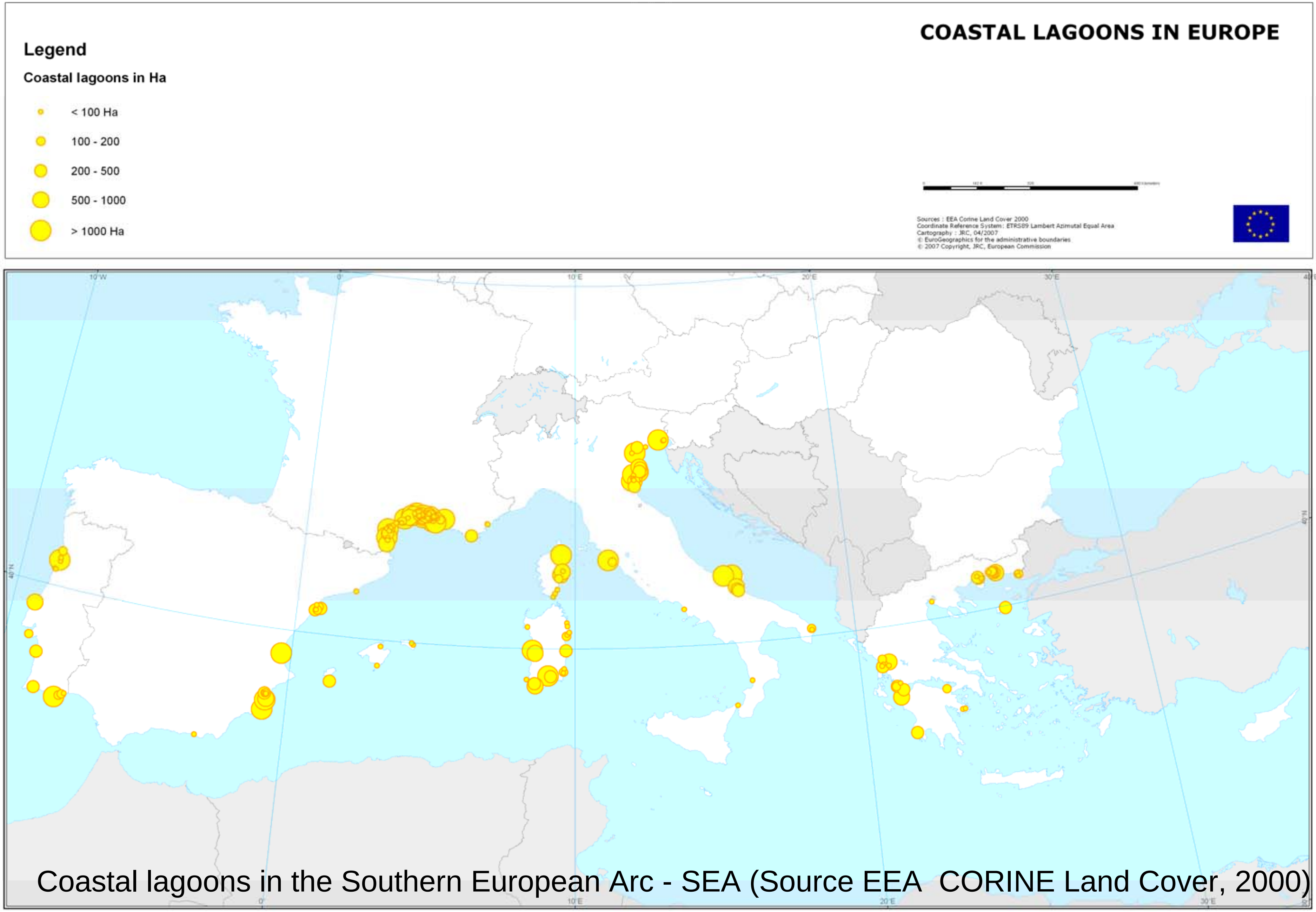
International Symposium "Effects of Climate Changes on the Wold's Oceans"
May 19-23, Gjión, Spain
S3.2 estuarine and wetland ecosystem functioning

Assessing ecosystem properties and responses of coastal lagoons to altered hydrology, nutrient cycling and direct anthropogenic pressures

Pierluigi Viaroli
Department of Environmental Sciences
University of Parma, Italy

With contributions by:
R Azzoni, M Bartoli, RR. Christian, G Giordani, M Naldi, D Nizzoli,
E Pierobon & JM Zaldivar

Photo courtesy of Archivio Magistrato alle Acque di Venezia – Consorzio Venezia Nuova



Coastal lagoons in the Southern European Arc - SEA (Source EEA CORINE Land Cover, 2000)

Surface range (km^2)	Lagoons		Total area	
	number	%	km^2	%
0.25-1.00	98	46.9	48.5	2.4
1.01-5.00	68	32.5	160.8	7.9
5.01-10.00	16	7.7	106.2	5.2
10.01-50.00	15	7.2	338.4	16.5
50.01-100.0	6	2.9	365.0	17.9
100.1-200.0	5	2.4	661.6	32.4
> 200.1	1	0.5	364.7	17.8
Total	209	100.0	2045.2	100.0

Small aquatic systems with surface area < 5 km^2

ca. 70% of the lagoons account for ca. 10% of the total lagoon surface

Surface area of 182 lagoons < surface area of the Venice lagoon

In the Southern European Arc, lagoons are threatened since ever

Historic threats

- wetland reclamation
- eutrophication

Recent pressures

- tourism (e.g. Venice)
- aquaculture (Etang de Thau, Sacca di Goro, Venice)

Expected pressures from altered hydrology in the watersheds and sea level rise

- water uses vs agriculture (e.g. Southern Spain)
- altered river hydrology due to climate changes
- sea level rise and flooding (e.g. Venice)

Eutrophication

- Benthic vegetation
- Ecosystem metabolism

shallow depth → sediment surface to water volume ratio → high ecosystem metabolism → controlled by benthic communities
main stressor → eutrophication

succession of aquatic vegetation along increasing eutrophication gradients according to 1: Nienhuis (1992), 2: Harlin (1993), Valiela et al. (1997) and Dahlgreen and Kautsky (2004); 3: Schramm (1999), Viaroli et al. (2008)

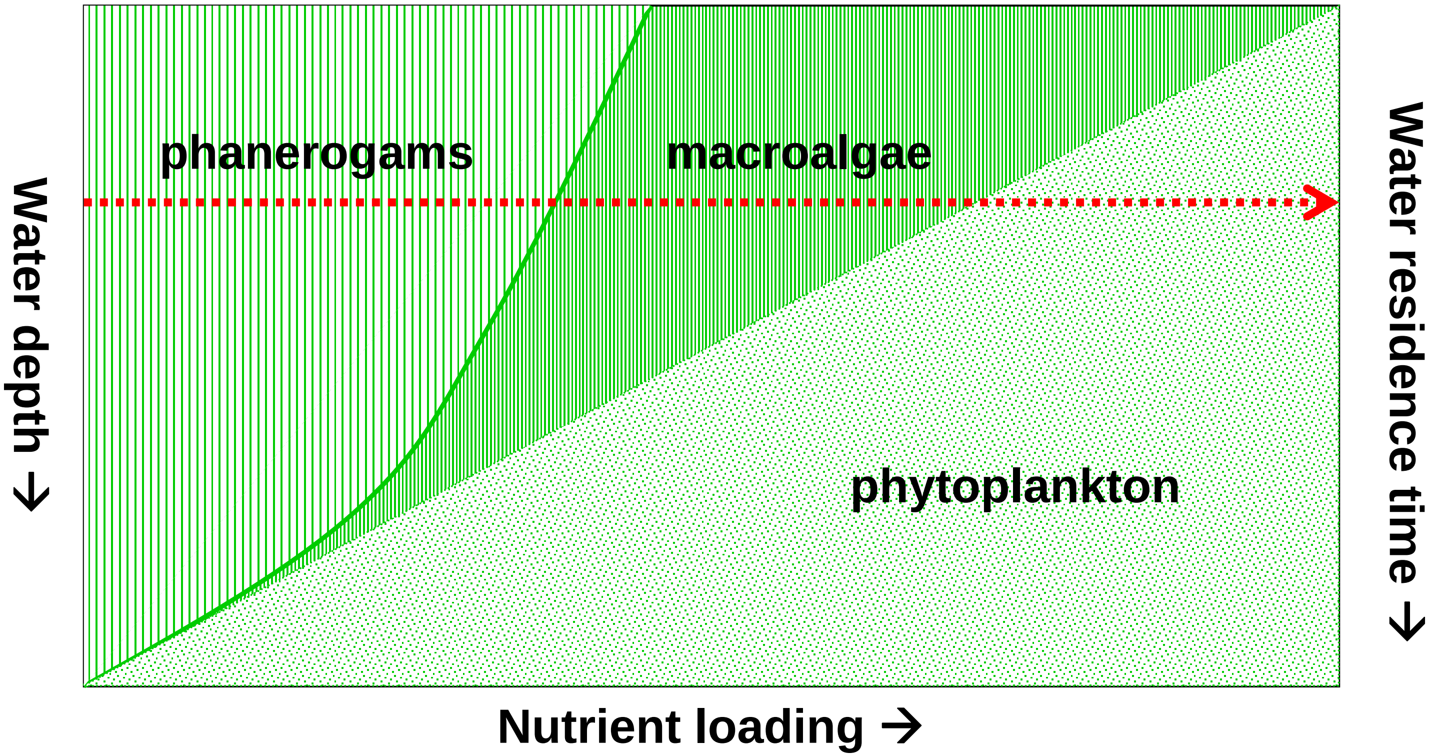
<table>
<tr><th colspan="4">succession phases (pristine → altered)</th><th>Ref</th></tr>
<tr><td>phanerogams</td><td>phanerogams+epiphytes</td><td colspan="2">macroalgae+phytoplankton</td><td>1</td></tr>
<tr><td colspan="2">seagrasses</td><td>macroalgae</td><td>phytoplankton</td><td>2, 3</td></tr>
<tr><td>perennial benthic macrophytes</td><td>macrophytes+ fast growing epiphytes</td><td>free floating macroalgae+phytoplankton</td><td>phytoplankton picoplankton cyanobacteria</td><td>4</td></tr>
</table>

Recent evolution of benthic communities in coastal lagoons of SEA.

Lagoon	Pristine conditions	1975-1995	present	Ref.
Sacca di Goro (Italy)	*R. cirrhosa, Z. noltii*	Severe blooms of *Ulva* and *Gracilaria*	Episodical blooms of *Ulva* and *Gracilaria*	1, 2
Venice , central basin (Italy)	*Z. noltii, C. nodosa*	*Ulva* blooms	phytoplankton	3
Orbetello (Italy)	*R. cirrhosa*	*Ulva* and *Gracilaria* blooms	*Gracilaria* blooms	4, 5
S'Ena Arrubia (Italy)	*R. cirrhosa*	*Ulva* and *Gracilaria*	Filamentous macroalgae and MPB	4, 6
Valli di Comacchio (Italy)	*R. cirrhosa, L. papulosum*	Filamentous macrolage blooms	Nanoplankton, cyanobacteria	7,8
Encanissada/Tancada (Spain)	*R. cirrhosa, Potamogeton crispus*	Moderate growth of *Chaetomorpha linum*	Patchy *R. cirrhosa, C. linum* and *P. crispus*	9
Etang du Prévost (France)	*Z. noltii, R. cirrhosa*	*Ulva* blooms	*Ulva* blooms	6, 10, 11
Nestos lagoons, several basins (Greece)	*R. cirrhosa*	n.a.	*R. cirrhosa, Ulva*, *Gracilaria* and Cyanobacteria	12
Tsopeli, and Amvrakikos Greece)	*Zostera noltii*	n.a.	*Ulva* blooms, *Zostera noltii*	13
Papas (Greece)	*Cymodocea nodosa*	n.a.	*Ulva*, *Gracilaria* blooms	14
Aetoliko (Greece)	*Cymodocea nodosa*	*Ulva* and *Cladophora*	n.a.	15

References - (1) Piccoli et al., 1991; (2), Viaroli et al. (2006), (3) Sfriso and Facca (2007); (4) Bombelli and Lenzi (1996); (5) Giusti and Marsili-Libelli (2005); (6) Viaroli et al. (1999), (7) Andreoli et al. (1998) ; (8) Piccoli (1998) ; (9) Menedez et al. (2002) ; (10) Castel et al. (1996) ; (11) Souchu et al. (2000) ; (12) Orfandis et al. (2001) ; (13) Reizopoulou (pers. Com.) ; (14) Reizopoulou and Nicolaidou (2004) ; (15) Bogdanos and Diapoulis (1984).

multivariate systems with multiple stressors



In nutrient poor, well-flushed and shallow waters phanerogams take advantage of nutrient supply from sediment. Long water residence times favour macroalgae and phytoplankton. Given a certain water residence time, the succession from perennial benthic species to macroalgae and phytoplankton seems mainly caused by nutrient loadings (Valiela et al., Limnology and Oceanography 42:1109-118, 1997; Dahlgreen & Kautsky, 2004. Hydrobiologia 514: 249–258,).

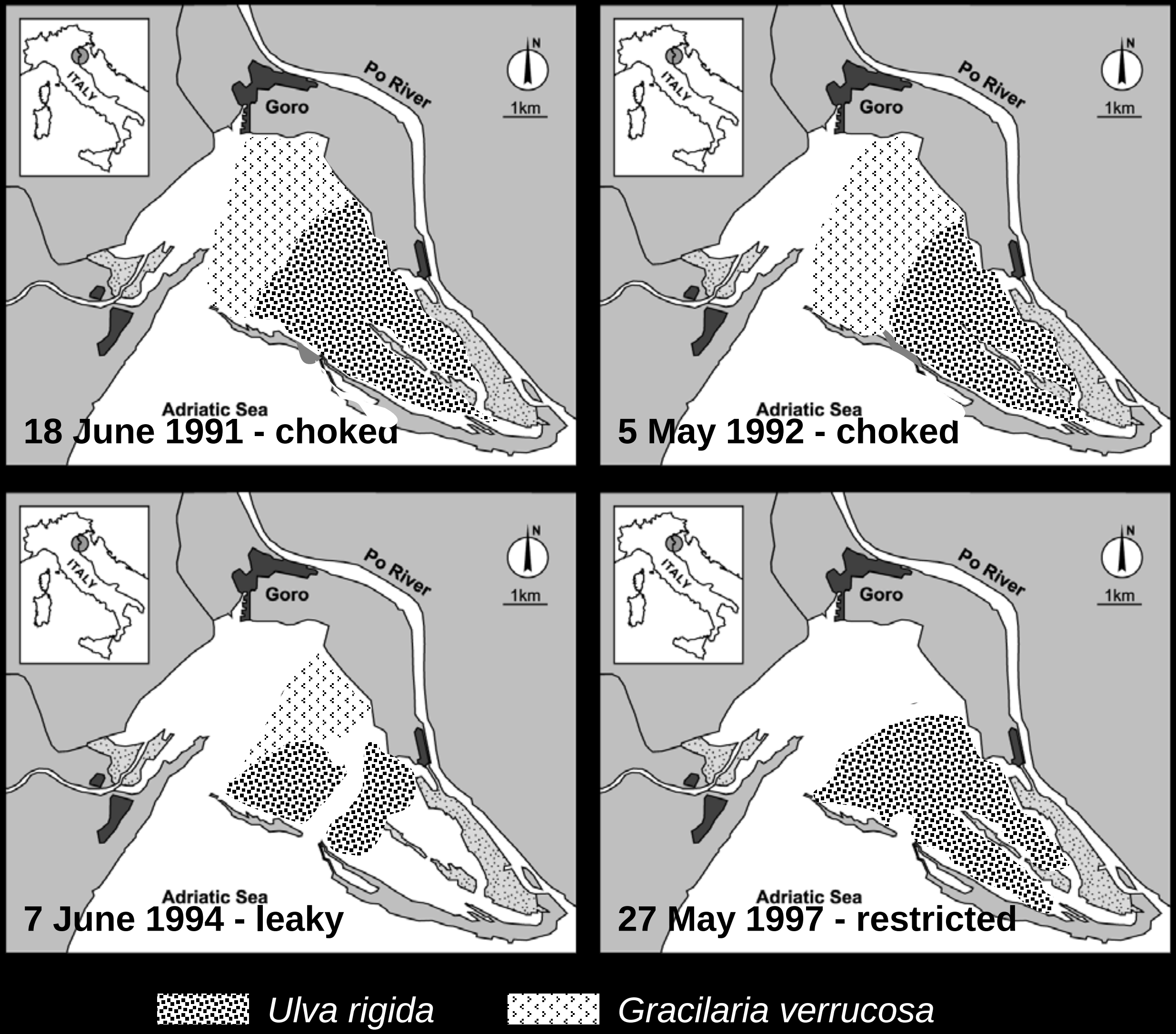
Only broad relationships between primary producers, Net Ecosystem Metabolism (NEM, in carbon units), water retention time (WRT) and nitrogen loadings (DIN)

Data from 13 coastal lagoons of the Southern European Arc (Giordani *et al*., LOICZ R&S 25, 2005; Giordani *et al.*, ECSS, 2007 and DITTY project data base, www.dittyproject.org).

Phy: phytoplankton, **Pha**: Phanerogams, **Ma**: Macroalgae

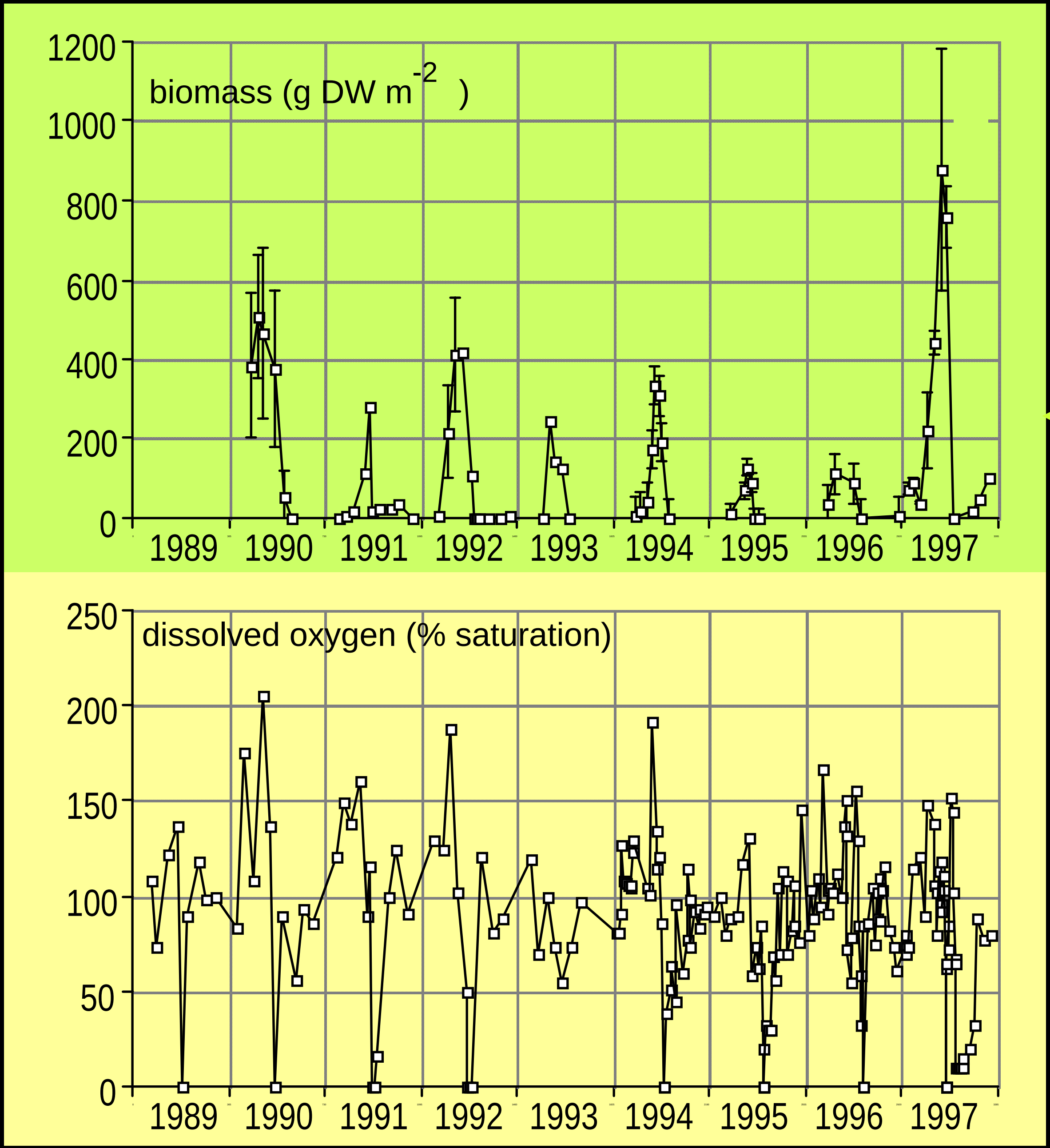
WRT (days)	**DIN loading ($g\ N\ m^{-2}\ y^{-1}$)**	**Primary producers**	**NEM ($mol\ m^{-2}\ y^{-1}$)**
40-100	0.6-7.6	Phy+**Pha**	0.2 to 4.6
4-200	9.9-16.1	Phy+Pha+**Ma**	-1 to 11.9
3-25	8.7-70	**Phy+Ma**	-8.2 to 14

Macroalgal coverage in the Sacca di Goro lagoon under different degree of restriction of the sea inlets (Viaroli et al., 2006, handbook Environmental Chemistry, Vol 5 -Estuaries, Springer, Berlin)



See also: Flindt MR, Salomonsen J, Carrer M, Bocci M, Kamp-Nielsen L, 1997. Loss, growth and transport dynamics of *Chaetomorpha aerea* and *Ulva rigida* in the Lagoon of Venice during an early summer field campaign. *Ecological Modelling* 102: 133-141.

Sacca di Goro lagoon (Italy): macroalgae distribution on 12 May 2008. Mixed stands of *Ulva* and *Gracilaria.* Sea inlets in the main littoral barrier are completely closed (choked lagoon)

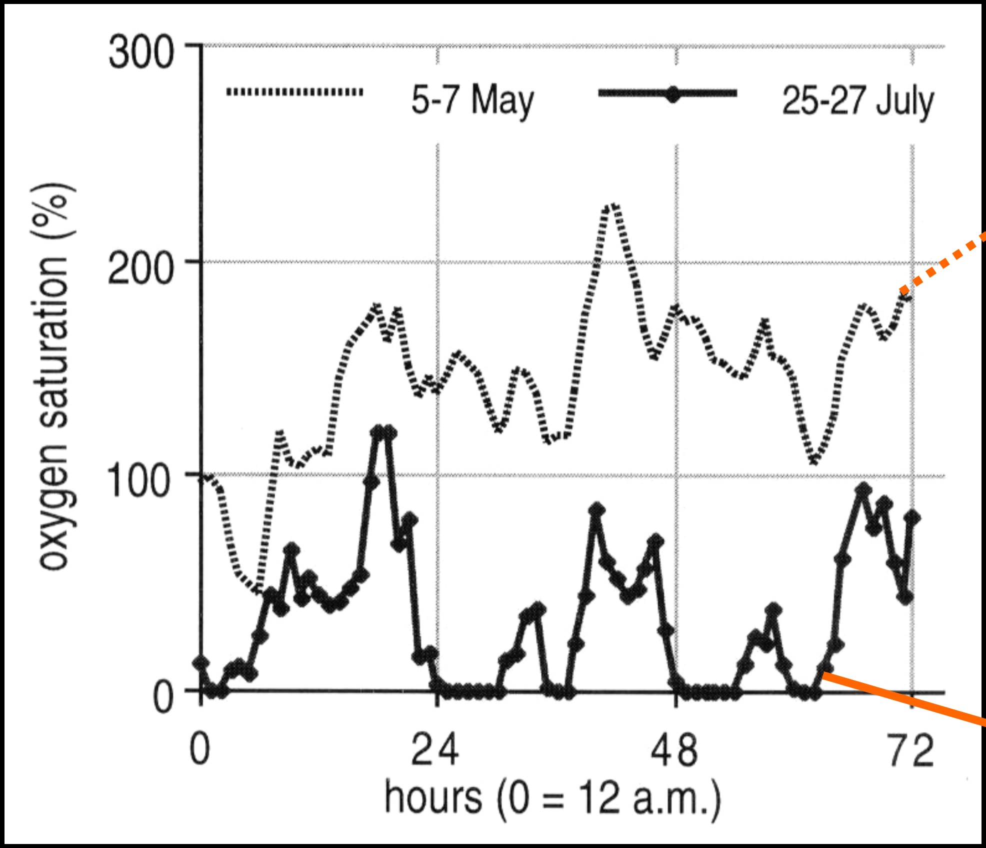


Sacca di Goro lagoon
(Po River Delta,
Northern Adriatic Sea)

biomass of the
seaweed *Ulva rigida*

and related dissolved
oxygen concentrations

Transition from macroalgal blooms to dystrophic crises (Sacca di Goro 1992)



nitrogen cycling in coastal lagoons with different benthic communities

MPB: microfitobentos; BS: bare sediment.

	Maximum denitrification rates	Maximum nitrogen bulk at biomass peak	Nitrogen uptake rates at biomass peak	references
	(mmol m^{-2} d^{-1})	(mmol m^{-2})	(mmol m^{-2} d^{-1})	
seagrass	0.1-0.4	200 - 600	10-25	1, 2, 3, 4, 8
macroalgae	0.2-2.0	500 - 1250	6-25	5, 6, 7
MPB/BS	0.4-2.0	10-20	2.5-5.0	4, 7, 8

References: 1: Welsh *et al*. (2000); 2: Risgaard-Petersen (2004); 3: Eyre and Ferguson (2002), 4: Bartoli *et al*. (2001), 5) Viaroli *et al*. (2005), 6) Sfriso and Marcomini (1996); 7: Sundback and McGlatery (2005), 8: Bartoli et al (2008)

Summary - main features of shallow coastal lagoons with different benthic vegetation

	Seagrass meadow	**Macroalgae (bloom forming)**	**Phytoplankton Microphytobenthos**
Biomass bulk	High/persistent	High/ephemeral	Low/transient
Growth rate	Low	High/very High	High
Biomass degradability	Refractory	Labile	Labile/refractory
Oxygen	Balanced	Unbalanced/dystrophy	Variable
Sulphide in pore water/bottom water	Absent to low	High	Absent to low
Nitrogen	Retention Low concentration	Pulsing. Low to high concentrations	variable

aquaculture

the catch fishery is declining

sea-food poduction is moving in the near-shore and/or in lagoons

Crossland, C.J., Kremer, H.H., Lindeboom, H.J., Marshall Crossland, J.I., Le Tissier, M.D.A., 2005. Coastal Fluxes in the Anthropocene. The Land-Ocean Interactions in the Coastal Zone. Project of the International Geosphere-Biosphere Programme. Global Change - The IGBP Series n° XX . Springer, 232 p.

Oysters 20,000 t y^{-1}

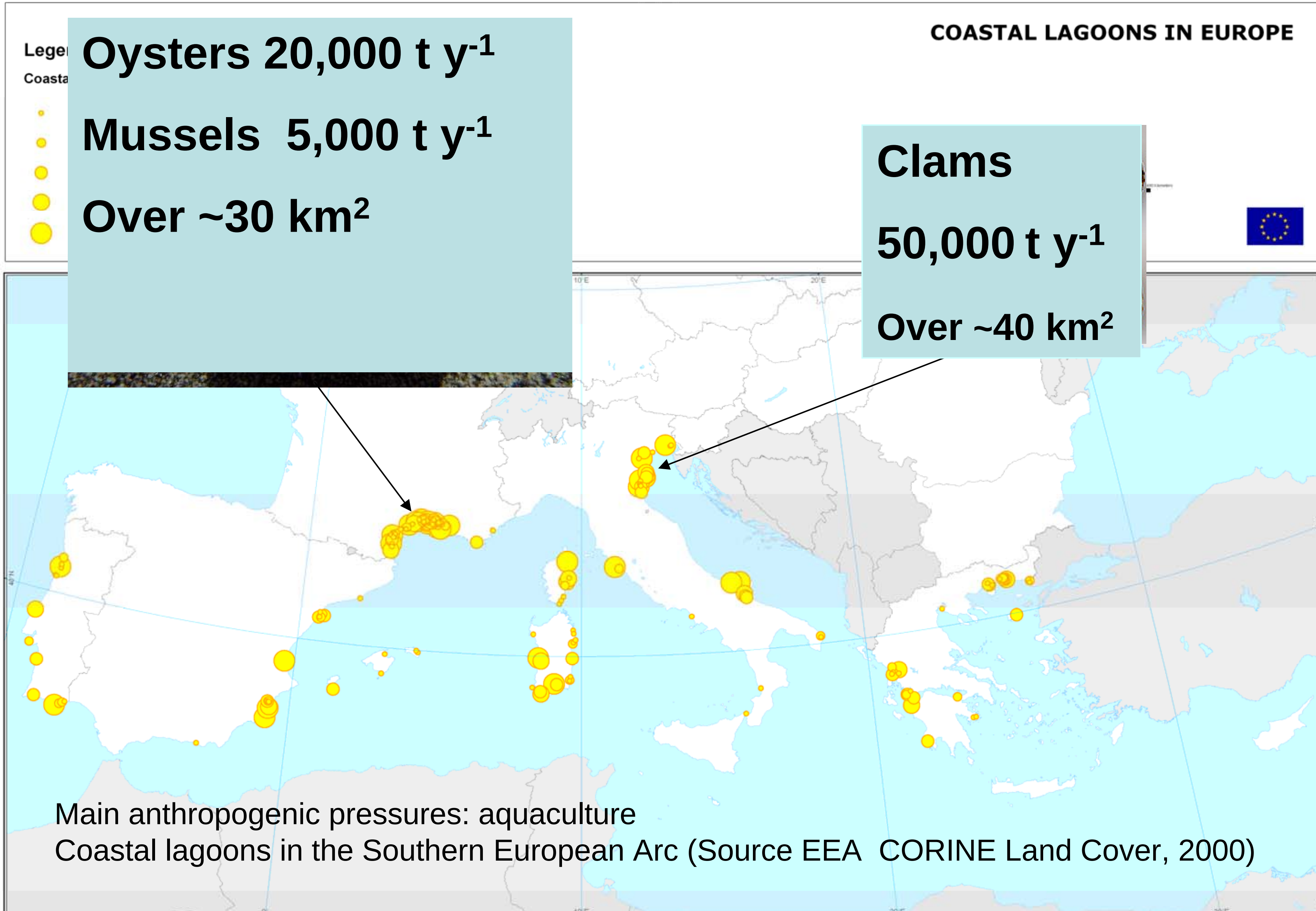
Mussels 5,000 t y^{-1}

Over ~30 km^2

Clams

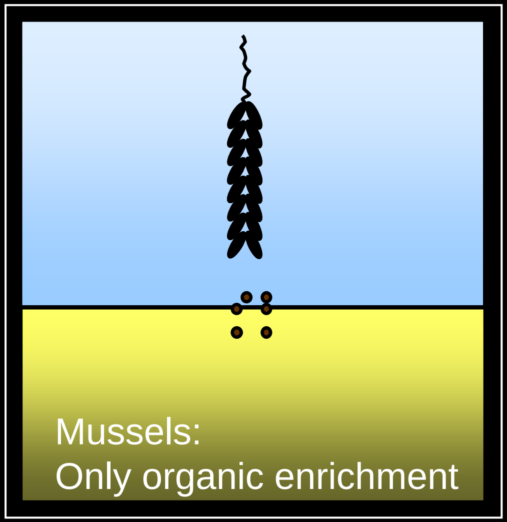
50,000 t y^{-1}

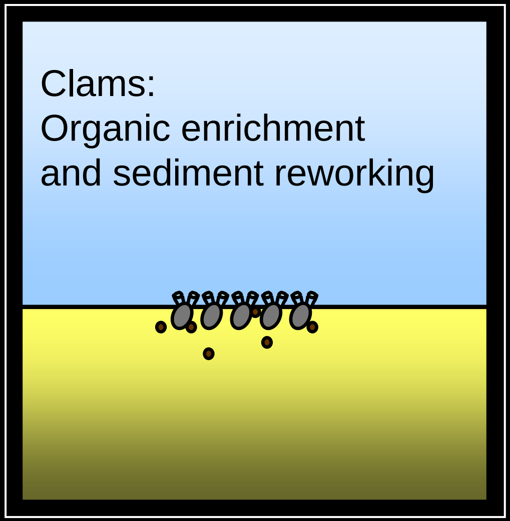
Over ~40 km^2

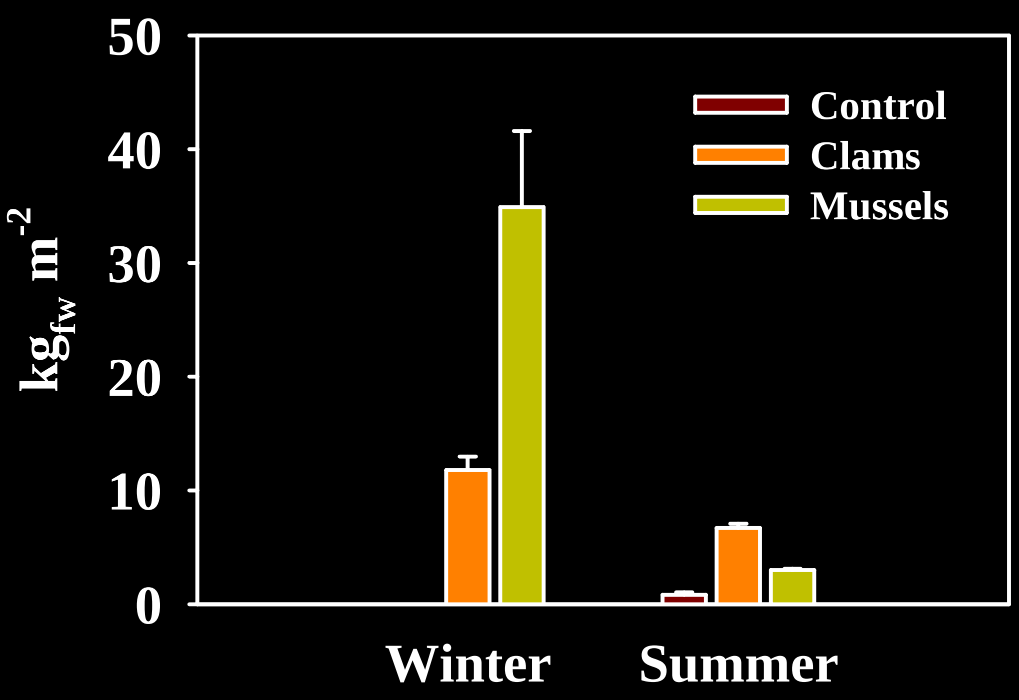


Main anthropogenic pressures: aquaculture
Coastal lagoons in the Southern European Arc (Source EEA CORINE Land Cover, 2000)

Impact of mussel and clam farming on sediment



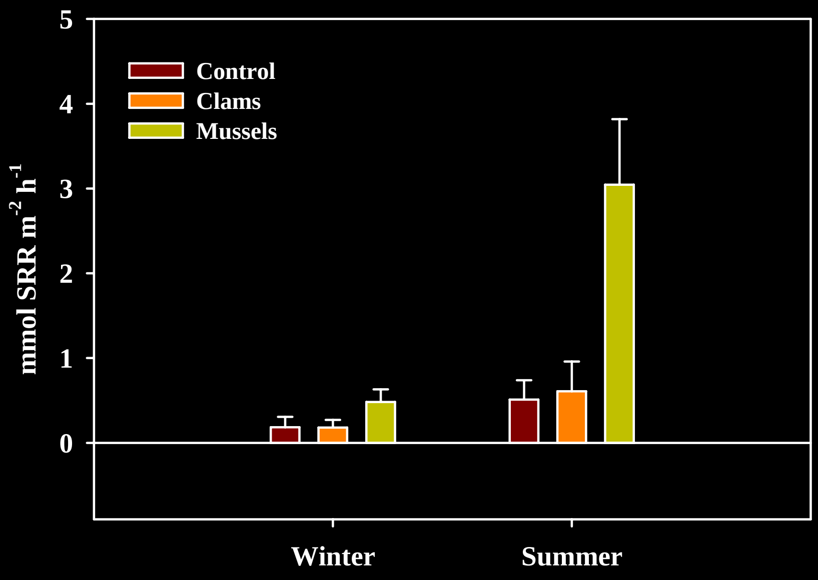




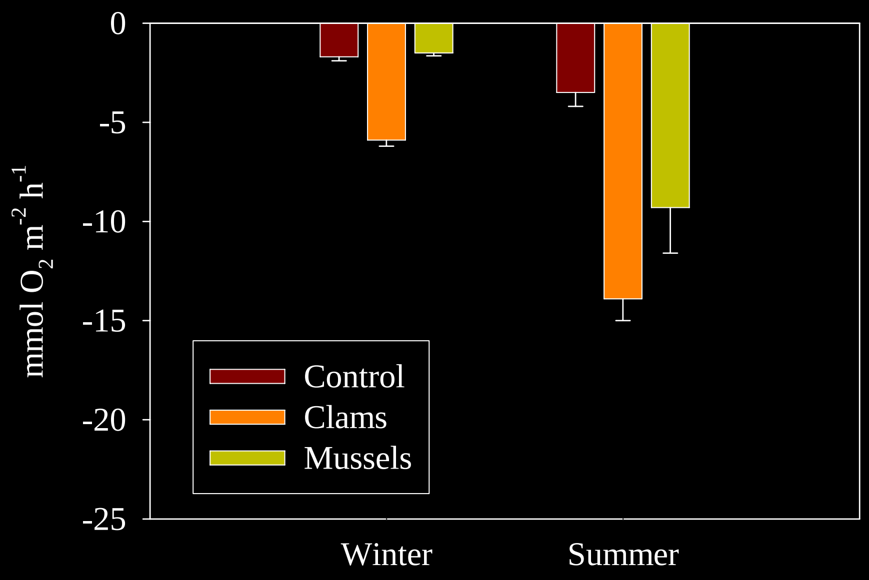
Typical biomass under farming conditions – harvesting in late spring (Northern Adriatic lagoons)

Oxygen consumption rates and bacterial sulphate reduction rates

Sulphate reduction

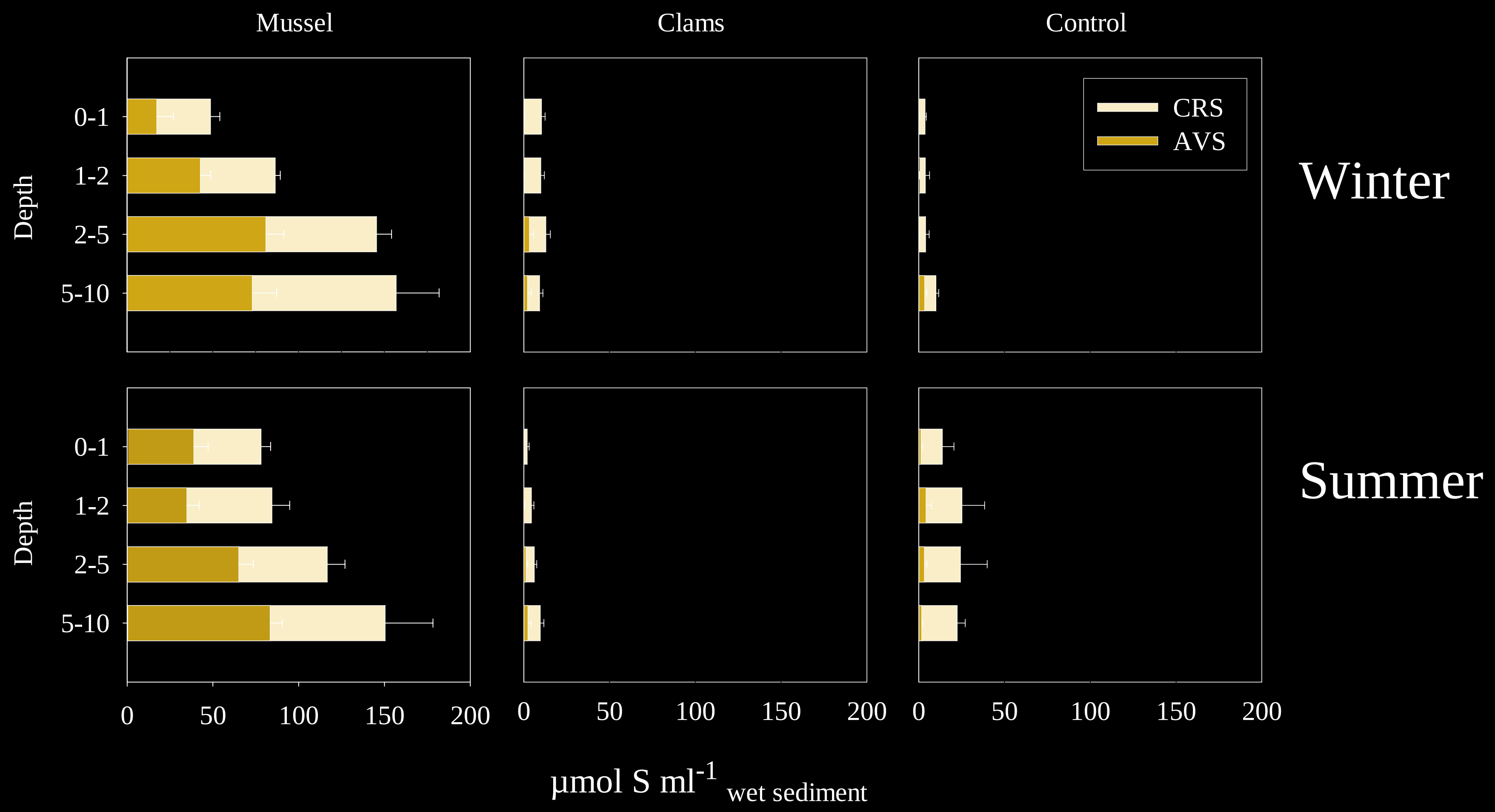


Oxygen consumption



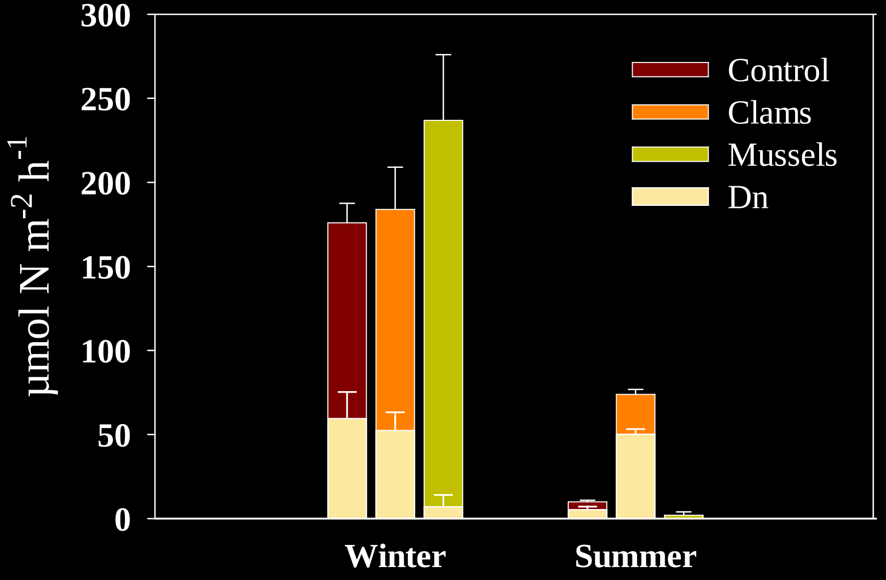
Nizzoli et al., 2005, MEPS ; Nizzoli et al., Hydrobiologia, 2007

reduced sulphur concentrations in the 0-10 cm sediment horizon



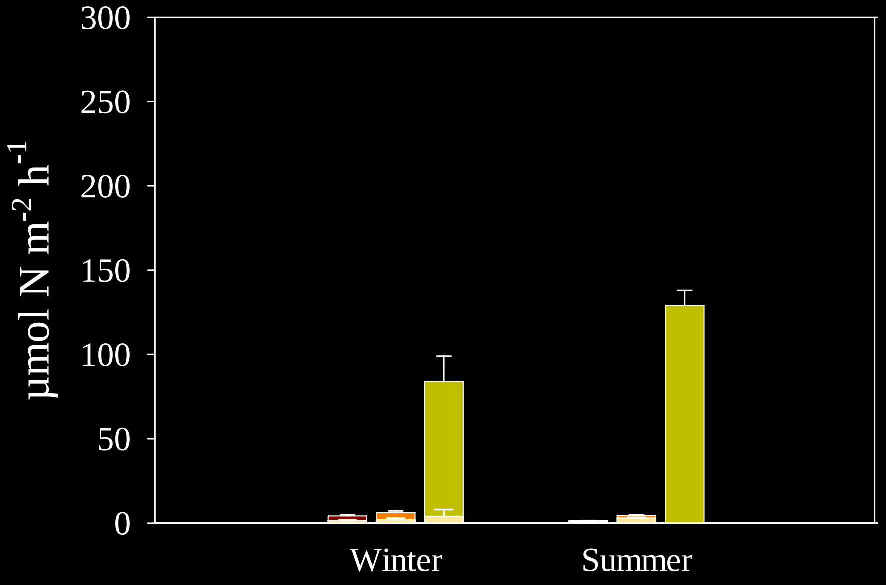
Denitrification and nitrate ammmonification rates

Denitrification



[NO3-]
Winter ~ 100 µM
Summer < 5 µM

Dissimilative Nitrate Reduction to Ammonium (DNRA)



Control and Clam: DNRA account 2-10% of total nitrate reduction both in winter and in summer

Mussel: DNRA accounts for 35% during winter whereas during the summer period it is the only sedimentary nitrate reduction processes

Clam harvesting impacts on sediment quality and fluxes

$\times 10^3 =$

clam harvesting with sediment dredging causes sediment resuspension and pulsed benthic fluxes (Viaroli et al., 2003, Chem. Ecol.)

Pre-H: before harvesting, H: during harvesting, Post-H: 8 hours after harvesting has ceased.

(units: mmol m^{-2} h^{-1})

	Pre-H	H	Post-H
Oxygen	-3.05±2.39	*- 60.90±8.91	-5.78±1.16
Ammonium	0.22±0.30	*11.40±2.31	0.10±0.23
Nitrate	0.13±0.23	-0.25±1.10	0.21±0.74
SRP	-0.017±0.068	*1.04±0.48	-0.019±0.056
DRSi	0.76±0.17	*11.90±0.74	-0.31±0.29

VENICE – main island

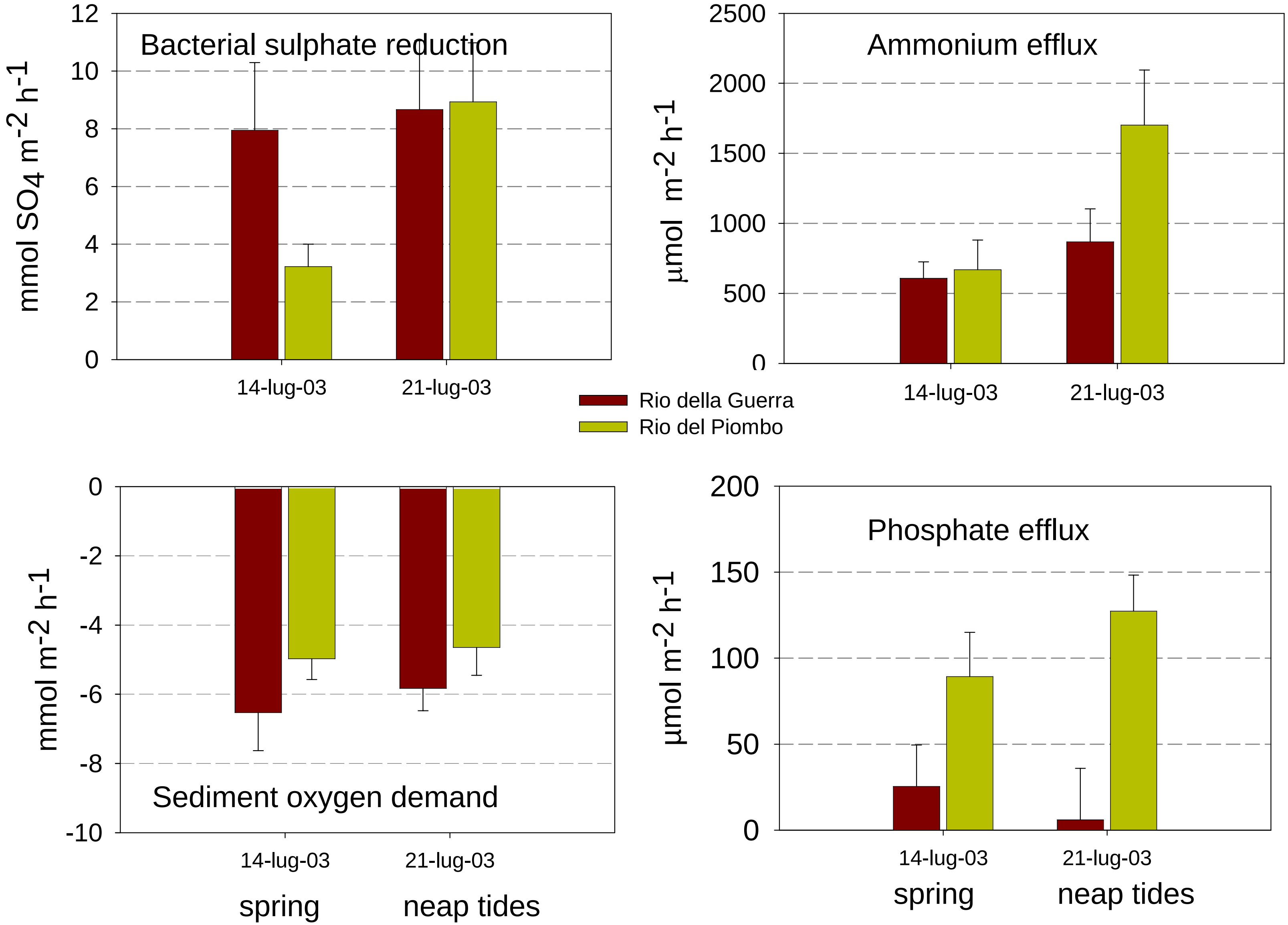
organic and nutrient loadings are directly delivered into the canal system of the urban center

flushing depends on canal hydrology and is driven by tidal regime

Biogeochemical transformations account for water and urban quality (e.g. sulphide smell in summer)

Biogeochemical processes and ecosystem metabolism in small canals in the urban area of Venice (ICARO project)

Process rates and fluxes under different flushing rates and tides in two canals in the urban area of Venice



Climate changes and coastal lagoons

-changes in fresh-water delivery into lagoons and coastal waters

-changes in nutrient loadings and reactivity

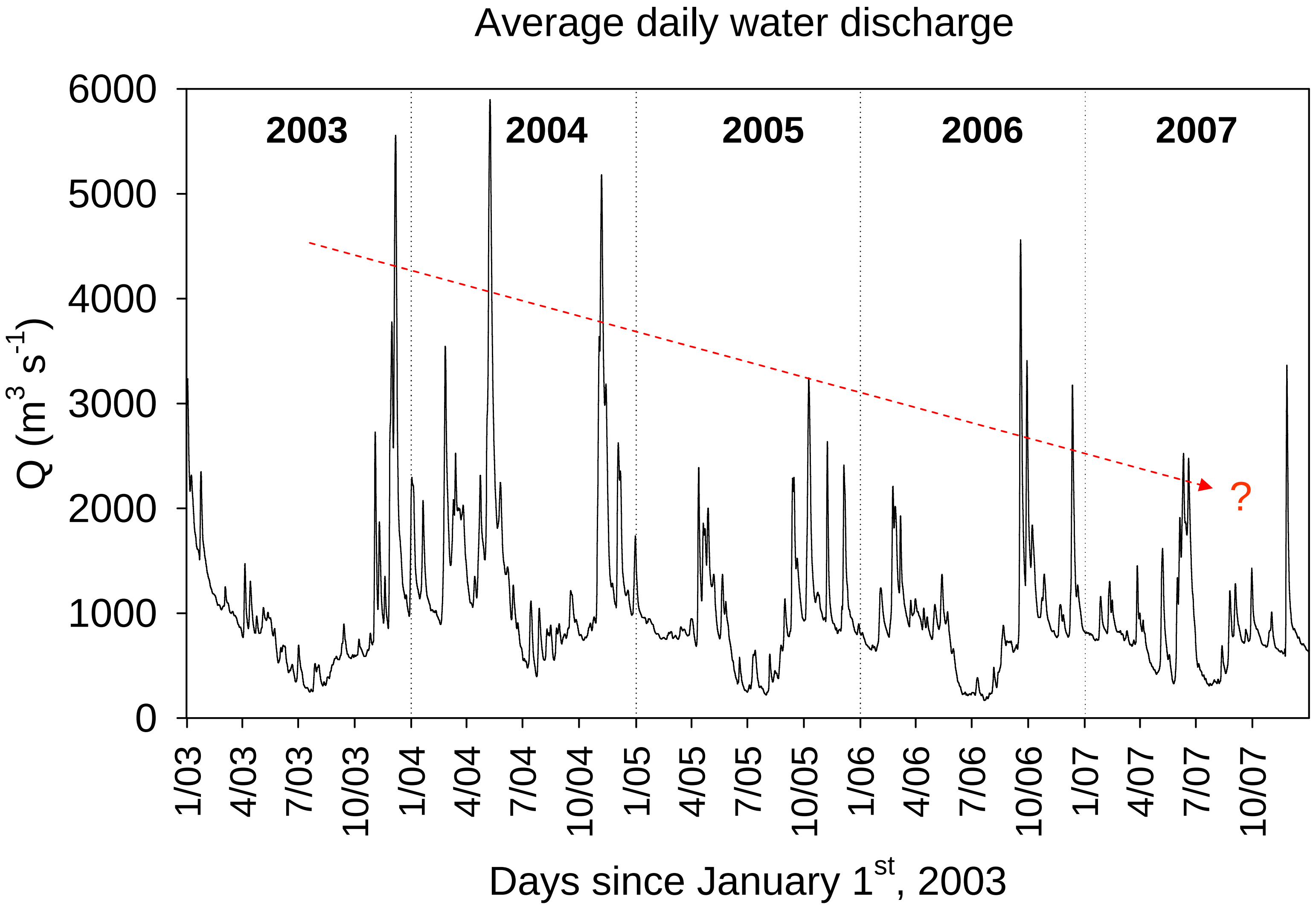
-changes in element stoichiometry

-saline wedge intrusion

-sea level rise

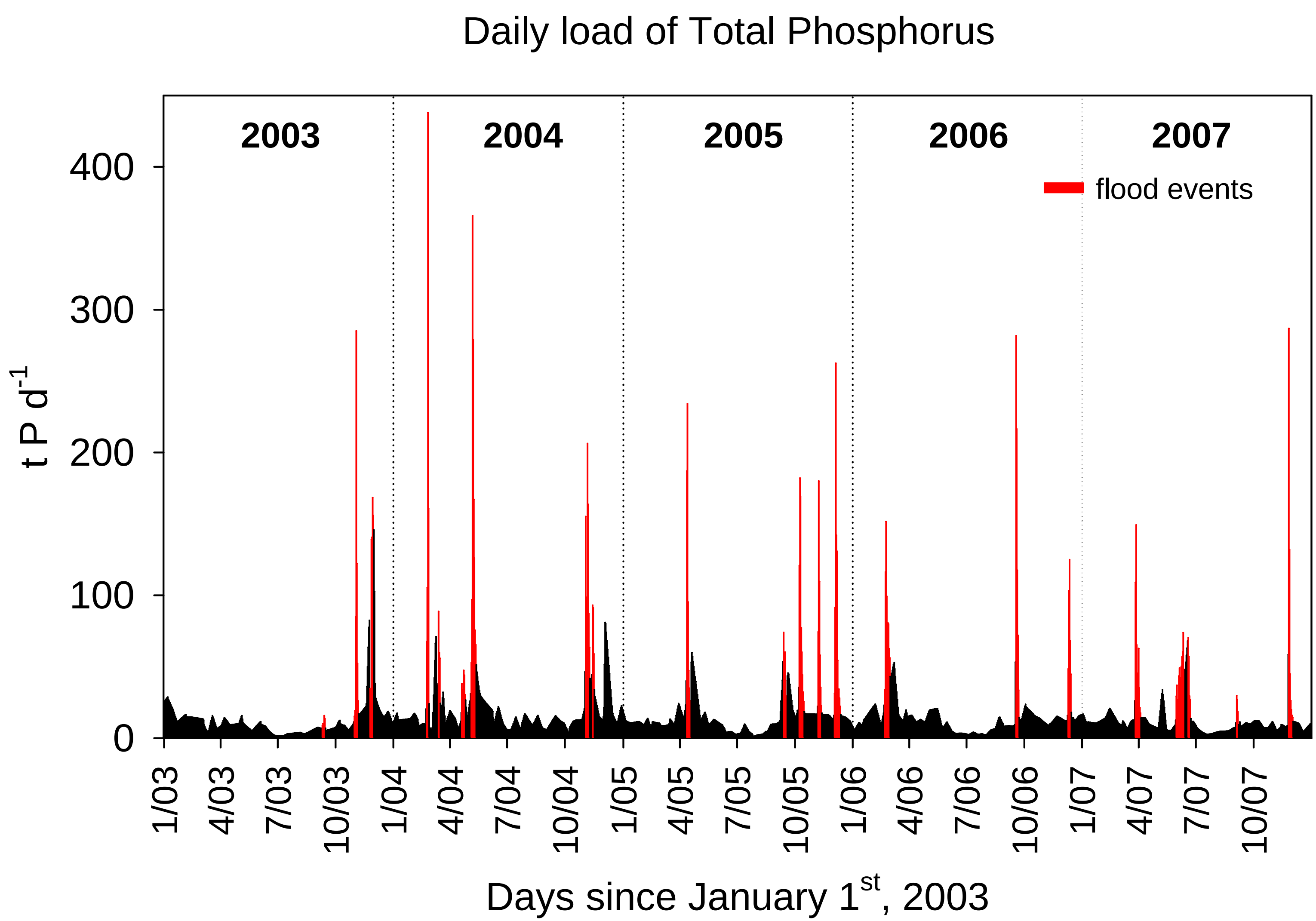
Po river: sudden changes in water discharge in the last decade

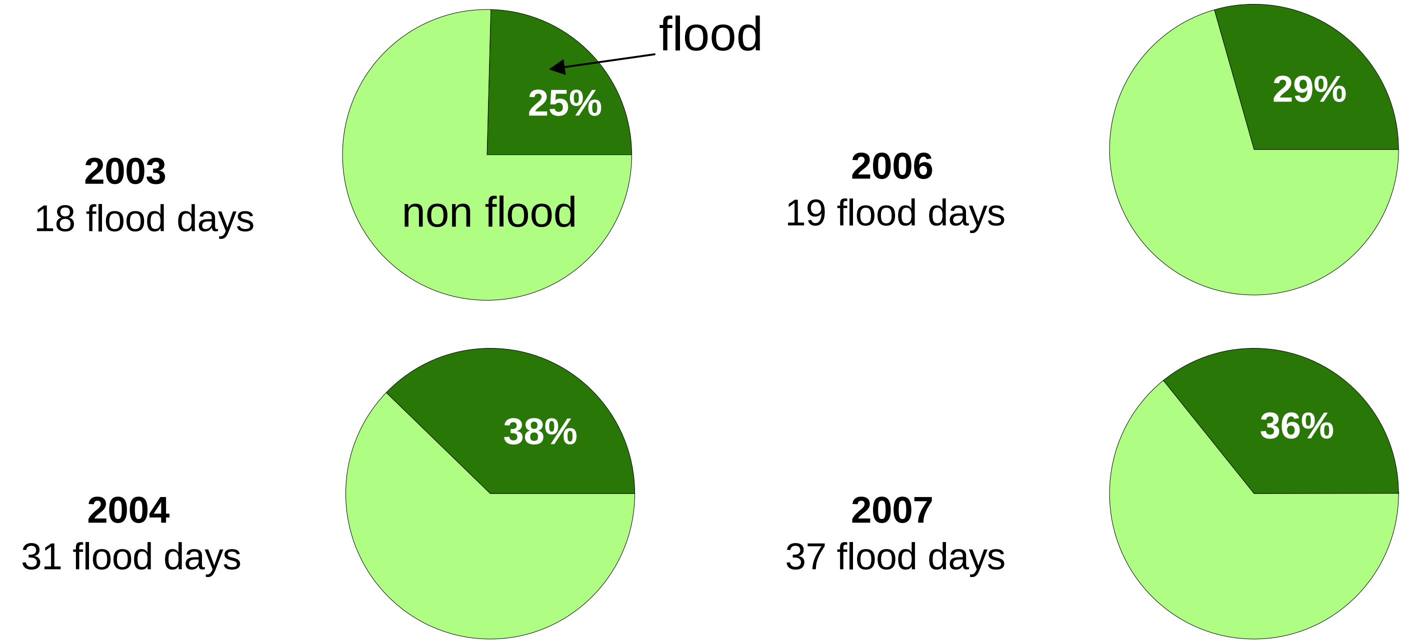
annual average from ~1500 m^3s^{-1} (1961-1991) to < 1000 m^3s^{-1} (2003-2007)

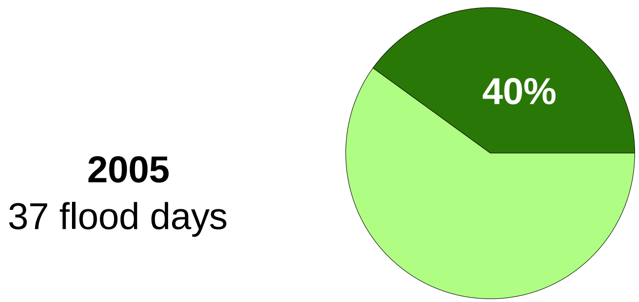


Project funded by the Authority of the Po Valley (Autorità di Bacino del fiume Po)

Effects of altered hydrology on nutrient loadings



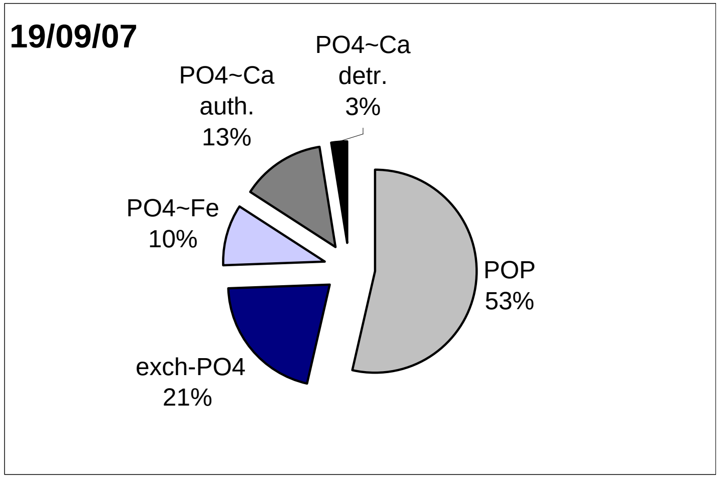


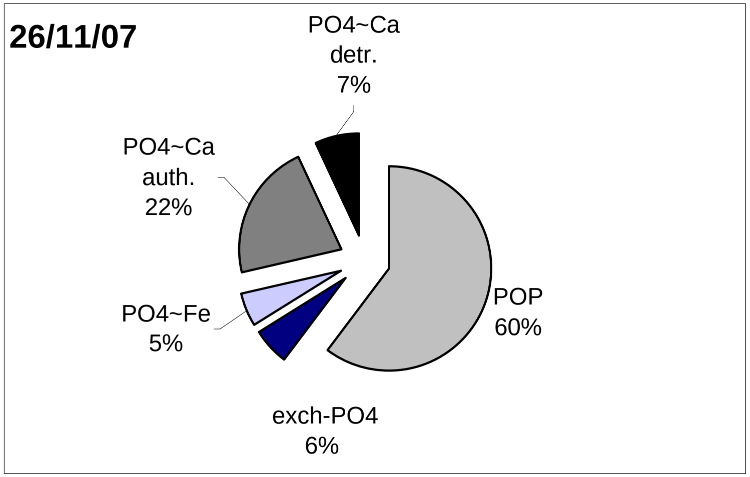


Under altered hydrology up to 40% of the annual P loading from the Po river into the Northern Adriatic Sea is delivered by flood events in a very short time (< 40 days)

Flood = discharge > 1500 $m^3\ s^{-1}$

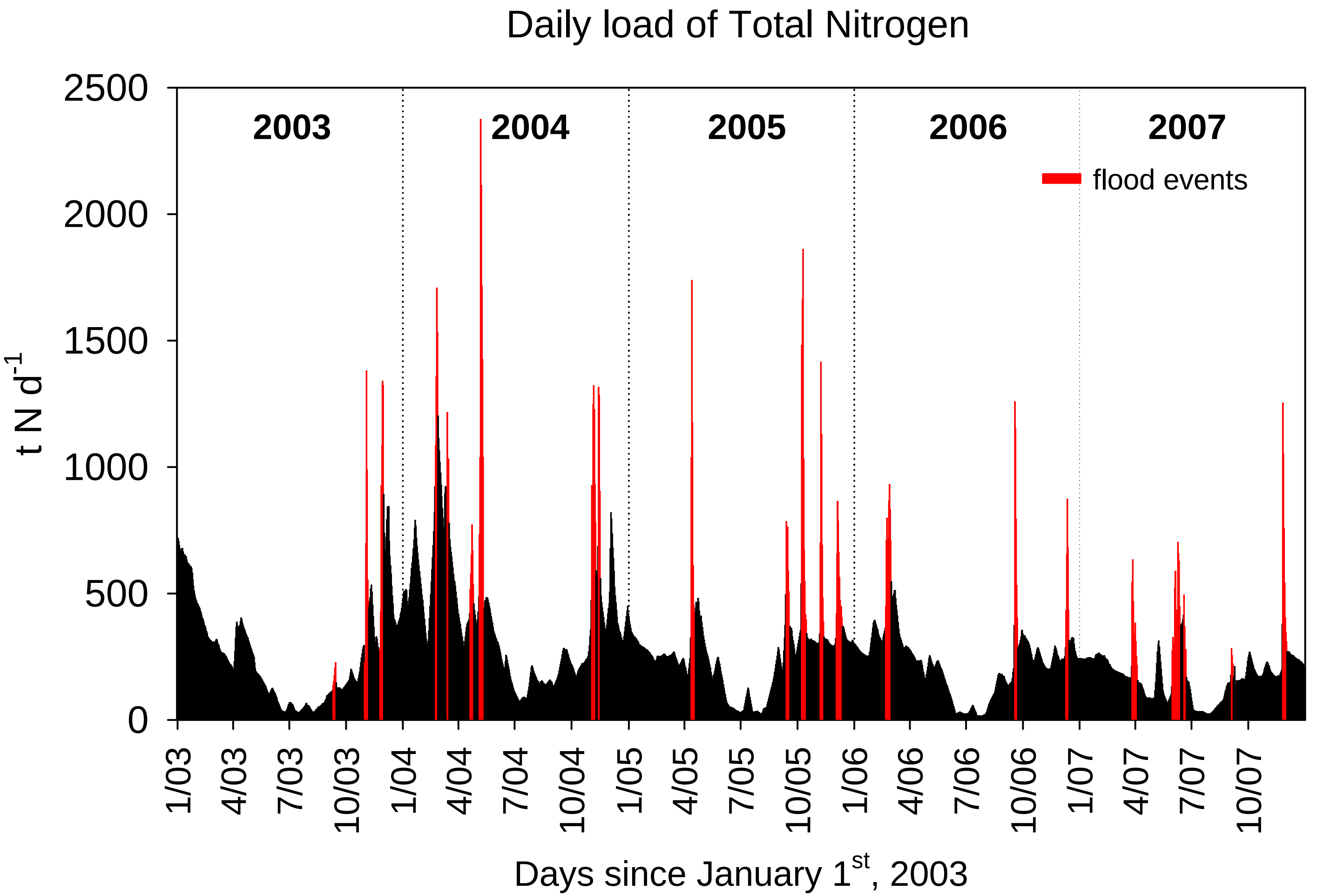
P loading from flood events is not readily available to primary producers





	19 september 2007 Non flood	26 November 2007 Flood
River discharge ($m^3\ s^{-1}$)	725	3419
Suspended Particulate Matter ($mg\ L^{-1}$)	102.5±11.9	1339.6±252.6
Total Particulate Phosphorus (µg P L^{-1})	164	1140
Exchangeable PO4 (µg P L^{-1})	34.3±1.6	65.8±4.5
Iron bound (µg P L^{-1})	16.3±5.4	59.7±3.6
PO4-Ca authigenic (µg P L^{-1})	22.1±2.2	247.1±76.7
PO4-Ca detritic (µg P L^{-1})	4.2±2.5	80.1±10.9
Particulate Organic P (POP) (µg L^{-1})	89.1	687.3

Less than 15% of the total N loading is delivered by flood events

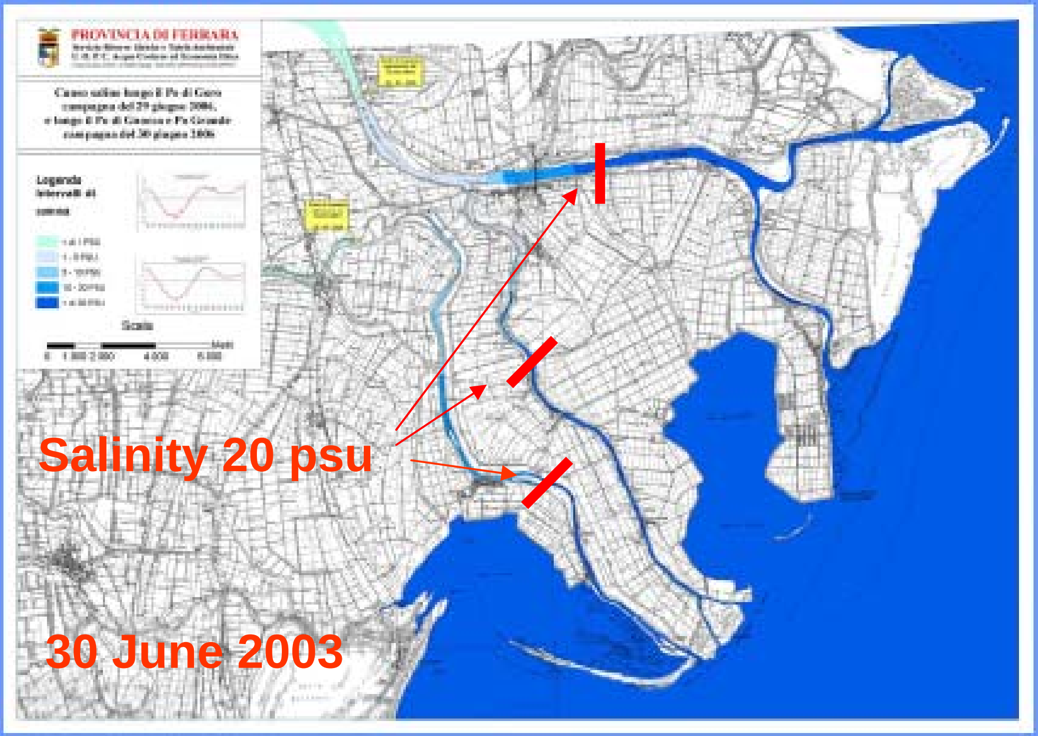


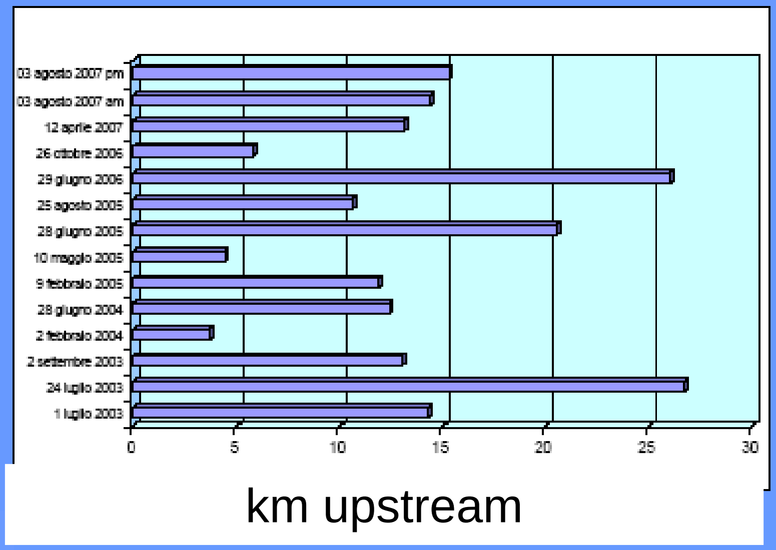
SALINE WEDGE IN THE PO RIVER DELTA

(NORTHERN ADRIATIC SEA)

With water discharge < 250 $m^3\ s^{-1}$ the saline wedge reaches up to 25 km upstream

brackish → marine?



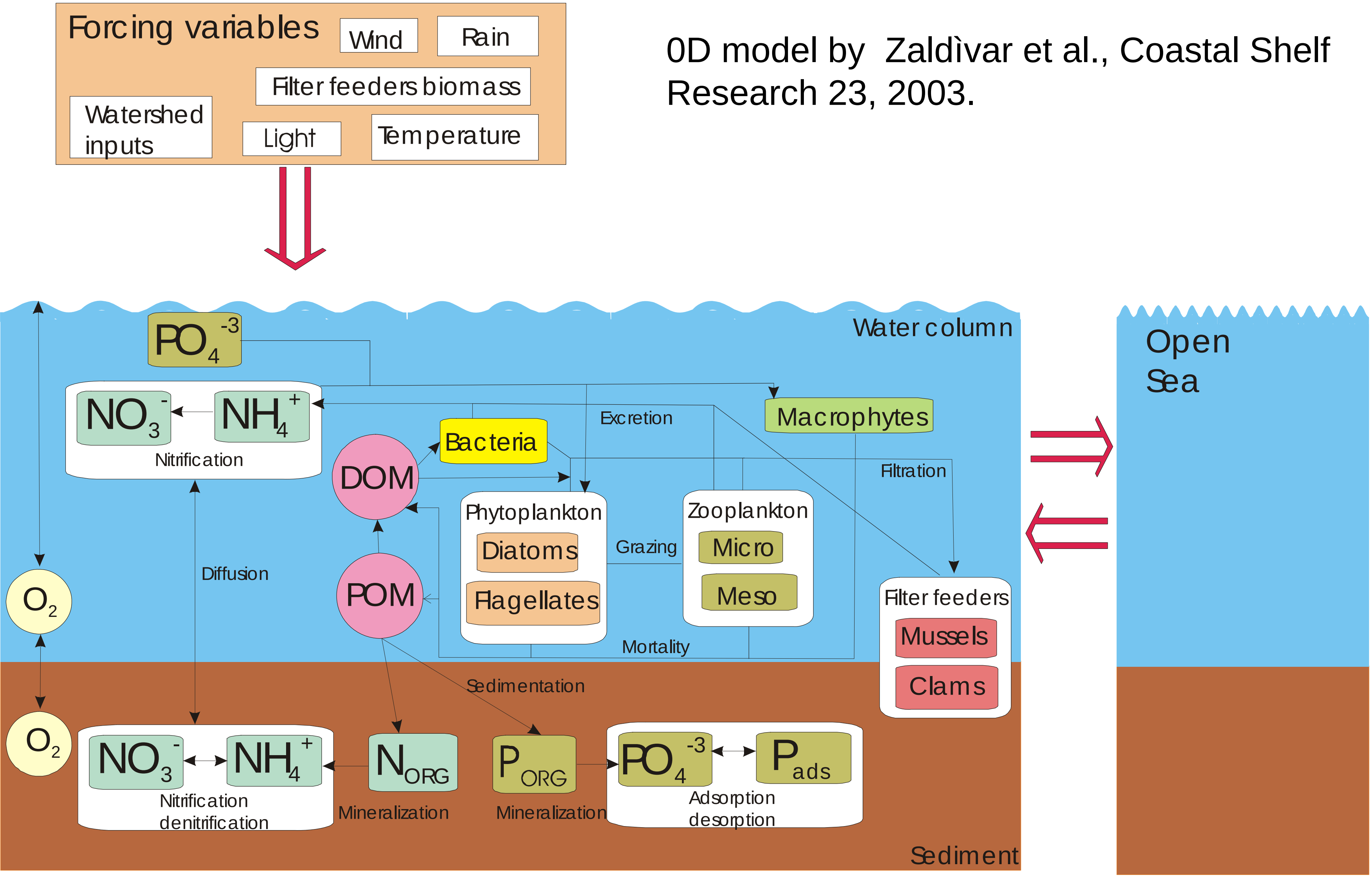


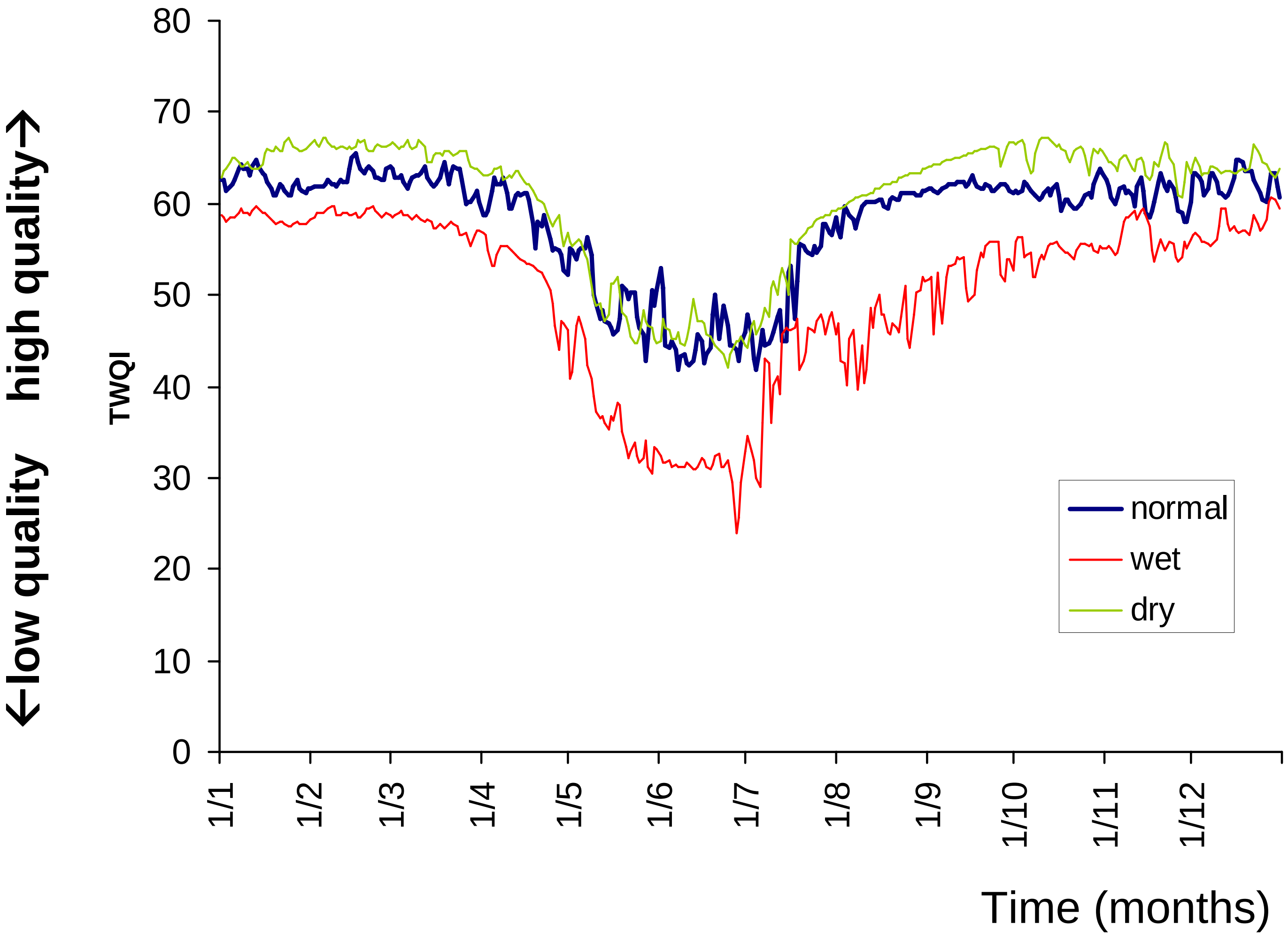
Provincia di Ferrara
Servizio Risorse Idriche e Tutela Ambientale
UOPC Acque Costiere ed Economia Ittica

Data source: Provincia di Ferrara. Servizio Risorse Idriche e Tutela Ambientale. UOPC Acque Costiere ed Economia Ittica

Scenario analysis with different hydrological regimes

0D model by Zaldìvar et al., Coastal Shelf Research 23, 2003.





Simulation of effects of different hydrological regimes on water quality in the sacca di Goro lagoon. Water quality is assessed with a modified version of the Water Quality Index (Giordani et al, Ecological Indicators, submitted)

more questions than answers…

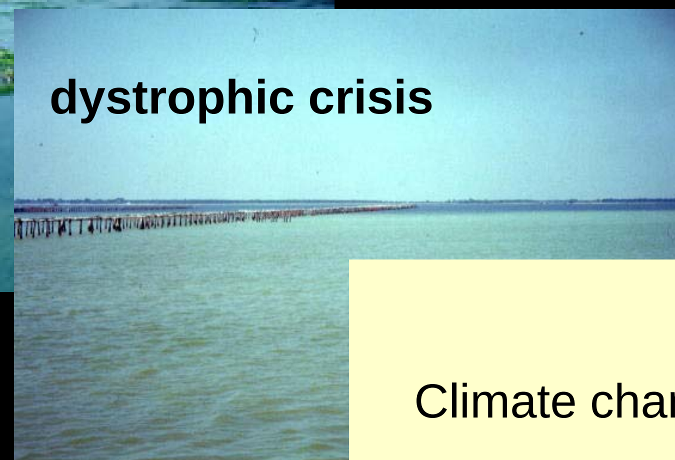
are lagoon becoming heterotrophic due to organic loading and aquaculture?

are nutrient ratios unbalanced due to changes in watershed hydrology?

- less P and more N → P limitation?
- less Si and more N → Si limitation?
- can internal loadings supply P and Si?
- can salinity enhance internal recycling?

are lagoons turning from brackish to marine waters?

Challenges: predicting future evolution of coastal lagoon ecosystems under threat



Climate change and altered hydrology?

Coastal lagoon responses to external stressors are not yet well supported by quantitative theories or models (Nixon et al., 2001, Human and Ecological Risk Assessment: 1457-1481)