr	Colautti et al. 2006
	Removal from native seaweed farm	Bankruptcy	Neill et al. 2006
Hypnea musciformis	Removal	US$55,000	Van Beukering and Cesar 2004
	Reduced property values		
Undaria pinnatifida Wakame	Eradication	NZ$2,923,500 (total)	Wotton et al. 2004
Invertebrates			
Carcinus maenas European green crab	Reduces bivalve aquaculture	US $22M/yr	Grosholz et al. 2000, Lovell et al. 2007
Eriocheir sinensis Chinese mitten crab	Invasion of fish salvage facility	US$1M (2000)	Aquatic Nuisance Species Task Force 2003
Mnemiopsis leidyi Ctenophore	Correlated loss of anchovy fishery	US$250M/yr	Zaitsev 1992
Mytilopsis sallei black striped mussel	Eradication	A$2.2M	Bax et al. 2002
Phyllorhiza punctata Scyphomedusa	Potential loss in shrimp landings	US$10M (2000)	Graham et al. 2003
Terebrasabella heterouncinata Sabellid polychaete	Reduced cultured abalone product quality	Bankruptcy	Culver and Kuris 2000
	Eradication	Several US$K	Kuris 2003
Teredo navalis Shipworm	Structural damage (ships, docks)	US$200M/yr	Cohen and Carlton 1995

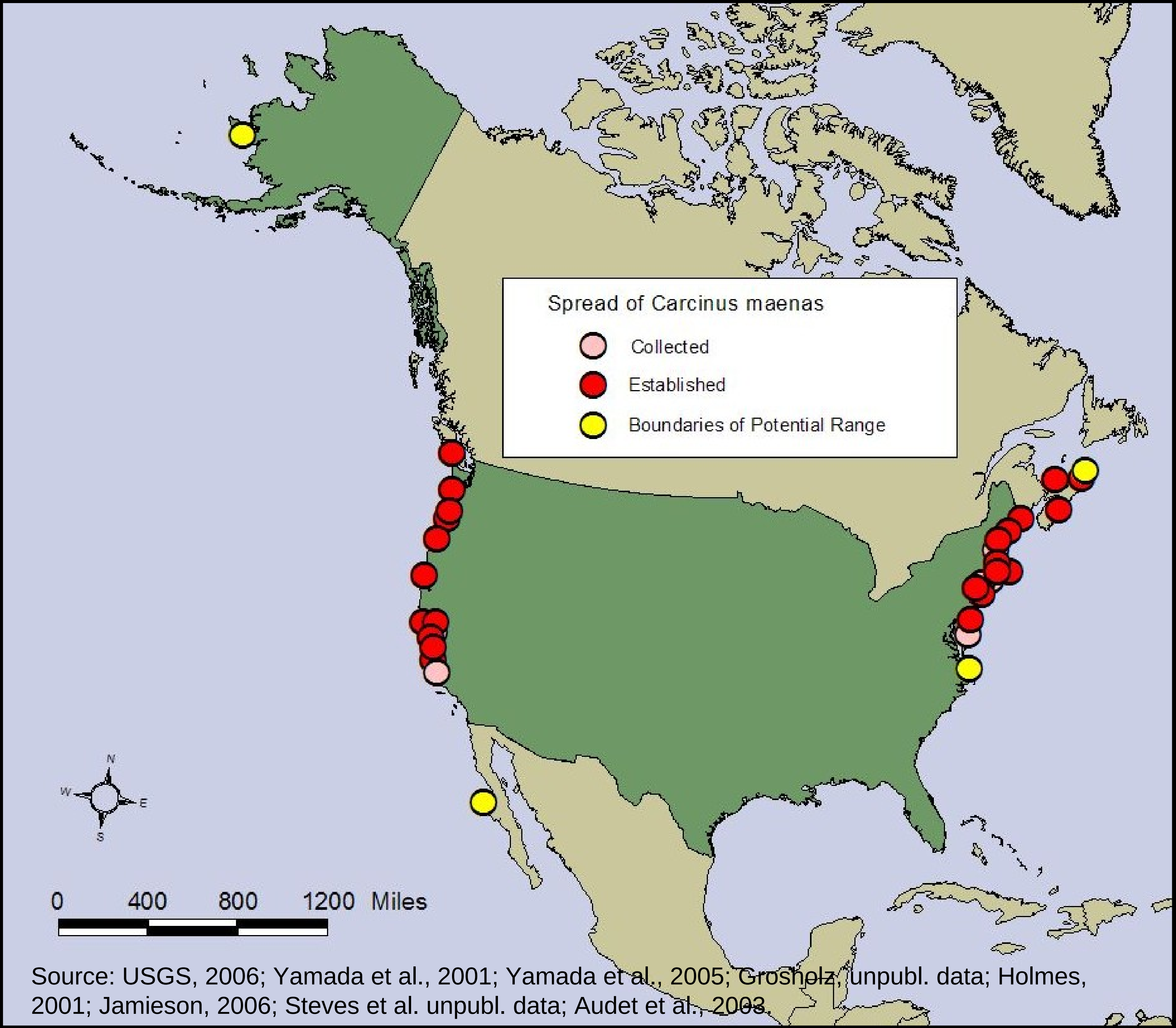
Types of Economic Impacts of Aquatic Invaders

- Production impacts
- Price and market effects
- Trade impacts
- Management and prevention costs
- Recreational impacts
- Aesthetic impacts
- Human and wildlife health impacts

Photo: Canada Department of Fisheries and Oceans.

Estimating Impacts of the European Green Crab (*Carcinus Maenas*)

- Goal of Study: Estimate the economic impacts of the GC on the West and East Coasts of the U.S.
  - Current impacts
  - Future impacts (West Coast)
  - Consider future alternative scenarios for West Coast expansion and control



Source: USGS, 2006; Yamada et al., 2001; Yamada et al., 2005; Grosholz, unpubl. data; Holmes, 2001; Jamieson, 2006; Steves et al. unpubl. data; Audet et al., 2003.

Species Preyed Upon by the European Green Crab

- **Consumes over 35 different species, including multiple commercially viable types of shellfish.**

- **Species affected include:**
    - Manila Clams
    - Northern Quahogs
    - Softshell Clams
    - Blue Mussels
    - Bay Scallops
    - Pacific Oysters
    - Razor Clams
    - Native California Clams

Penn Cove Shellfish, LLC

City of Edmonds, WA. 2003

Britannica Concise

Potential Economic Impacts

- Commercial and recreational fishing and shellfishing
- Damage to eelgrass beds and effects on habitat restoration
- Indirect impacts on shorebirds due to reduction in prey, with impacts on recreational birding
- Non-use impacts (e.g., existence of healthy aquatic community)


Bowdoin College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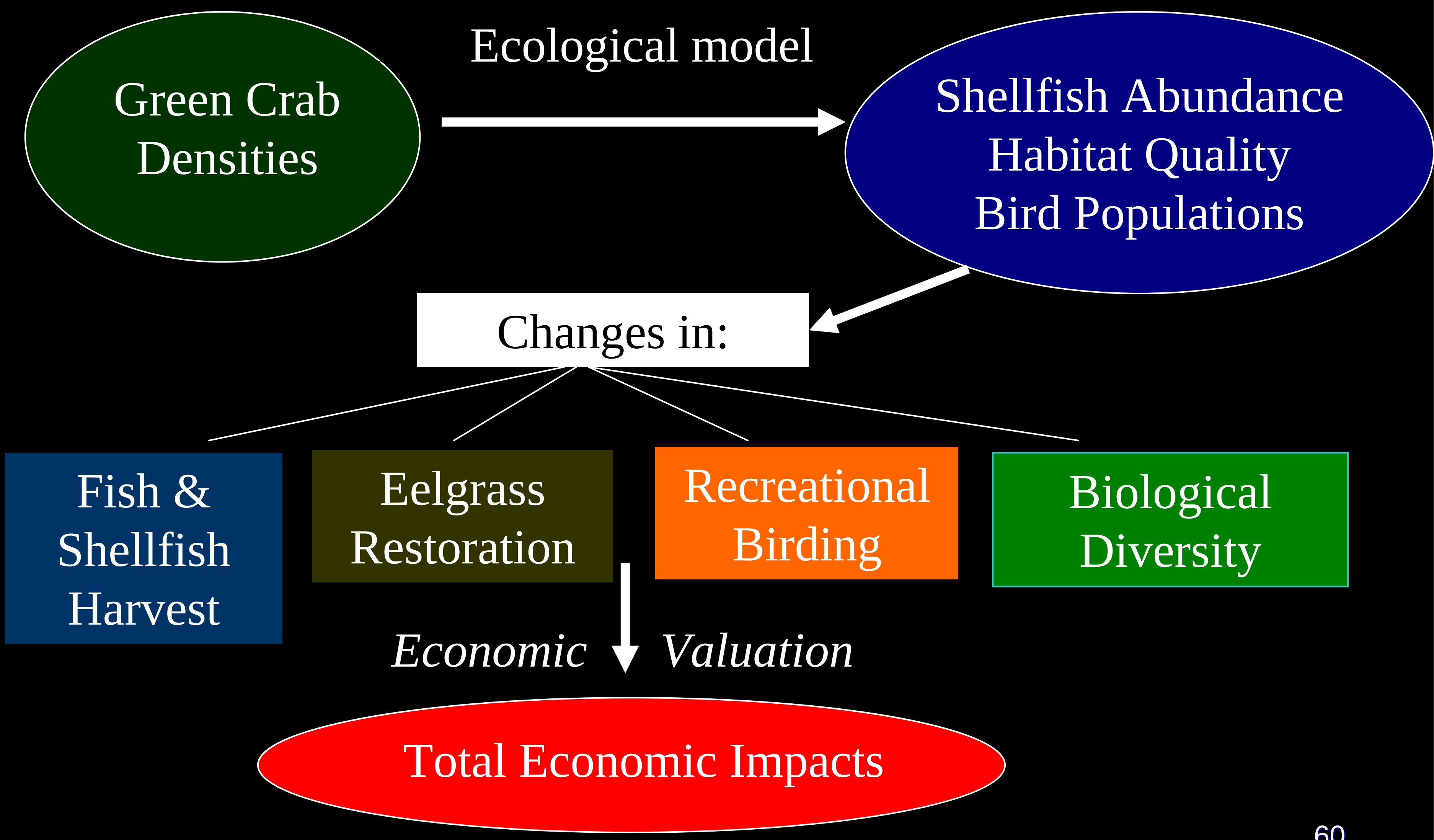
Rob Robinson

Integrated Model



Integrating Ecological and Economic Models for Impacts on Shellfish

- Use GARP (Steves *et al.*) to predict the outer boundaries of the potential future GC distribution on the West Coast; use logistic regression models to predict invasion of specific estuaries
- Use statistical models to determine relationship between Green Crab densities in estuaries and survival rates for shellfish
- Use economic models to estimate damages to fishermen, seafood consumers, and recreational users

Modeling Probability of Green Crab Presence

Probability of Green Crab Presence (p_i):

$$p_i = \frac{\exp(a + \mathbf{X}_i \boldsymbol{\beta} + \mathbf{Z}_i \gamma)}{\exp(a + \mathbf{X}_i \boldsymbol{\beta} + \mathbf{Z}_i \gamma) + 1}$$

Where:

X is a vector of variables that measure estuary characteristics and

Z is a vector of spatial variables.

Independent Variables

The variables included in X:

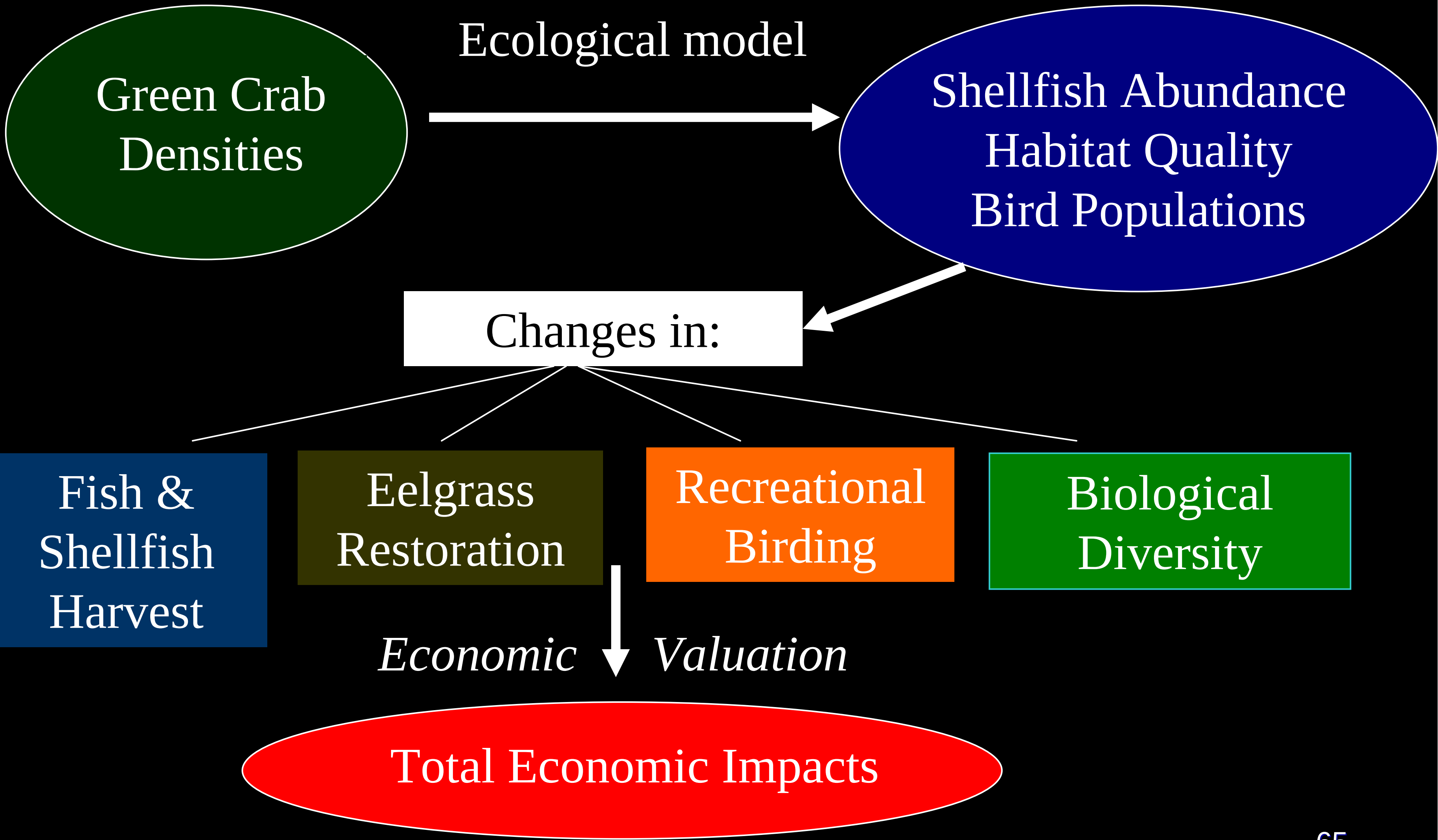
WaterEDA:	Water EDA/CDA area (miles)
Mzone:	Mixing Zone (sq. miles)
Human:	Overall Human Influence (ordered from 1-5 in increasing order of influence)
Temp:	Mean surface and bottom temperature (Deg C)
Sal:	Mean surface and bottom dissolved oxygen (mg/L)
Coll:	Collection depth at which bottom readings were collected (meters)
Oth_Crab:	Ordered from 0-5 measuring the presence of other crabs in increasing order of abundance.
Shell:	Number of shellfish varieties present (1-6)
Pol_Flow:	Total watershed estimated flow of pollution (mg/y)

Independent Variables (cont.)

The spatial variables included in Z:

DistanceSF:	Distance of estuary from San Francisco Bay (miles)
Cont_Num:	Number of contiguous estuaries with Green Crab presence

Integrated Model



Ecological Damage Model:

Species Considered:

- Manila Clams
- Softshell Clams
- Hardshell Clams
- Blue Mussels
- Scallops

Ecological Damage Model:

Data Sources

- Manila Clams
  - data from Tomales Bay, CA (from Grosholz et al. 2001)
- Softshell Clams
  - data from Rowley River, MA (from MA Dept. of Fish & Game 2001)
- Hardshell Clams
  - data from 10 sites on Martha’s Vineyard, MA (from Walton 2003)
- Blue Mussels
  - data from Menai Straits, North Wales (from Dare & Edwards 1976)
- Scallops:
  - data from the Poquonock River, CT (from Tettelbach 1986).

Green Crab Impacts on Shellfish

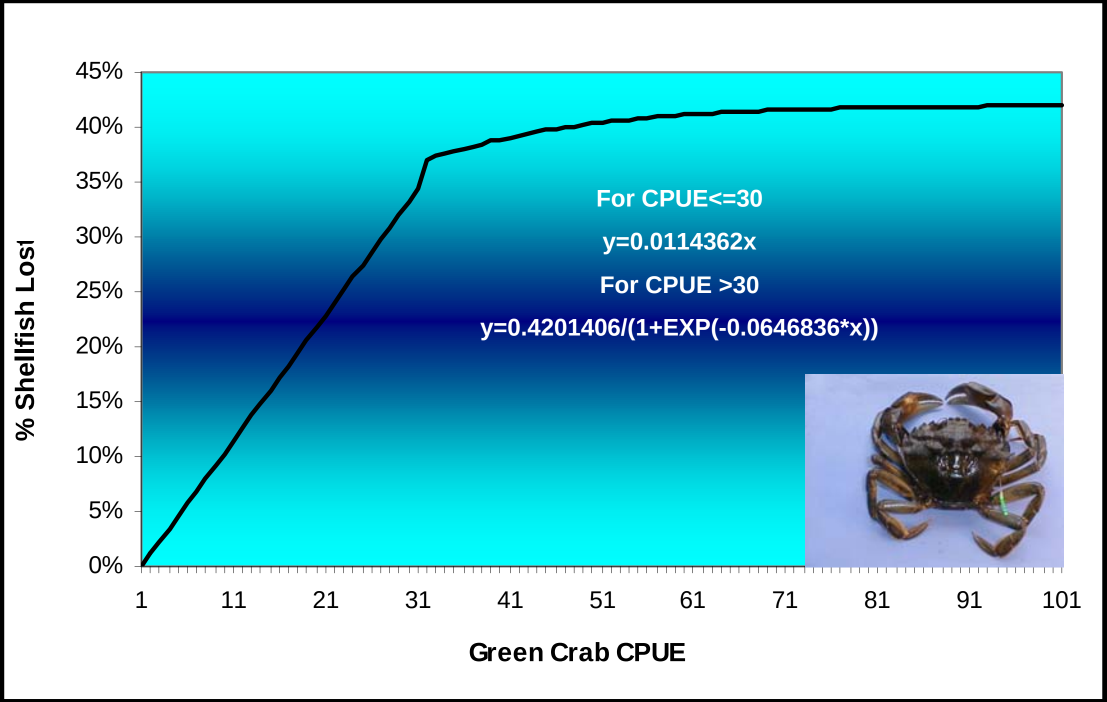

Penn Cove Shellfish, LLC


Edmonds Discovery Programs. 2005


mehp.vetmed.ucdavis.edu


City of Edmonds, WA. 2003

Percent Shellfish Lost by Green Crab Density

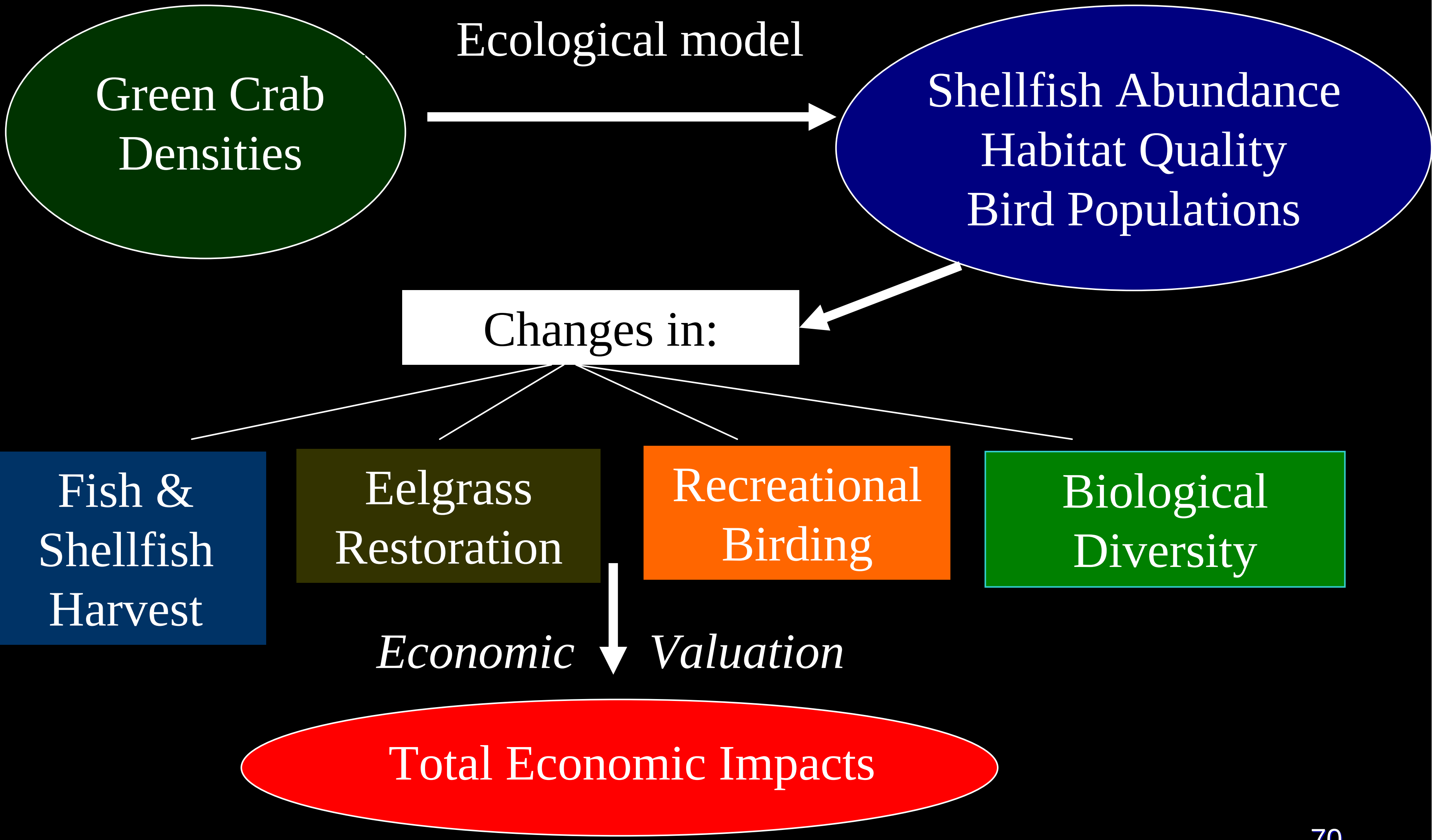


- **Based on combined dataset for manila clams, hardshell clams, softshell clams, bay scallops and blue mussels**

Limitations of Ecological Models

- Lack of data on green crab effects on many species, including
  - other shellfish species
  - finfish
  - shore birds
- Data used in this analysis are limited to a few observations and thus do not allow rigorous statistical modeling

Integrated Model



Modeling Market Impacts of GC:

- Estimate changes in commercial harvest due to GC predation (in pounds)
- Use data on dockside prices to estimate gross value of changes in harvest
- Estimate changes in producer's normal profit (PS) as a proportion of changes in gross value. Producers net benefit ratios:
  - aquaculture = 0.5;
  - wild shellfish harvest =0.58
- Estimate welfare changes (CS) to final and commercial consumers of fish due to changes in shellfish price.

Current and Historical Impacts of Green Crab Predation on the East Coast

Estimated Total and Annual Losses to Green Crab Predation on the East Coast				
	Average Annual Losses		Total Harvest Losses, 1975-2005	
Species	Millions of Pounds*	Millions of 2006$**	Millions of Pounds*	Millions of 2006$**
Hardshell Clam (Quahog)	35 - 39.6	$13.9 - $15.7	1,085.4 - 1,227.8	$431.5 - $486.9
Softshell Clam	16.1 - 17.8	$6.5 - $7.3	500.5 - 550.6	$202.8 - $227.1
Blue Mussel	12.6 - 15.9	$0.8 - $1	391.2 - 492.8	$25 - $32.1
Bay Scallop	3.7 - 3.7	$1.9 - $1.9	115.1 - 115.1	$59.7 - $59.7
Total	67.5 - 77	$23.2 - $26	2,092.2 - 2,386.3	$719.1 - $805.9

* All shellfish losses are presented in whole weight.
** Measured as the total value of consumer and producer surplus lost.

Input Data:

- Green crab densities range from 27.4 to 410.
- Anti-predator netting efficiency: Low = 13%; High = 54%

Current Annual Commercial Shellfish Harvest Losses due to Green Crab Predation on the West Coast

(Preliminary Estimates)

Current Annual Losses by Species and State

	California		Oregon		Washington		Alaska		West Coast Total	
	000's of Pounds*	000's of 2006$**	000's of Pounds*	000's of 2006$**	000's of Pounds*	000's of 2006$**	000's of Pounds*	000's of 2006$**	000's of Pounds*	000's of 2006$**
Hardshell Clam	0	$0	0***	$0* - $0*	0	$0	0	$0	0 - 0	$0 - $0
Softshell Clam	0	$0	0***	$0* - $0*	0	$0	0	$0	0 - 0	$0 - $0
Manila Clam	0.7 - 1.4	$0.4 - $0.8	0	$0	0.3 - 0.5	$0.1 - $0.3	0	$0	1 - 1.9	$0.6 - $1.1
Blue Mussel	0.2 - 0.4	$0.1 - $0.2	0	$0	0	0	0	$0	0.2 - 0.4	$0.1 - $0.2
Total	1 - 1.8	$0.5 - $1	0 - 0	$0	0.3 - 0.5	$0.1 - $0.3	0 - 0	$0	1.2 - 2.3	$0.7 - $1.3

* All shellfish losses are presented in whole weight.
** Measured as the total value of consumer and producer surplus lost.
***Value >0

Input Data:

- Current green crab density ranges (CPUE): CA = 0.005-15.3; OR = 0.05-1.15; WA = 0.06-0.14
- Potential future green crab densities range from 0.01 to 31.5 CPUE.
- Anti-predator netting efficiency: Low = 13%; High = 54%

Potential Future Commercial Shellfish Harvest Losses due to Green Crab Predation on the West Coast

(Preliminary Estimates)

Potential Future Annual Losses by Species and State

	California		Oregon		Washington		Alaska		West Coast Total	
	000's of Pounds*	000's of 2006$**	000's of Pounds*	000's of 2006$**	000's of Pounds*	000's of 2006$**	000's of Pounds*	000's of 2006$**	000's of Pounds*	000's of 2006$
Hardshell Clam	0	$2.4 - $6	0.1 - 0.1	$0.3 - $0.7	16.3 - 26.6	$9.9 - $16.3	10.1 - 15	$6.1 - $8.9	26.6 - 41.8	$18.8 - $31.9
Softshell Clam	0	$1.5 - $5.7	0***	$0.2 - $0.6	76.3 - 146.9	$12 - $23.5	0	$0 - $0.1	76.3 - 146.9	$13.7 - $29.9
Manila Clam	2.2 - 4.4	$56.4 - $169	0	$5.6 - $17	920.3 – 1,596.9	$396.9 - $691.6	0	$1.0 - $3.1	922.6 - 1601.3	$460 - $880.6
Blue Mussel	44 - 84.2	$24.6 - $65.3	0	$1.0 - $3.8	191.4 - 368.5	$64.6 - $127.5	0.2 - 0.4	$0.3 - $0.8	235.6 - 453.1	$90.5 - $197.4
Total	46.2 - 88.6	$85 - $245.9	0.2 - 0.2	$7.2 - $22.1	1204.4 - 2138.9	$483.4 - $858.9	10.3 - 15.4	$7.4 - $12.9	1261.1 - 2243	$583 - $1139.7

* All shellfish losses are presented in whole weight.
** Measured as the total value of consumer and producer surplus lost.
*** Value >0

Net Present Value of potential losses over 25 years: $15 - $29 million (discounted at 3%)

Modeling Non-market Impacts of GC:

- Recreational shellfishing/fishing
- Bird watching
- Eelgrass restoration efforts
- Impacts on biological communities/species assemblage

Costs of Green Crab Management Options*

As Estimated in the Management Plan for the European Green Crab (2002)

Values are likely underestimate activity costs (2006$)

Prevention and Containment

- **$50K in 2005; not estimated for later years**

Detection and Forecasting

- **$222K/ year in 2005-2006; $194K/year in 2007-2010**

Control, Eradication and Mitigation

- **$111K/year in 2005-2010**

Information Management

- **$11K/year**

Potential Total Cost per Year

- **$316K to $394K per year**

*** While the cost estimates include both the East and West Coast, most of the activities are likely to take place on the West Coast.**

Costs and Benefits Comparison

Potential total cost per year to prevent further expansion of Green Crabs

$316K to $394K per year*

Potential avoided damages to commercial shellfishing from preventing green crab expansion further north in WA and AK ($/year)

$681K per year (*average estimate*)

Both costs and benefits are likely to be underestimated. Additional benefit categories may include:

- **Avoided damages to other shellfish species**
- **Avoided damages to recreational users (shellfish harvest and birding)**
- **Avoided damages to habitat restoration efforts in the state of WA**
- **Nonuse values**

*** While the cost estimates include both the East and West Coast, most of the activities are likely to take place on the West Coast.**

Outline

- Ecological impacts of introduced species
  - Effects from populations to ecosystems
  - Specific example of *Spartina* cordgrass in San Francisco Bay, CA, USA
- Economic impacts of introduced species
  - Summary of examples of estimated impacts
  - Formal analysis of economic impacts of European green crab in U.S.
- A new agenda for invasive species research
  - Focusing science to assist invasive species management

Changing Views of Managing Invasive Marine and Estuarine Species

- 10-15 years ago eradication was viewed as impossible in estuarine and marine systems and ballast water was viewed as the only important vector
- Within in past ten years, several successful eradication programs have been conducted, three in CA
- Many other vectors including hull fouling, live bait and seafood, aquaculture may as, if not more, important than ballast water

A New Agenda for Management Focused Research

- New methods for eradication and control
  - Biological control, chemical control, transgenic approaches, pheromonal control
- Understanding connectivity
  - Molecular genetics, trace elements, dispersal models
  - Prioritize control methods
- Ecological economics models
  - Incorporating non-market impacts

From Williams and Grosholz, 2008. Estuaries and Coasts.

Table 2 Examples of eradication programs for introduced estuarine and coastal marine species, listed in chronological order

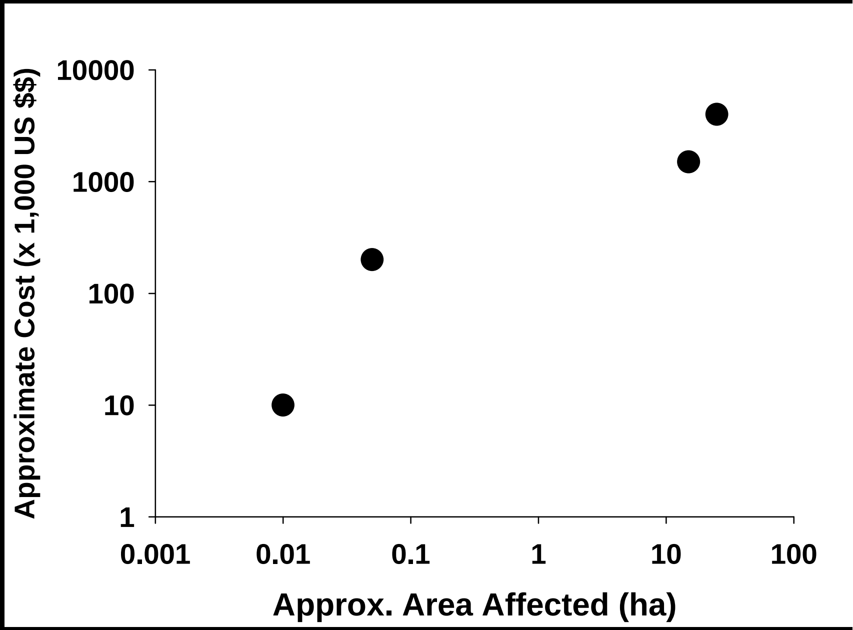
Introduced Species	Eradication Site	Date Initiated	Status	Reference
Thais clavigera Japanese oyster drill	British Columbia, Canada	1951	Successful	Carlton 2001
Spartina anglica hybrid cordgrass	Ireland	1960s	Unsuccessful; reverted to control	Hammond and Cooper 2002
Macrocystis pyrifera Giant kelp	Hawaii, USA	1972, 1980s	Successful	Shluker 2003
Sargassum muticum Wireweed	England	1973, 1976	Unsuccessful	Carlton 2001
Avicennia marina black mangrove	California, USA	1980	Completed 2000; reappeared 2006	Kay et al. 2006
Spartina alterniflora, *S. anglica*, and hybrids cordgrasses	New Zealand	1987	Successful in Southland; ongoing elsewhere	http://www.biodiversity.govt.nz/news/media/current/05nov04.html (accessed 14 December 2007) Krikwoken and Hedge 2000
Spartina alterniflora, *S. patens*, and hybrids cordgrasses	Oregon,	1990	Completed one site; ongoing	Pfauth et al. 2003
	Washington,	2003		Murphy et al. 2007
	California, U.S	2005		Olofson et al. 2007
Asterias amurensis Northern Pacific seastar	Victoria, Australia	1993 2002	Unsuccessful in Port Phillip Bay; near completion at Inverloch	Dommisse and Hough 2004
Perna canaliculus green lipped mussel	South Australia	1996	Successful	Bax and McEnnulty 2001
Terebrasabella heterouncinata sabellid parasite of abalone	California, USA	1996	Successful	Culver and Kuris 2000
Undaria pinnatifida wakame seaweed	Tasmania, Australia	1997	Ongoing	Hewitt et al. 2005
	Catham Islands, New Zealand	2001	Successful	Wotton et al. 2004
	California, USA	2002	Unsuccessful; reverted to control	Lonhart 2003
Mytilopsis sallei black-striped mussel	Northern Territory, Australia	1999	Successful	Bax et al. 2001
Caulerpa taxifolia 'killer' algae	California, USA	2000	Successful	Authors
Ascophyllum nodosum Atlantic rockweed	California, USA	2002	Successful	Miller et al. 2004
Didemnum vexillum colonial sea squirt	New Zealand	2003	Unsuccessful in some areas; ongoing	Coutts and Forrest 2007
Zostera japonica Japanese eelgrass	California, USA	2003	Ongoing	Eicher 2006
Littorina littorea periwinkle snail	California, USA	2005	Near completion	Chang et al. *personal communication*
Batillaria attramentaria horn snail	California, USA	2006	Ongoing at 2 sites	Weiskel and Zabin *personal communication*
Carcinus maenas European green crab	California, USA	2006	Ongoing	Grosholz et al. *unpublished*

Examples of Eradication Attempts in Marine/Estuarine Systems

From Williams and Grosholz, 2008. Estuaries and Coasts.

Costs of Successful Eradication

Species	Site
Mytilopsis sallei (black striped mussel)	Australia (NT)
Caulerpa taxifolia (Med algae)	California (SD, HB)
Terebrasabella heteroucinata (SA abalone parasite)	California (MB)
Ascophyllum nodosum (NE algae)	California (SF)



Grosholz, unpubl. data

Conceptual Model to Guide Eradication Decisions

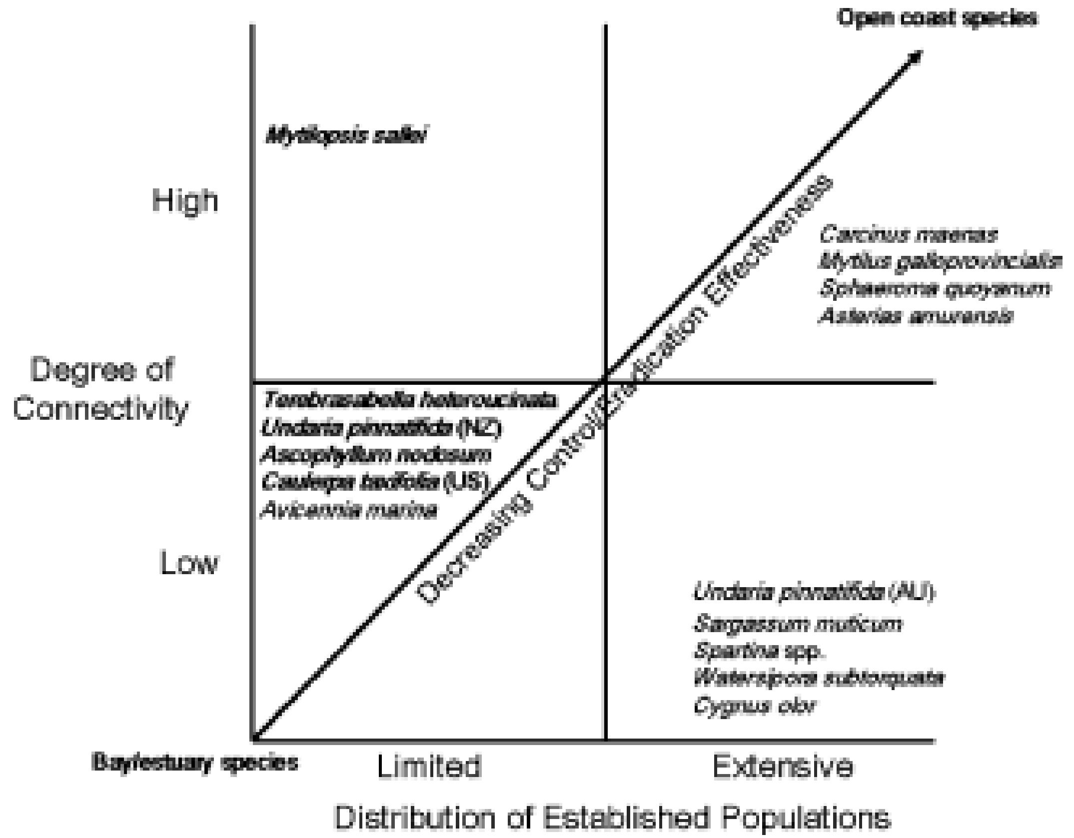


Fig. 4 Conceptual relationship between connectivity (natural dispersal) and expanse of populations of introduced species and the probability of successful management. Species in bold have been successfully eradicated

From Williams and Grosholz, 2008. Estuaries and Coasts.

A New Agenda for Management Focused Research

- Community and ecosystem impacts of ecosystem engineers
  - Identifying the most important impacts
- Trait-based approaches for prevention
  - Screening targeted species
- Decision support
  - Delivery of information about management methods, species biology, etc.

From Williams and Grosholz, 2008. Estuaries and Coasts.

Major Functional Groups of Concern

12 Estuaries and Coasts: J CERF (2008) 31:3–20

Table 4 Examples from major functional groups of concern for estuarine and coastal introduced species and their effects

Type of Species	Example	Effect	Reference
Clonal or Weedy	*Caulerpa taxifolia* (seaweed)	Overgrows seagrasses	Ceccherelli and Cinelli 1997
	Caulerpa racemosa (seaweed)	Overgrows seagrasses	Ceccherelli and Campo 2002
	Watersipora subtorquata (bryozoan)	Fouls ship hulls and marinas	Floerl et al. 2004
Predator	*Carcinus maenas* (green crab)	Eats bivalves and crabs	Grosholz et al. 2000, 2001
	Rapana venosa (veined whelk)	Eats commercially important bivalves	Savini and Occhipinti-Ambrogi 2005
	Asterias amurensis (seastar)		Ross et al. 2002
Filter feeder	*Corbula amurensis* (Asian clam)	Reduces phytoplankton Correlates with zooplankton declines	Alpine and Cloern 1992; Kimmerer et al. 1994
Ecosystem Engineer	*Spartina alterniflora* (smooth cordgrass)	Converts mudflats; reduces shorebird foraging	Neira et al. 2005, 2006, 2007; Levin et al. 2006; Tyler et al. 2007
	Zostera japonica (Japanese eelgrass)	Converts mudflats	Posey 1988
	Crassostrea gigas (commercial oyster)	Creates reefs	Ruesink et al. 2005
	Musculista senhousia (Asian mussel)	Creates byssal mats in sediments	Crooks & Khim 1999

From Williams and Grosholz, 2008. Estuaries and Coasts.
also Grosholz and Ruiz, 2009. Marine Bioinvasions: Ecology, Conservation and Management Perspectives**.**

A New Agenda for Management Focused Research

- Early detection
  - Genetic dip sticks, shotgun sequencing for screening water column
- Improved systematics
  - Increasing experts, faster/accessible methods
- Evolutionary potential
  - Rapid evolution, changing invaders

From Williams and Grosholz, 2008. Estuaries and Coasts.

Linking Overconsumption by USA with Sea Level Rise

New Yorker August 28, 2006, p. 23

A New Agenda for Management Focused Research

- Climate change impacts
  - Increasing temperature and shifting/expanding ranges
  - Rising sea levels and changing inundation patterns
  - Increasing pCO_2 and decreasing pH
  - Changes in wind stress, upwelling, and advection of propagules

From Williams and Grosholz, 2008. Estuaries and Coasts.

Climate Change and Coastal Invasions

- Bays and estuaries highly invaded and highly susceptible to climate change impacts
- Shallow coastal systems are expected to show greater warming
- Estuaries (lower alkalinity) are more susceptible to lower pH
- Inundation patterns in coastal habitats strongly affected by rising sea levels

Overall Conclusions

- Measuring ecological impacts will require more comprehensive approach involving a broader range of response variable and spatio/temporal scales
- Quantifying economic impacts will require better ecological and fisheries data with new valuation and modeling methods
- Future invasion research should require a broader dialogue between science and management - scientists need to listen

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