Ocean acidification and the potential for carbon sequestration by coastal seagrasses

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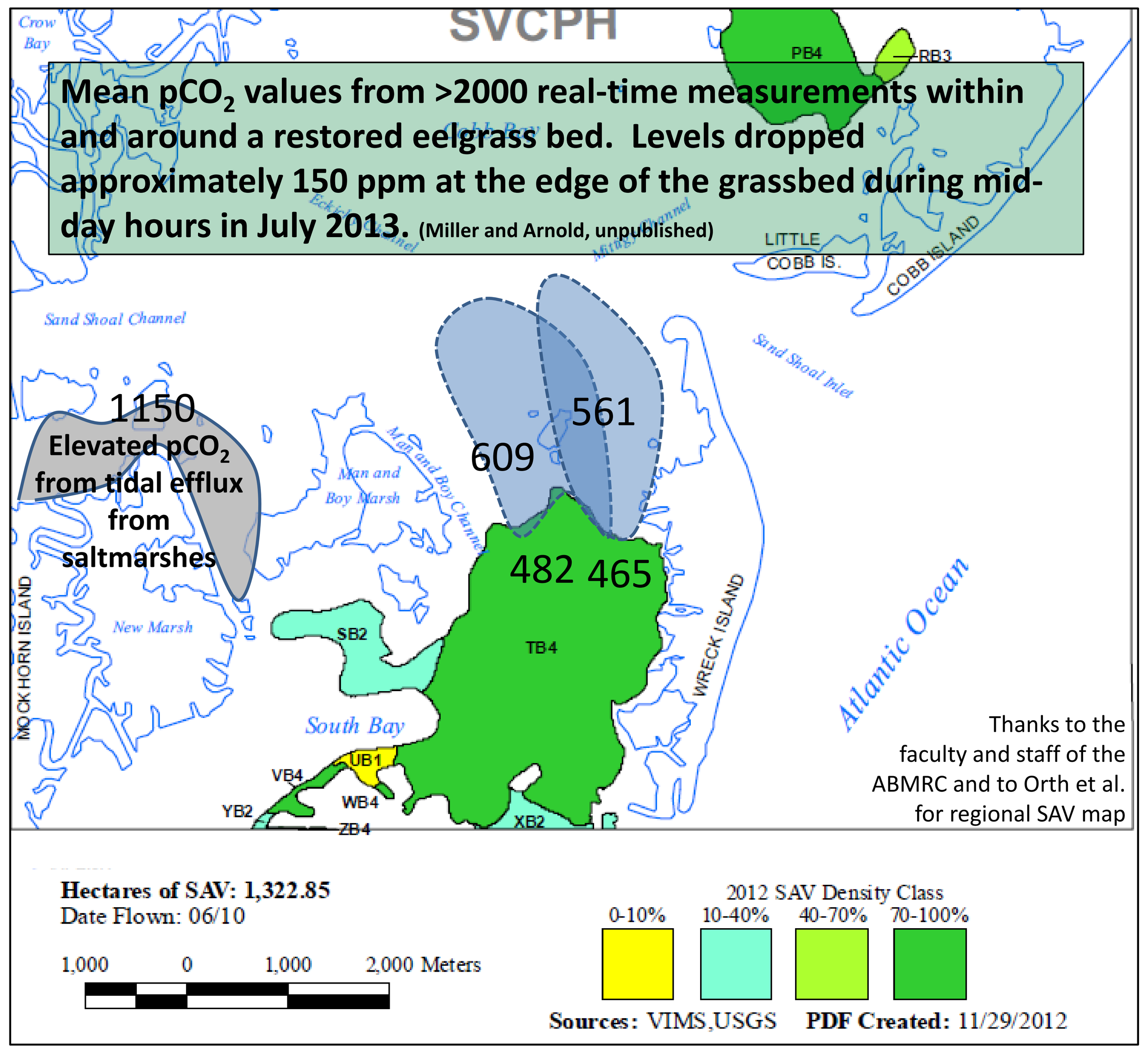
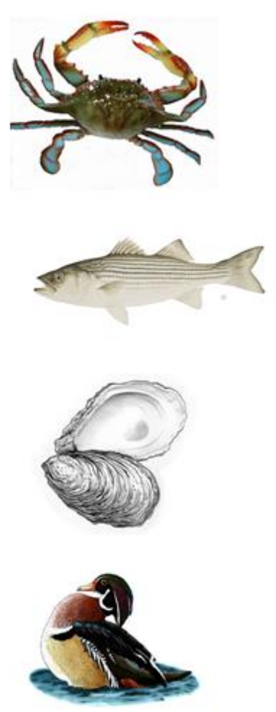
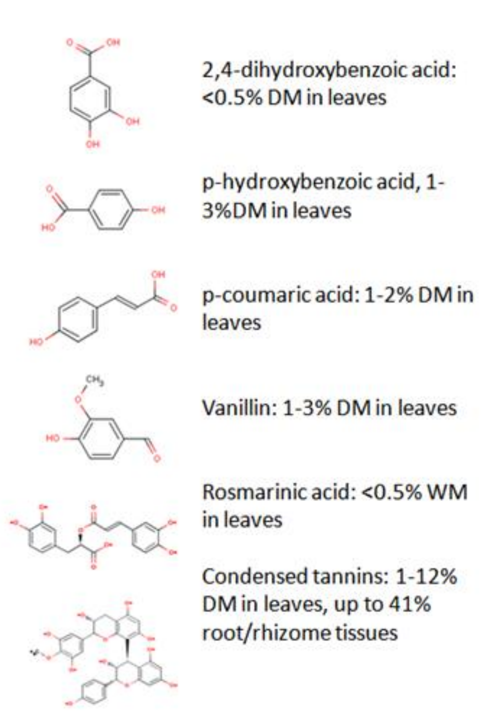
Seagrasses cover a global area of approximately 177,000 km^2 and provide ecosystem services worth an estimated $1.9 trillion per year. Their high rates of carbon assimilation may reduce local pCO_2 levels by >50% during daytime. As a result seagrasses sequester "blue carbon", storing as much as 19.9 Pg of organic carbon in the form of anaerobic, organic-rich loams. They are responsible for an estimated 10–18% of oceanic carbon burial.

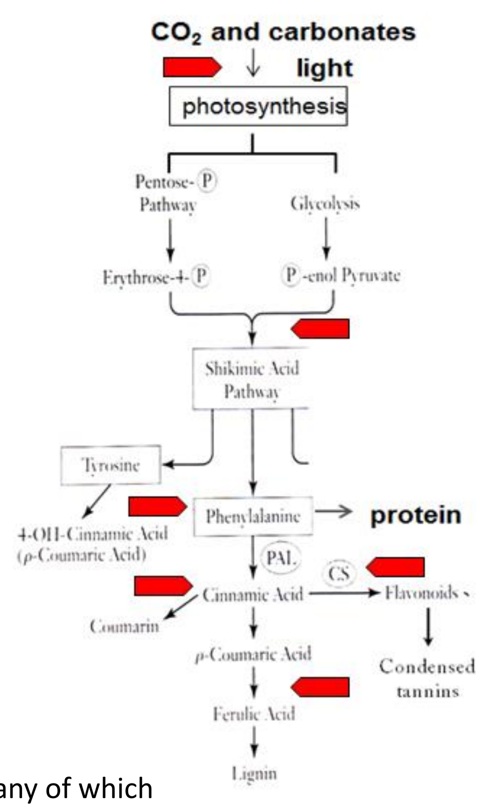
We have observed this phenomena within a restored eelgrass (*Zostera marina*) bed in South Bay, Virginia (below) using a real-time MarCOm pCO_2 monitor. High pCO_2 exist within bays surrounded by saltmarshes but levels dropped dramatically over eelgrass beds during July 2013.



This suggests the potential for significant carbon uptake and storage. However, not all plant products have the same **"sequestration potential" (SP).** Plant phenolics (below, center), which in land plants tend over-accumulate under high CO_2 conditions, resist decomposition for relatively long periods of time. These are products of the shikimic acid / phenylpropenoid pathways (below, right), which is stimulated by carbon availability. For terrestrial plants, more carbon generally yields more plant phenolics. In seagrasses, phenolics accumulate to ~10% of plant dry mass and often serve as anti-microbials and anti-feedants, impacting habitat and food availability for many marine species (below, left).







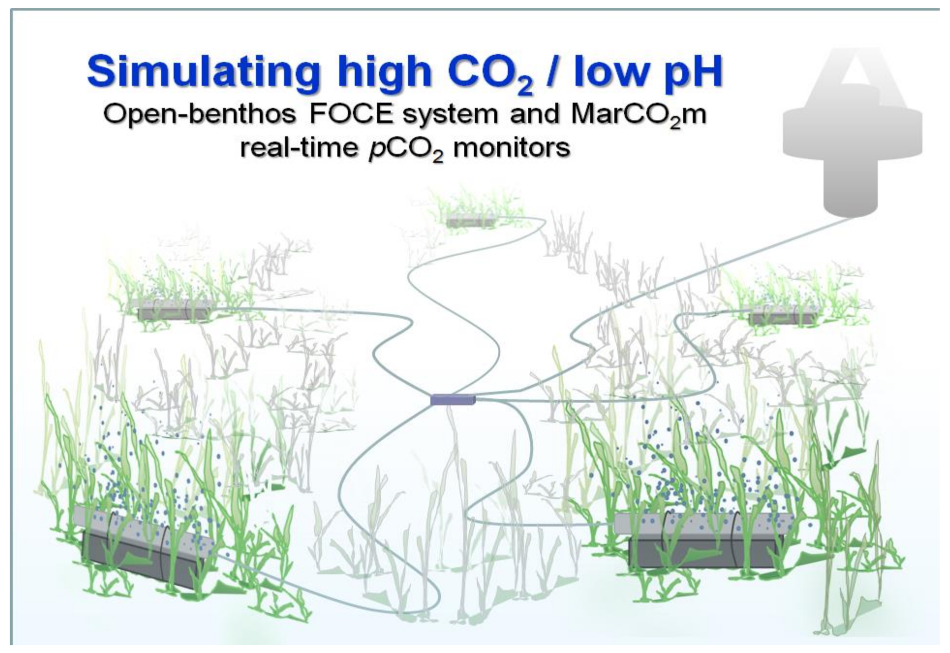
Red arrows indicate regulatory points of the SA/PP pathway, many of which are stimulated by combinations carbon, sugar, and light availability.

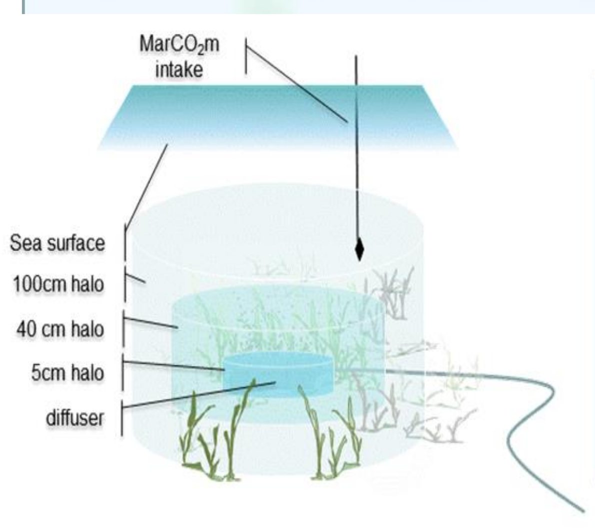
HIGH CO_2 / LOW PH CONDITIONS REDUCE LEVELS OF SOLUBLE (POLY)PHENOLS IN SEAGRASSES

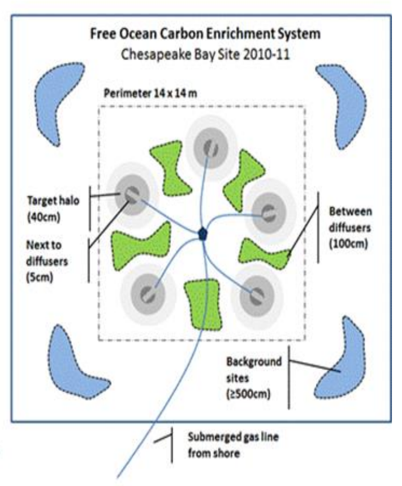
Using Free Ocean Carbon Enrichment technology and and natural underwater CO_2 vent sites we tested the impact of high CO_2 / low pH conditions on seagrass phenolics, observing that OA triggered a 10x *decrease* in concentrations of small- and medium-sized phenolics in five populations of seagrasses, including four species from three continents. These lost phenolics have known bioactivity as anti-feedants and anti-microbials; we have observed corresponding increases in fish grazing and predict increased outbreaks of the seagrass wasting disease, both of which would compromise seagrass SP by releasing organic carbon back into the carbon cycle.

OPEN-BENTHOS F.O.C.E.

With real-time MarCOm pCO_2 monitors. Increasing pCO_2 levels while maintaining natural estuarine variations and eliminating the artifacts associated with chambers (Arnold et al. 2012).







Chesapeake Bay sites (USA)

Chesapeake Bay Site 1

***Ruppia maritima*, ST. MARY'S RIVER (USA)**
FOUR WEEKS OF EXPOSURE (MAY-JULY 2010)

Loss of soluble phenolics

Conditions	Seawater carbonate chemistry		
Distance from injector	**500cm**	**40cm**	**5cm**
Temperature (C)	25.0	25.0	25.0
Salinity	17	17	17
pH	8.4	8.0	6.9
pCO_2 (µtm)	157.8	469.3	6792.0
TA (µmol kg^{-1})	1467.0	1444.0	1455.0

Ruppia maritima (long)	Concentration (mg g^{-1} WM)			General trend	Test	*P*
Proanthocyanindins	5.92±0.99^a	4.69±.068^a	2.41±0.31^b	*60% decrease***	2	0.002
Total reactive phenolics	3.43±.30^a	1.67±.26^b	1.88±.31^b	*45% decrease***	1	<0.001
Coumaric acid	0.31±.05^a	0.18±.01^{ab}	0.15±0.01^b	*53% decrease***	2	<0.001

Statistical analyses: 1, one-factor ANOVA with Holm-Sidak multiple comparisons; 2, Kruskal-Wallis One Way Analysis of Variance on Ranks with Tukey or Dunns multiple comparisons. Letters indicate results of pairwise comparisons test *P*<0.05.

Size of plants, numbers of buds, flowers, and seeds, total sugar and starch levels were unchanged. Total and adjusted protein levels were 10% lower in high CO_2 / low pH conditions

Chesapeake Bay Site 2

***Ruppia maritima*, SEVERN RIVER (USA)**
FOUR WEEKS OF EXPOSURE (MAY-JULY 2011)

Conditions	Seawater carbonate chemistry			
Distance from injector	**500cm**	**100cm**	**40cm**	**5cm**
Temperature (C)	28.3	28.3	28.3	28.3
Salinity	4.3	4.3	4.3	4.3
pH	8.34±0.01	8.26±0.02	7.82±0.04	7.32±0.06
pCO_2 (µatm)	243±9	295±13	948±89	3465±527
TA (µmol kg^{-1})	1122±0.5	1122±0.5	1122±0.5	1122±0.5

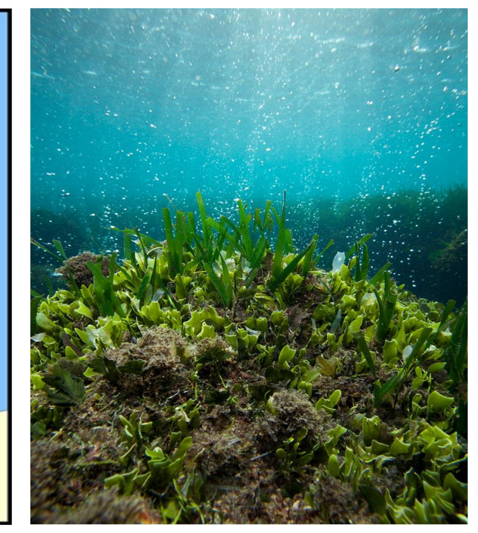
Loss of soluble phenolics

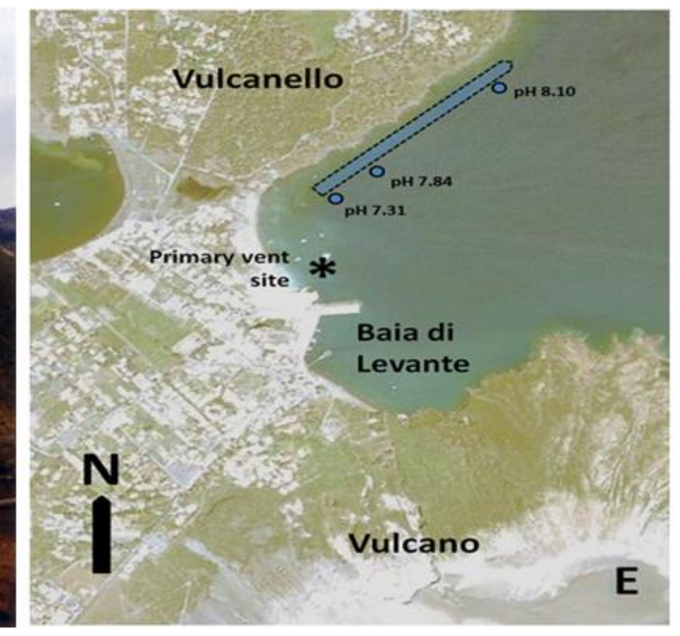
Ruppia maritima (short)	Tissue	Concentration (mg g^{-1} WM) 100cm	40cm	Trend	Test	*P*
Proanthocyanindins	whole plants	25.00±7.19	6.33±0.55	*75% decrease***	1	0.018

Experiments repeated in 2009-11 for various species of submerged aquatic vegetation, with similar results.

VENT EXPERIMENTS (VULCANO, ITALY)

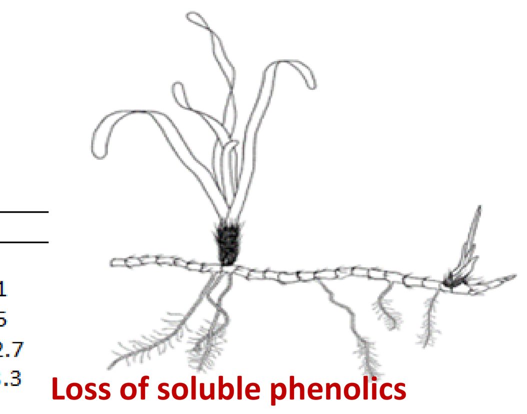
Vulcano Site 3





Vulcano Site 3

***CYMODOCEA*, ISLAND OF VULCANO (ITALY)**



Conditions	Seawater carbonate chemistry		
Distance from seep	**380m**	**300m**	**260m**
Salinity	37.16±0.07	37.12±0.06	37.05±0.1
pH (units)	8.11±0.01	7.84±0.04	7.32±0.05
pCO_2 (µtm)	422±43	976±269.5	4009±1442.7
TA (µmol kg^{-1})	2549.6±29.6	2555.9±28.9	2592.5±48.3

Loss of soluble phenolics

Cymodocea nodosa	Concentration (mg g^{-1} WM)			General trend	Test	*P*
Proanthocyanindins	13.62	10.17	10.92	***25% decrease****	**1**	**0.088**
Total phenolic acids	4.66±0.59^a	5.30±1.45^{ab}	1.89±0.19^b	***59% decrease*****	**2**	**0.017**
Gallic acid	0.50±0.05	0.41±0.03	0.50±0.04	*no change*	1	0.252
Syringaldehyde+4-HBA	0.07±0.01^a	0.05±0.01^{ab}	0.03±0.01^b	***58% decrease*****	**1**	**0.006**
Vanillin	1.02±0.65	2.57±1.38	0.36±0.24	*65% decrease*	2	0.344
Acetovillinone	3.06±0.88	2.27±1.47	1.00±0.25	*67% decrease*	1	0.413
Coumaric acid	0.29±0.16	0.16±0.05	0.17±0.09	*41% decrease*	2	0.882
Ferulic acid	0.38±0.18	0.31±0.11	0.19±0.09	*50% decrease*	2	0.195
All phenolics†	109.30±4.39^a	104.51±4.48^{ab}	93.12±4.26^b	***15% decrease*****	**3**	**0.026**

DECREASES IN SOLUBLE PHENOLICS ....

Short-term carbon flux

- Black rabbitfish, *Siganus fuscescens,* exhibited **a strong feeding preference** for high CO_2 / low pH seagrasses with low soluble phenolic contents. This may explain the **higher-than-usual rates of grazing** observed near undersea CO_2 vents.
- The seagrass wasting disease pathogen, *Labyrinthula* spp., is inhibited by specific soluble phenolics such as caffeic acid; a OA-induced decline in these antimicrobials could trigger seagrass disease outbreaks.
- Both herbivory and disease increase **"blue" carbon efflux** from seagrass meadows.

...BUT INCREASES IN INSOLUBLE PHENOLICS.

Long-term carbon flux

In each of these experiments we have traced the assimilated carbon to pools of insoluble polyphenols. **For example, under high CO_2 / low pH conditions seagrasses accumulated an average of 33% more lignin, a insoluble polyphenol that contributes to plant toughness.** Lignin has a high sequestration potential; as a result, we hypothesize that OA will promote to two opposing processes:

- a short-term increase in above-ground carbon recycling *via* herbivory and disease.
- a longer-term increase in the SP of plant tissues with enhanced lignification in marine sediments.