Blue Carbon as an Ecosystem Service
A Biogeographical Perspective

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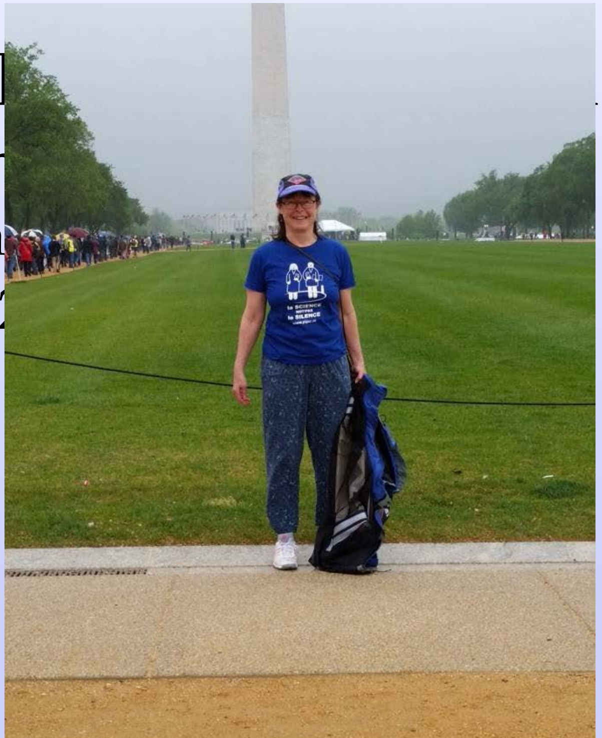


Oceans are critically important in controlling global climate.

Autotrophs in marine ecosystems take up CO_2 synthesize organic carbon.

Some of this carbon -is be transferred to pelagic and benthic food webs (*i.e.* ***regional ecosystem service***),

-is respired to CO_2 or

-is exported from the surface and sequestered as particles in the nearshore or in the deep ocean, or transformed into long-lived dissolved organic compounds (*i.e. global ecosystem service*).

Organic carbon that is transported to, or produced/ transformed in the marine environment, and that is prevented from returning the atmosphere for >100 years is considered sequestered and is relevant for climate processes.

What are Ecosystem Services?

Benefits provided by ecosystems are collectively known as **ecosystem services**.

Role of, and services provided by, ecosystem have been recognized for decades, however the concept was formlized and developed by the Millennium Ecosystem Assessment.

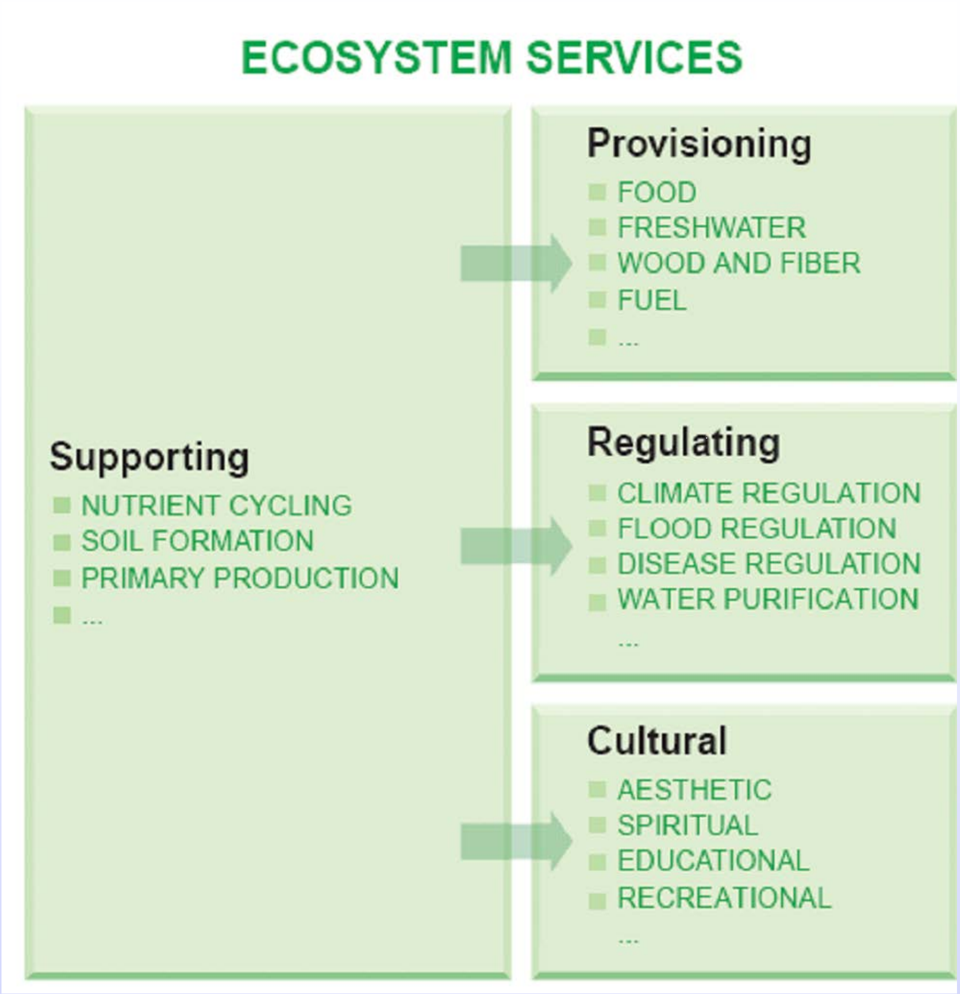
Divided services among four categories that provide services to "humans"

provisioning- production of food and water;

regulating- **the control of climate and disease;**

supporting- nutrient cycles and pollinations;

cultural- spiritual and recreational benefits.



Most changes to *"regulating services"* are a consequence of the enhancement of the *"provisioning services"*.

Substantial modification of the *climate regulating service of ecosystems* has occurred through changes in <u>land use</u> in <u>fuel extraction</u>, <u>processing</u>, and <u>combustion</u> and this has lead to increases in the release of CO_2 and other greenhouse gases.

The **Blue Carbon** Initiative initially focuses on carbon in coastal ecosystems - mangroves, tidal marshes, seagrasses *and macroalgae*.

These ecosystems sequester and store large quantities of carbon both in plant biomass and in the sediment. This sequestration helps mitigate climate change due to CO_2 emissions.

The form and location of carbon storage depends on the ecosystem type, region and ecological state.

For example, in seagrass meadows over 95% of the carbon is stored in the soils, whereas for marcoalgae, carbon is mostly stored in plant biomass.

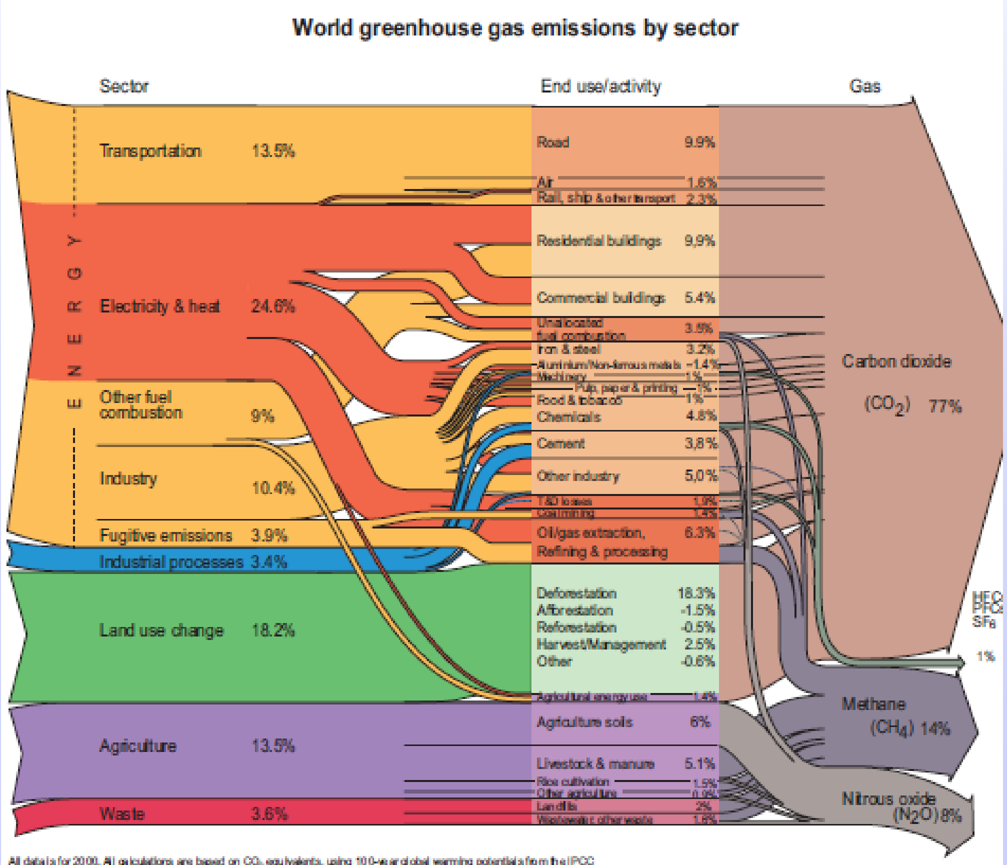
The **Blue Carbon** concept is evolving and includes carbon stored/sequestered in <u>both</u> coastal and ocean ecosystems. Including the open ocean may alter some of the conceptual considerations of carbon storage.

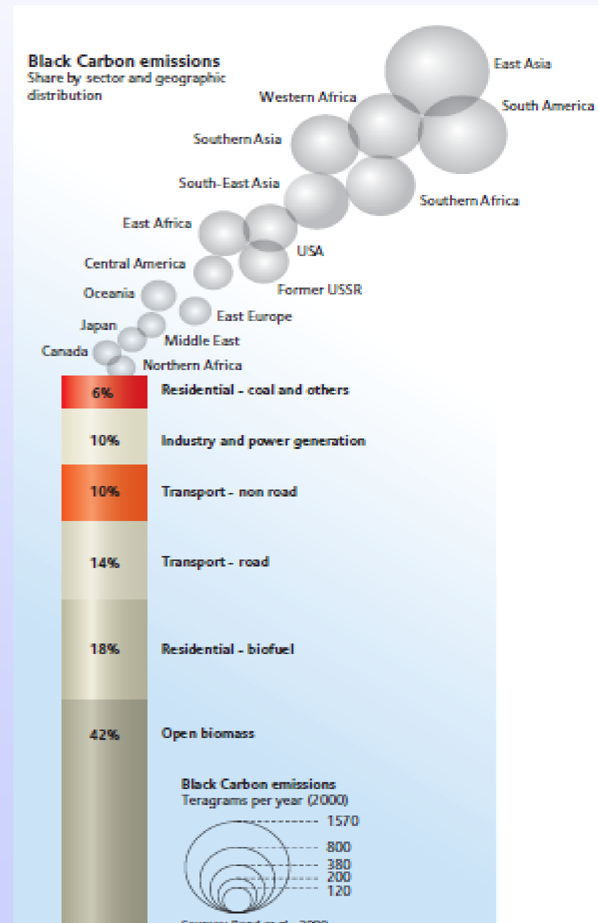
Organic carbon comes in many colors…

Terrestrial carbon stored in plant biomass and is "**Green Carbon**".

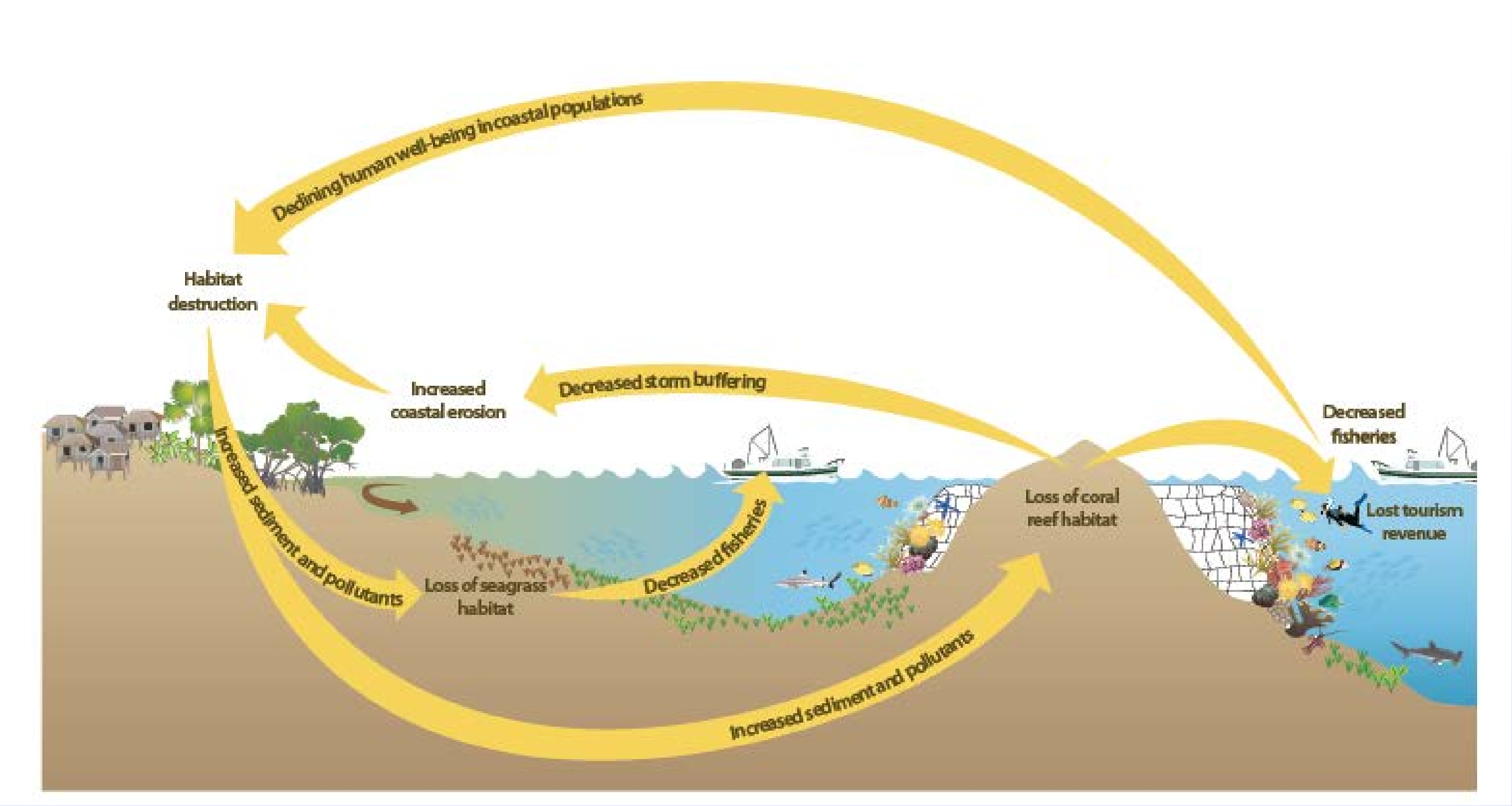
The burning of fossil and biofuels fuels releasing CO_2, is "**Brown Carbon**" and particles is "**Black Carbon**".

Nellemann et al al 2009





"Blue Carbon ecosystems" provide a range of ecosystem services including supporting nursery areas for fish and mariculture, water purification and coastal protection, sediment stabilization carbon and nutrient sequestration.

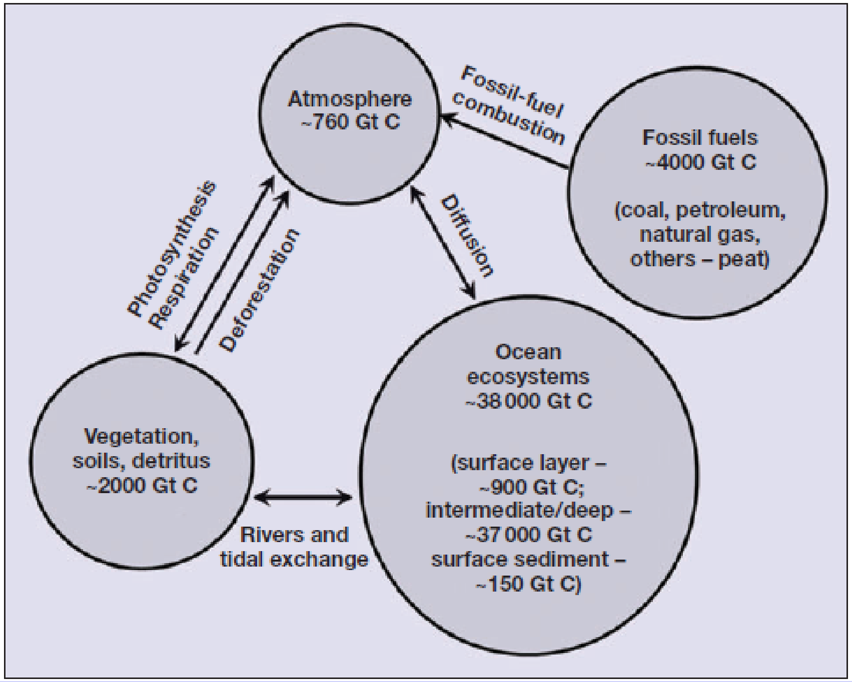


The spatial and temporal distribution of these services will vary and there are potentially strong feedbacks among the services.
<u>Many of these services are now being monetarized.</u>

Coastal systems are at interface between ocean and land and include coral reefs, intertidal and subtidal marshes, estuaries, coastal aquaculture, macroalagal and seagrass communities.

Nearly half of the world's major cities are located within 50 kilometers of the coast, and coastal population densities are 2.6 times larger than those inland.

Over 80% of the global carbon is circulated through the ocean. Coastal systems and continental margins occupy ~7% of the ocean area and < 0.5% of the ocean volume, they have a disproportionally large role in regulating biogeochemical cycles.



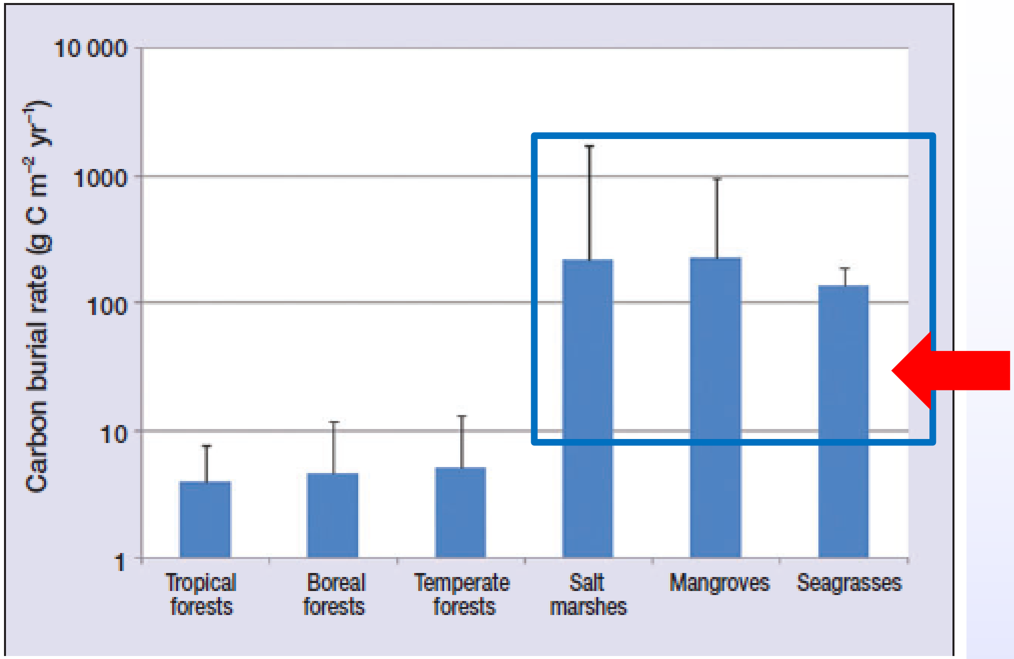
McCloud et al 2011

Laffoley and Grimsditch 2009

Ecosystem type	Standing carbon stock ($gC\ m^{-2}$) Plants	Soil	Total global area ($*10^{12}\ m^2$)	Global carbon stocks ($*10^{15}\ gC$) Plants	Soil	Longterm rate of carbon accumulation in sediment ($gC\ m^{-2}\ y^{-1}$)
Tropical forests	12045	12273	17.6	212	216	2.3-2.5
Temperate forests	5673	9615	10.4	59	100	1.4 – 12.0
Boreal forests	6423	34380	13.7	88	471	0.8 – 2.2
Tropical savannas and grasslands	2933	11733	22.5	66	264	
Temperate grasslands and shrublands	720	23600	12.5	9	295	2.2
Deserts and semi-deserts	176	4198	45.5	8	191	0.8
Tundra	632	12737	9.5	6	121	0.2 – 5.7
Croplands	188	8000	16	3	128	
Wetlands	4286	72857	3.5	15	225	20
Tidal Salt Marshes			Unknown (0.22 reported)			210
Mangroves	7990		0.152	1.2		139
Seagrass meadows	184	7000	0.3	0.06	2.1	83
Kelp Forests	120-720	na	0.02- 0.4	0.009-0.02	na	na

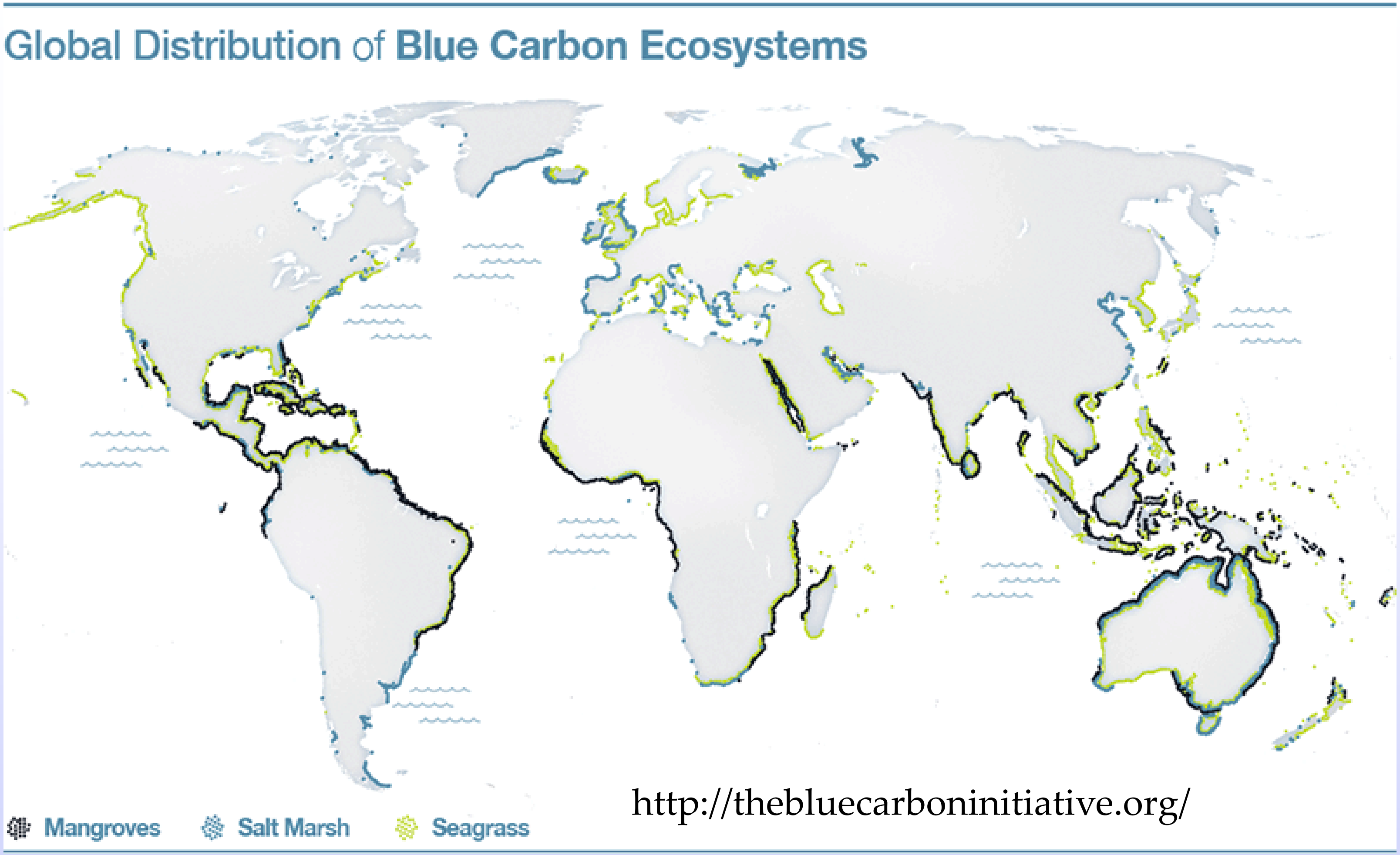
Carbon stocks and accumulation rates differ in terrestrial and marine habitats and among ecoregions within habitats.

McCloud et al 2011

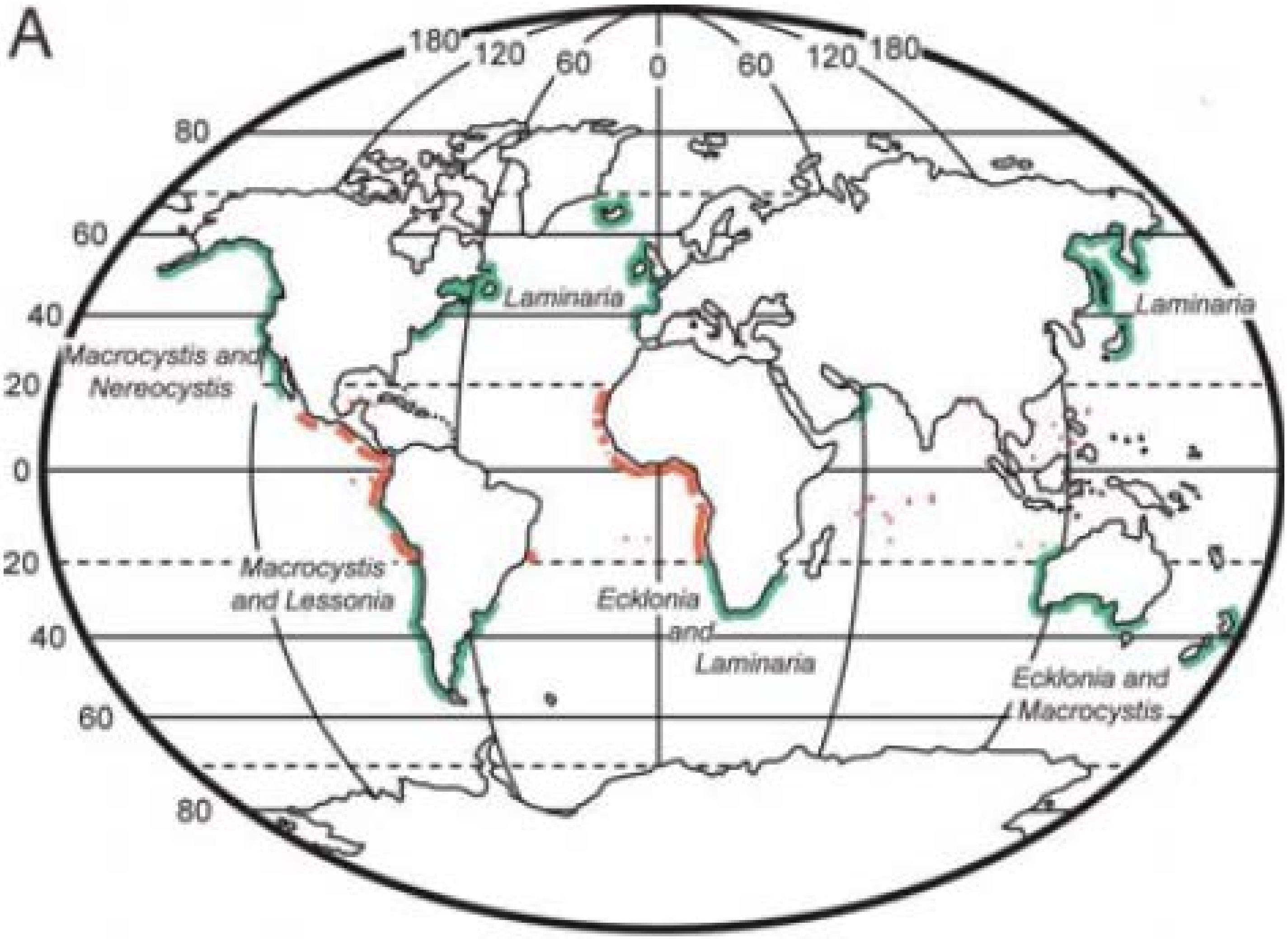


Carbon storage rates in the coastal zone are 10- to 100-fold greater than in terrestrial habitats.

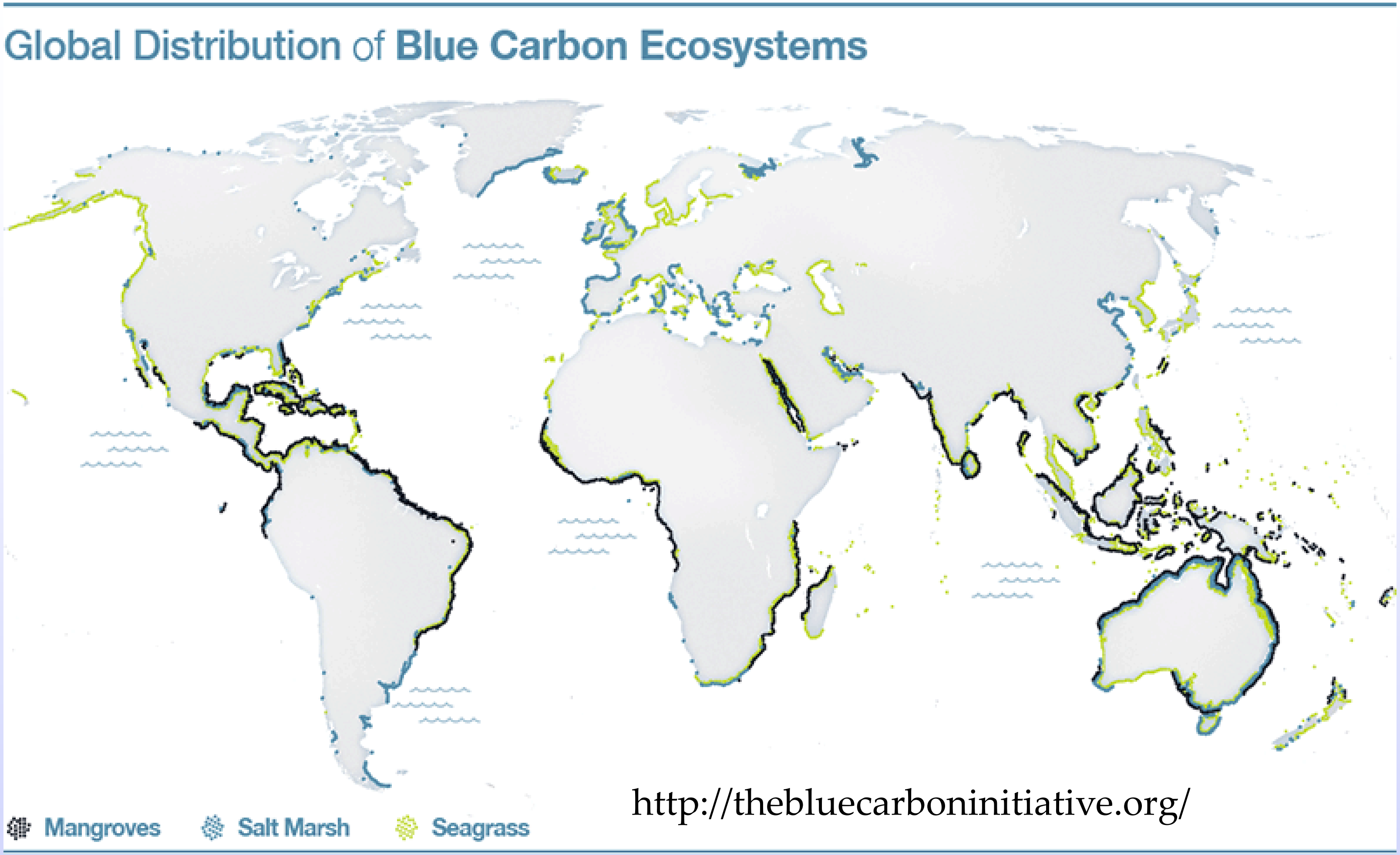
Macroalgae = ~50 (18 to 79 g C/m2/y)



http://thebluecarboninitiative.org/



Geographic distribution of kelp forests in surface (green line) and deep (red line) waters, reproduced from Santelices - Santelices, B., 2007. The discovery of kelp forests in deep-water habitats of tropical regions, PNAS, 104 (49), 19163 – 19164 by kind permission of Proceedings of the National Academy of Sciences (PNAS).



Global coastline, 1,162,000 km… how does it break down by country?

Length of coastline (km)

1-	Canada	202,080
2-	Indonesia`	54,716
3-	Greenland	44, 087
4-	Russia	37,653
5-	Philippines	36,289
6-	Japan	26,751
7-	Australia	25,576
8-	Norway	25,148
9-	United States	19,924
10-	Antarctica	17,968
12-	***China***	***14,500***

Global coastline, 1,162,000 km

High latitude countries ~ 30% of total!

Lack mangrove, or significant seagrass and saltmarsh areas.

Extensive macroalgal beds!

We have seen the importance of macroalgal carbon to global **Blue Carbon.**

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The form and location of carbon storage depends on the ecosystem type, region and ecological state.

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The **Blue Carbon** concept is evolving and includes carbon stored/sequestered in <u>both</u> coastal and ocean ecosystems. **Including the open ocean Blue Carbon may alter some of the conceptual considerations of carbon burial-storage-sequestration.**

What is the relationships among oceanic carbon production, food web transfer and accumulation/sequestration of carbon?

Primary production (**PP**) has five principal fates: carbon export and sequestration (**E**), microbes (**M**) and zooplankton (**Z**) and harvestable marine resource (**H**)

$$\mathbf{PP} = \mathbf{E} + \mathbf{M} + \mathbf{Z} + \mathbf{H}$$

R **E**

At steady state, the fluxes to **M**, **Z** and **H** will be either transferred to **E** or will be respired (**R**) by heterotrophs.

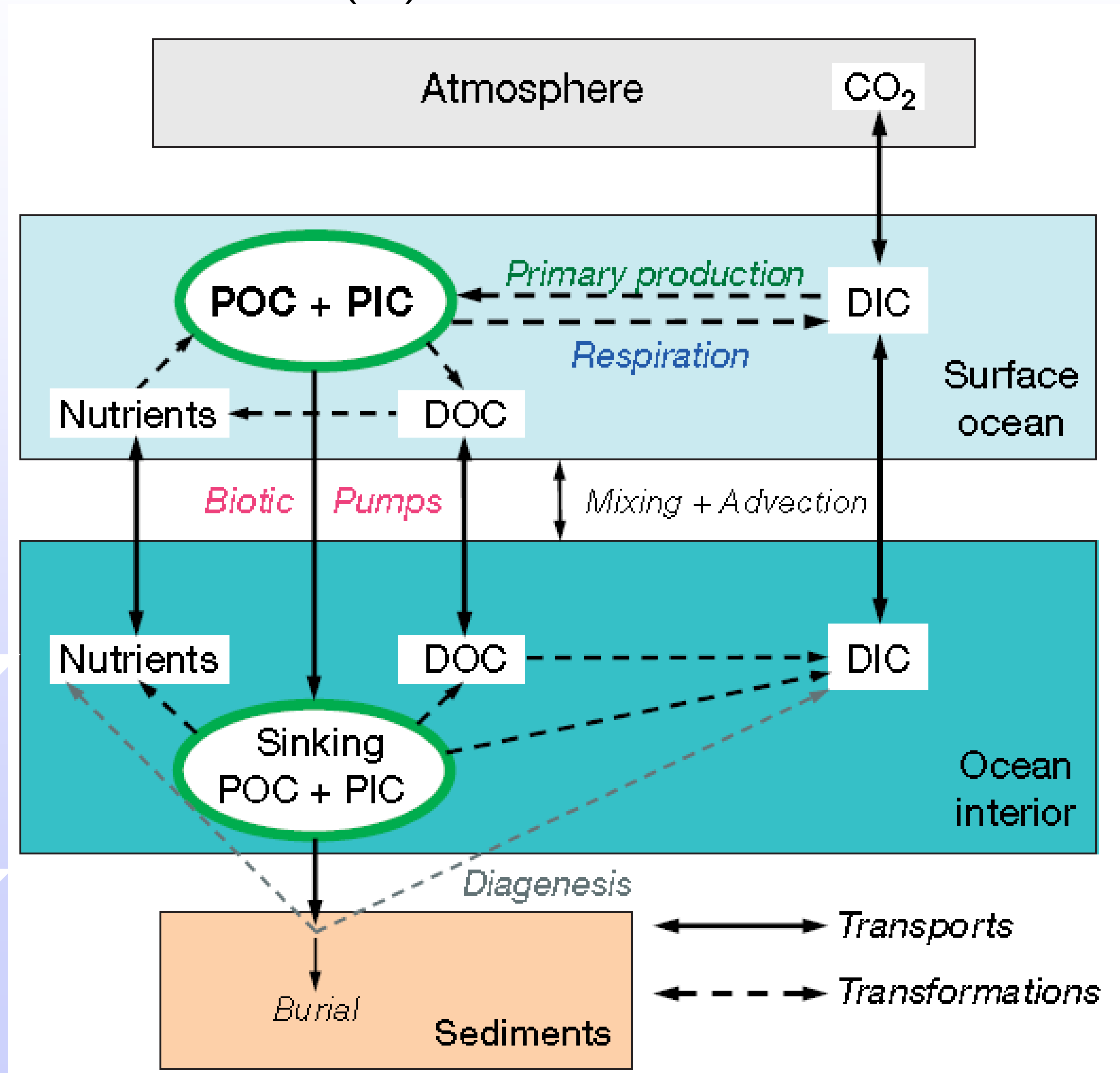
$$\mathbf{PP} = \mathbf{E} + \mathbf{R}$$

Primary production (**PP**) which is exported (**E**) from the euphotic zone represents the fraction that escapes microbial-mediated solubilisation and remineralization (**R**).

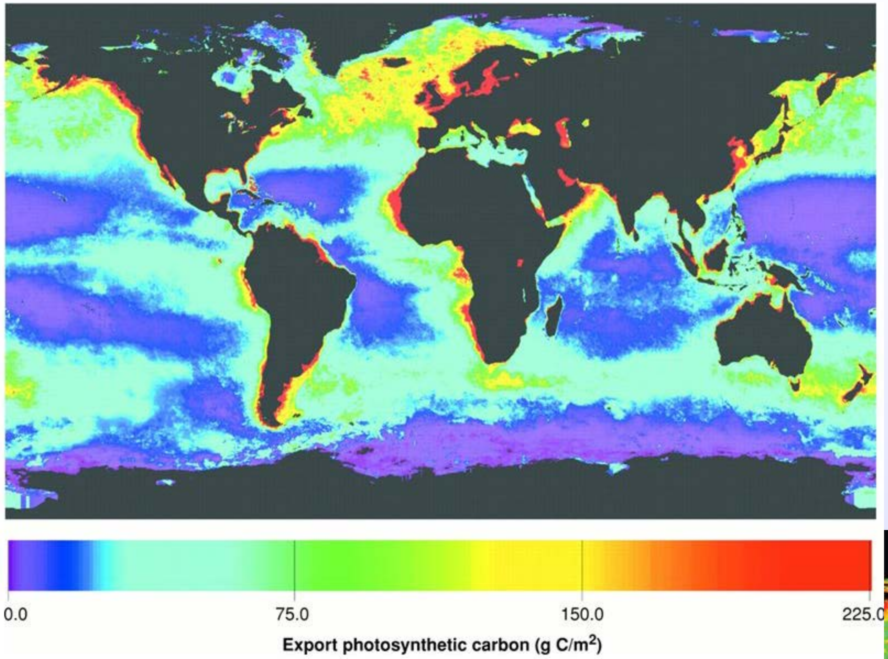
E = P - R

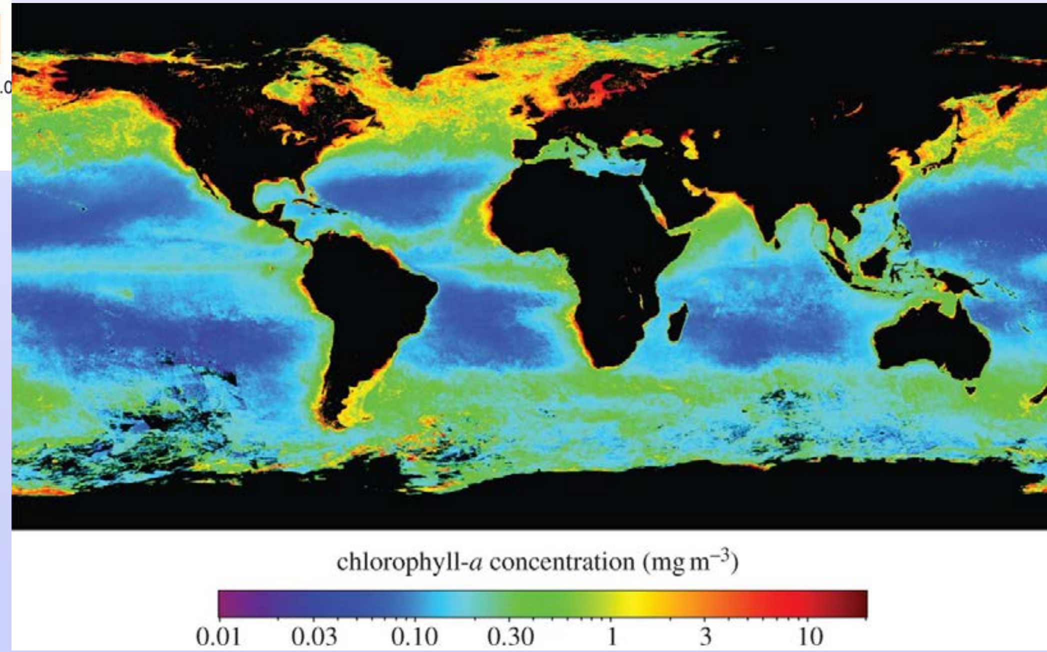
Biologically mediated carbon pumps

BCP
MCP
$CaCO_3$



Phytoplankton biomass, production and carbon export from the surface ocean varied spatially and temporally.





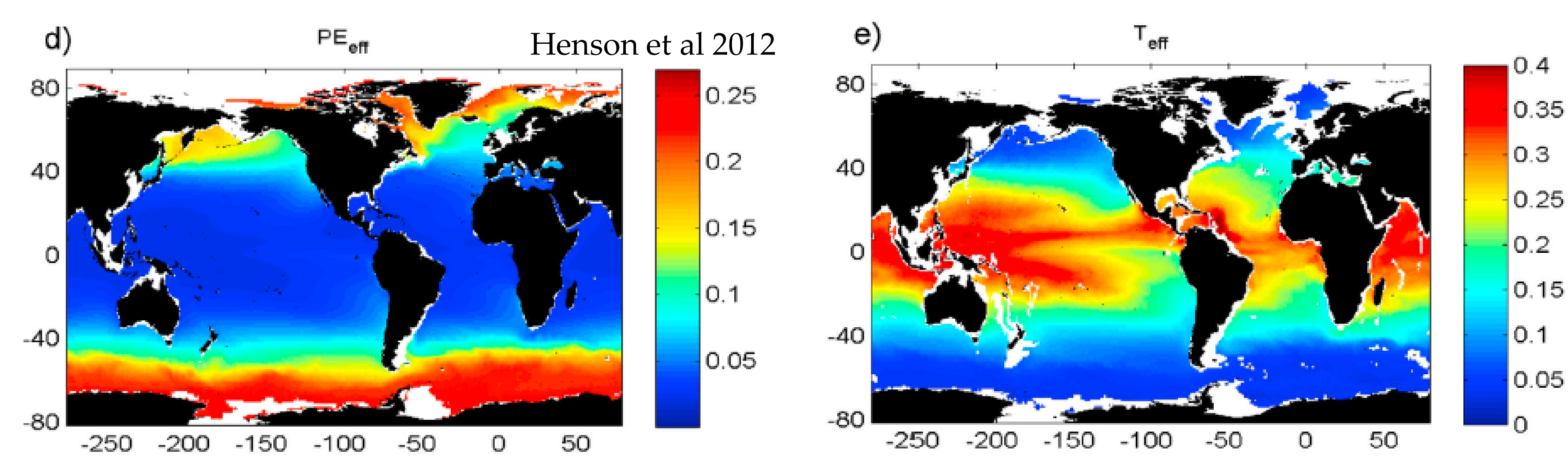
The biological pump is relatively inefficient. Most of the carbon fixed into phytoplankton is remineralized in the euphotic and the mesopelagic zones.

Two commonly used metrics to quantify export are:

Particle export efficiency ($\mathbf{E_{eff}}$), the proportion of **PP** that is exported from the surface ocean, i.e., **E/PP** and,

Particle transfer efficiency ($\mathbf{T_{eff}}$), the fraction of exported organic matter that reaches the depth of sequestration (**S**) ~1000m, i.e., **S/E**

Is carbon sequestration in the open ocean functionally equivalent to carbon burial in the sediments in the coastal zone…?



The spatial gradients in E_{eff} (<u>~10% to 40%) & </u>T_{eff} (<u>~1% to 20%)</u> suggest that at <u>high latitudes, more of the PP is exported below the mixed layer than in low latitudes</u>, but that this material is rapidly remineralized and is not effectively sequestered.

The spatial pattern in T_{eff} is due to selective recycling of organic carbon in between the base of the euphotic zone and ~1000 m.

For macroalgae E_{eff} ~45% & T_{eff} ~26%

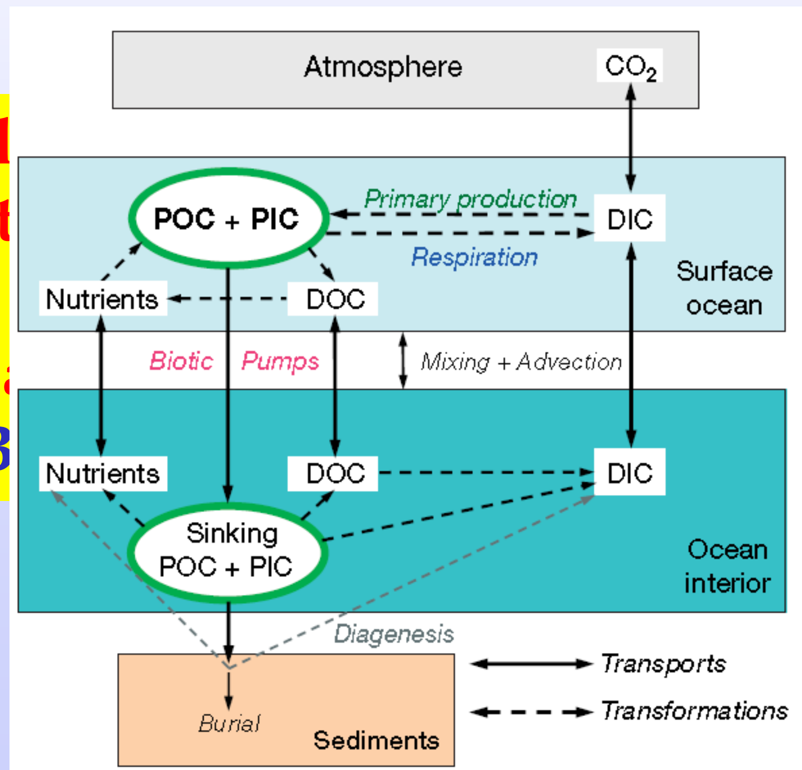
Krause-Jensen & Duarte, 2016

At low latitudes, the high T_{eff} may reflect intense microbial recycling of organic matter in the euphotic zone… so the exported organic material is "refractory" and the T_{eff}/E_{eff} is high.

At high latitudes, the low high T_{eff} may reflect low rates of microbial recycling of organic matter in the euphotic zone … so the exported organic material is "labile" and the T_{eff}/E_{eff} is low.

How can we rel… …esses in the open ocean and coast…

Should ocean c… …idered in the accounting of B…



Carbon is sequestered when it is transported to an environment where, or transformed to a chemical state that prevents the carbon it from being exchanged with the atmosphere.

In the ocean, carbon sequestration has been inferred from deep sediment traps (i.e. BCP) and from the production of refractory/recalcitrant organic matter (i.e. MCP).

Recent estimates vary;

→ BCP 0.6 to 1.2 PgC/y at 1000m and is 1-2% of **PP.**

→ MCP 0.07 to 0.18 PgC/y

Total oceanic carbon sequestration ~ 0.7 to 1.4 PgC/y.

Will assume that ocean carbon sequestration is considered in the accounting of Blue Carbon!

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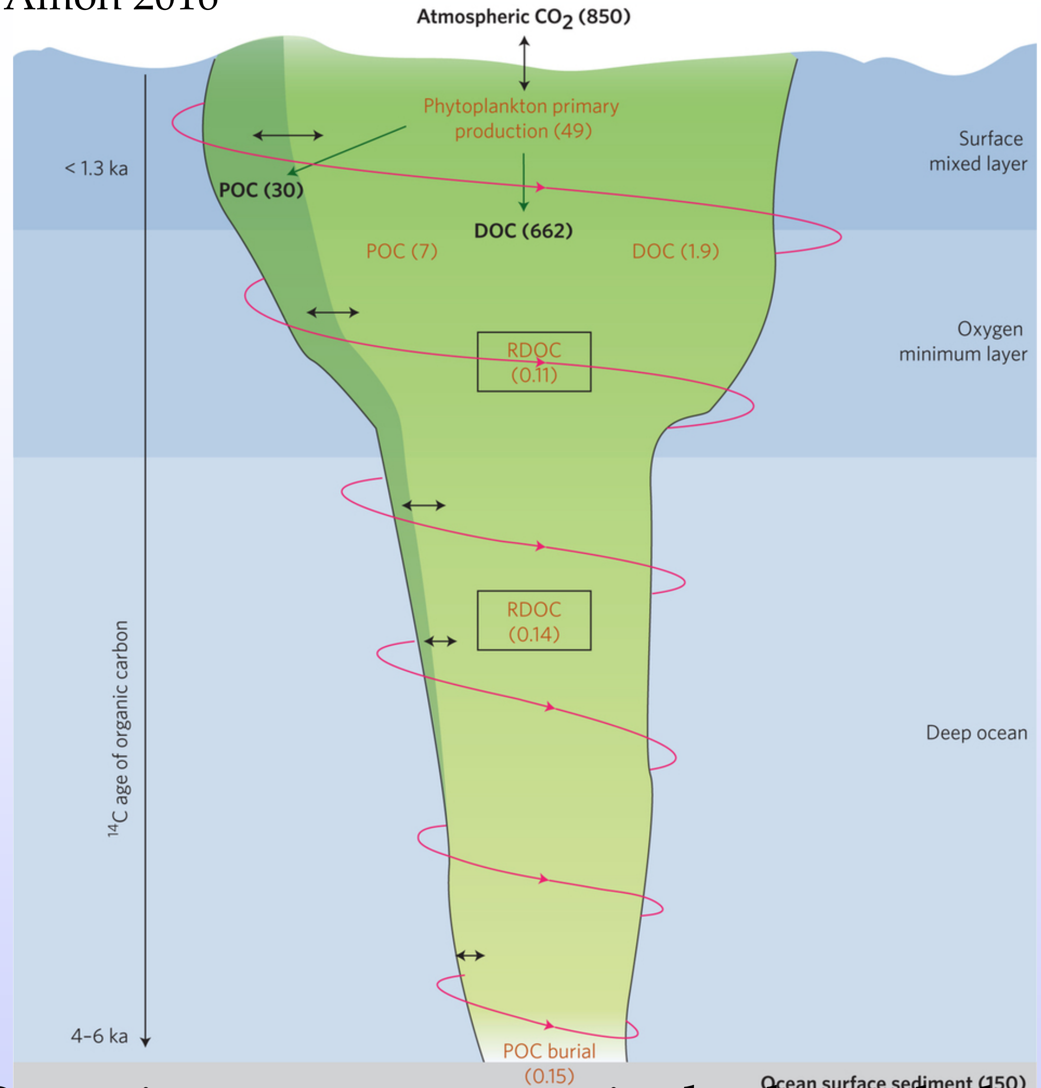
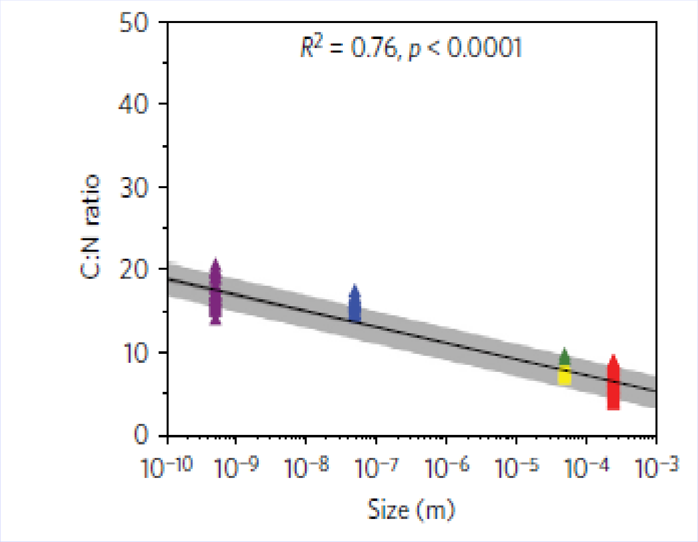
Amon 2016



Deep ocean DOC has an average age of ~6,000 y with some pools having a radiocarbon age of ~12,000 y.

The ratio of refractory to labile DOC as well as the C:N ratio increases with depth ^{14}C-age and molecular size (Walker et al 2016).



Organic matter progressively degraded as it decreases in size, and that small particles and molecules persist in the ocean longer than large ones.

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Will assume that ocean carbon sequestration is considered in the accounting of Blue Carbon

This is consistent with the recognition that macroalgal production that is transported below ~1000 m is Blue Carbon.

Recalculation of the sequestration of global **Blue Carbon** in the ocean.

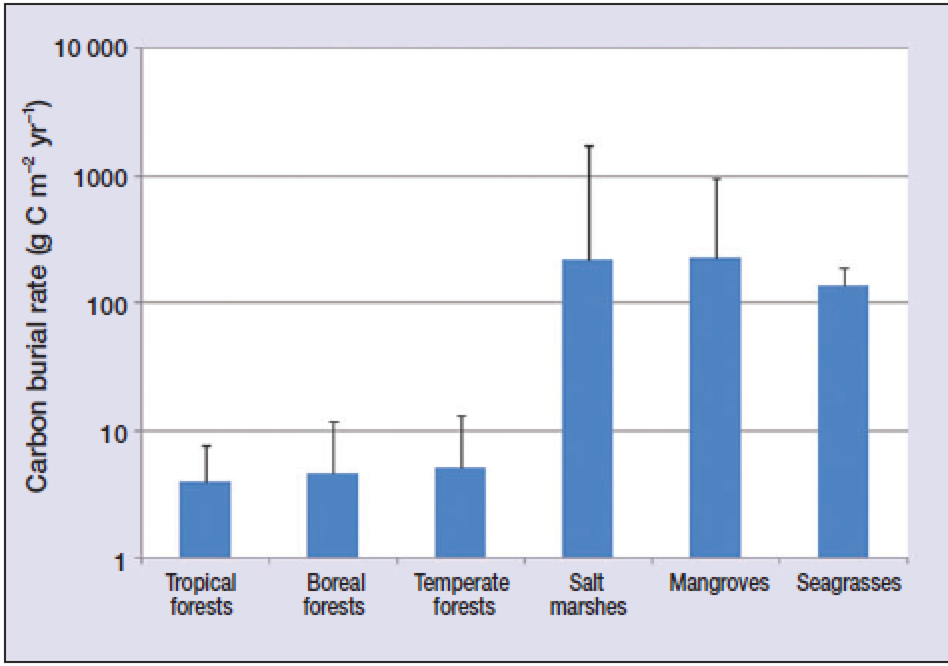
Tg C/y	PP	R	NCP	E/S/A
Mangrove	417	373	214	22-26
Marsh	1438	904	634	46-60
Sea grass	628	228	400	25-27

Can we iterate to a more comprehensive assessment of the 'global' estimate of the sequestration of **Blue Carbon**?

We need to consider:

Usual coastal suspects (Seagrass, mangroves, etc.)
Macroalgae,
Pelagic oceans,

McCloud et al 2011



Carbon storage rates differ in terrestrial and marine habitats and among ecoregions within habitats

Laffoley and Grimsditch 2009

Ecosystem type	Standing carbon stock (gC m^{-2})		Total global area (*10^{12} m^2)	Global carbon stocks (PgC)		Longterm rate of carbon accumulation in sediment (gC m^{-2} yr^{-1})	Tg C/y
	Plants	Soil		Plants	Soil		
Tidal Salt Marshes			Unknown (0.22 reported)			210	46
Mangroves	7990		0.157	1.2		139	22
Seagrass meadows	184	7000	0.3	0.06	2.1	83	25
Kelp Forests	120-720	na	3.5	~5	na	na	173
Phytoplankton			**~300**	**0.2 pg C**			**~ 1000 (700-1300)**

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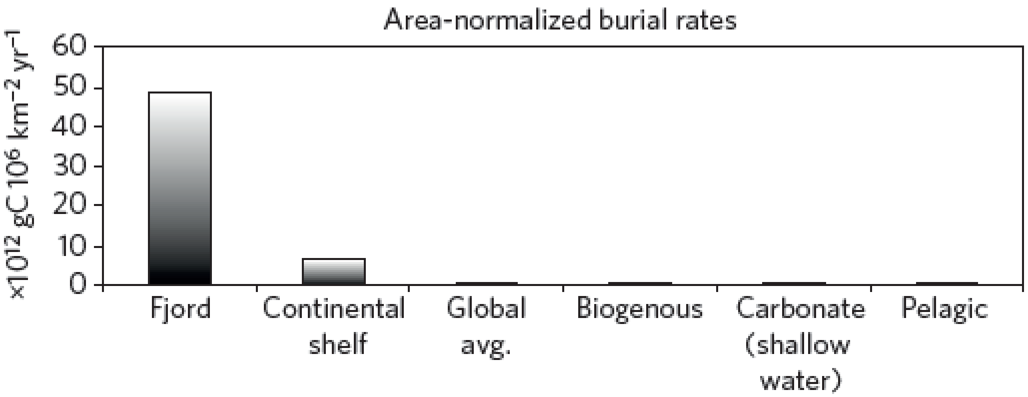
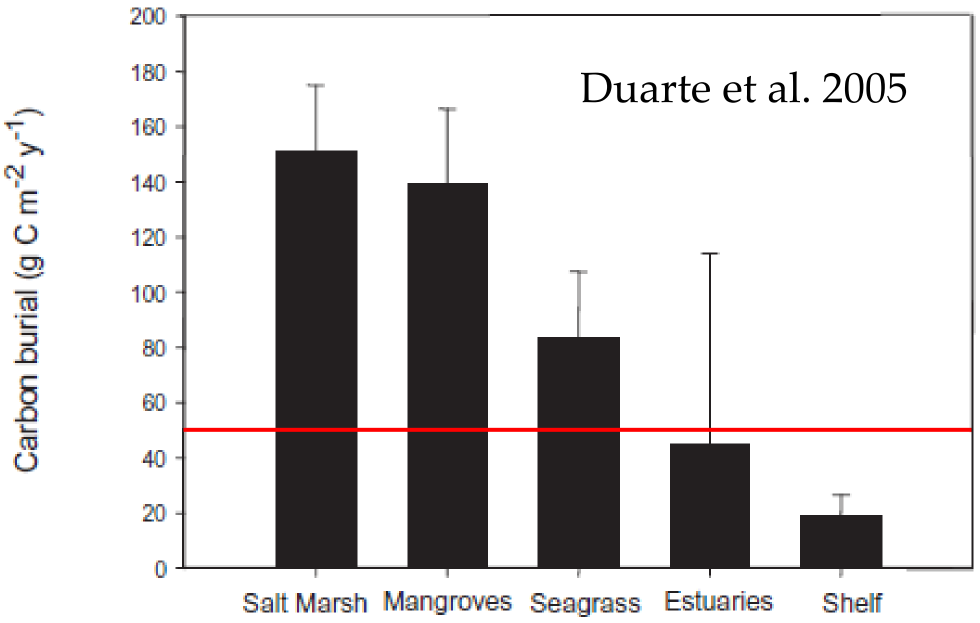
Mangrove	417	373	214	22-26
Marsh	1438	904	634	46-60
Sea grass	628	228	400	25-27
Macroalgae	1521	576	945	173
Phytopl.	50,000	5,500	44,500	1,000

Smith et al 2015



The surface area of fjords (0.45 x 10^6 km^2) is small relative to, continental shelves (~20 x 10^6 km^2); biogenous sediments (~45x 10^6 km^2); shallow water carbonates (~46x 10^6 km^2) and the pelagic ocean (~284x 10^6 km^2)

We need to consider the input from fjords.



Organic carbon sedimentation in marine environments
(Middelburg 2015; Goldshmidt conference)

Environment Tg C/y	Berner 1982	H&K 1985	Revised with Smith et al. 2015
Deltaic	104	70	
Mangrove			26
Salt Marsh			60
Seagrass			27
Estuaries			81
Fjord			20 Sum=214
Shelf	6	68	120 Sum=335
High-Productivity	10	10	10
Pelagic	5	5	5
TOTAL	126	160	350

The contribution of near shore carbon burial may be greater that burial in the deep ocean!

But there are other forms of carbon sequestration.

Researchers of both **Blue Carbon** and ocean biogeochemistry may be missing some important components of the marine carbon that is sequestered…

Macroalgae ~175 TgC/y
Sum = 510 Tg C/y

BCP + MCP ~1000 Tg C/y

Recalculation of the sequestration of global **Blue Carbon** in the ocean.

Tg C/y	PP	R	NCP	E/S/A
Mangrove	417	373	214	22-26
Marsh	1,438	904	634	46-60
Sea grass	628	228	400	25-27
Macroalgae	1,521	576	945	173
Phytoplankton	50,000	5,500	44,500	1,000
Fjords				*20*
	Total	**Blue Carbon**		**1,296**

…As we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns—the ones we don't know we don't know… (Secretary of State Donald Rumsfeld; February 12, 2002).

As we gain knowledge, we realize that we have overlooked important features of the biota, the environment and their interactions.

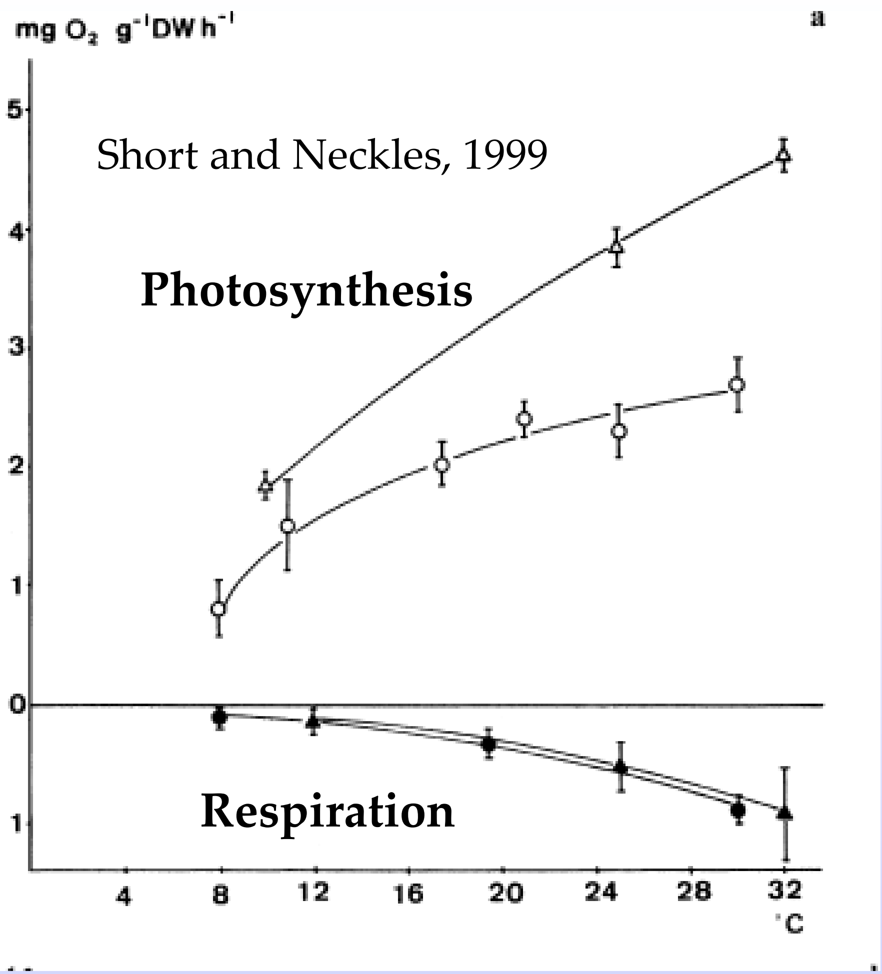

Thank you for your attention

Climate mediated changes in sea level and temperature will to affect coastal zone carbon sequestration.

The fixation of carbon via primary productivity is an essential ecosystem function and any shifts in the balance of primary productivity and respiration could alter the carbon balance of ecosystems.

Temperature influences production (photosynthesis) and loss (respiration) and this in turn may alter growth and mortality rates, and metabolism and overall energy and mass balance.

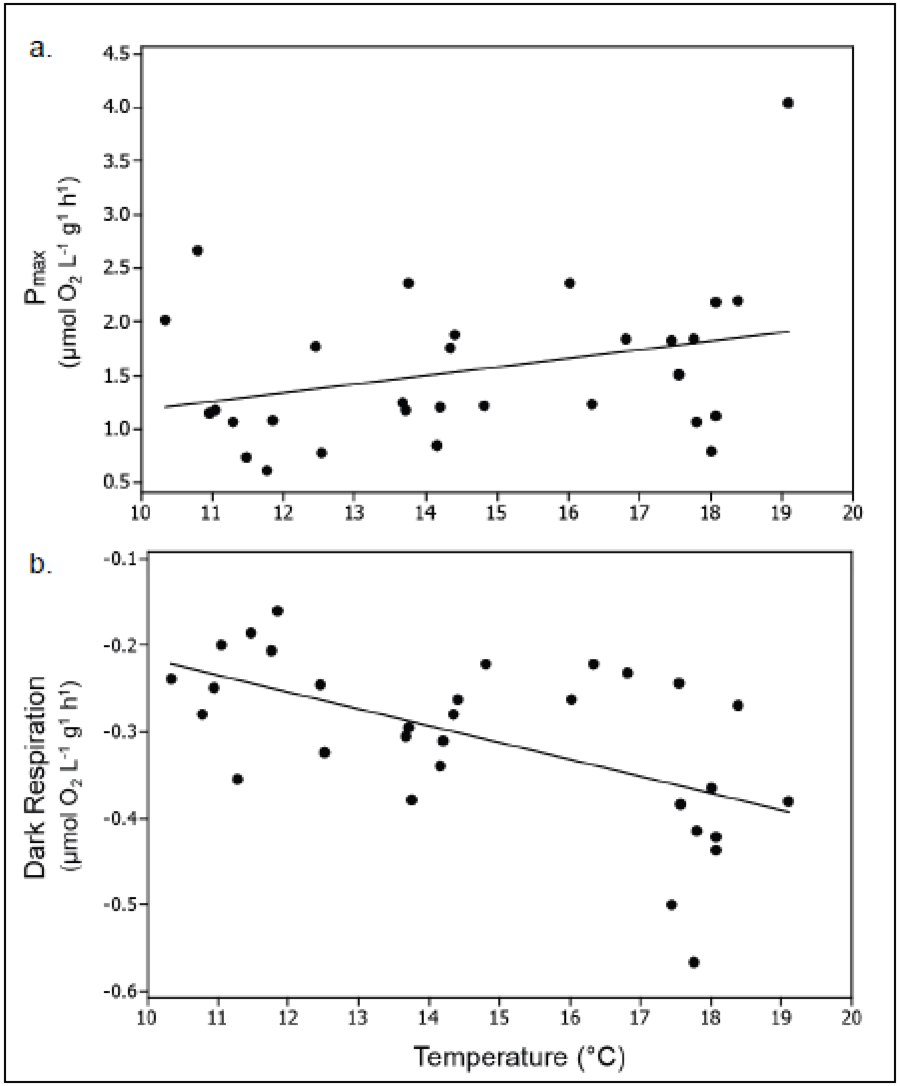
What is the effect of temperature on some of the **Blue Carbon** components?



For the seagrass, *Cymodocea nodosa,* the temperature dependent trends of photosynthesis and respiration differed and leads a greater P/R ratio at high than low temperatures.

The consequence is a higher NPP at high temperatures due to a lower remineralization rate of carbon

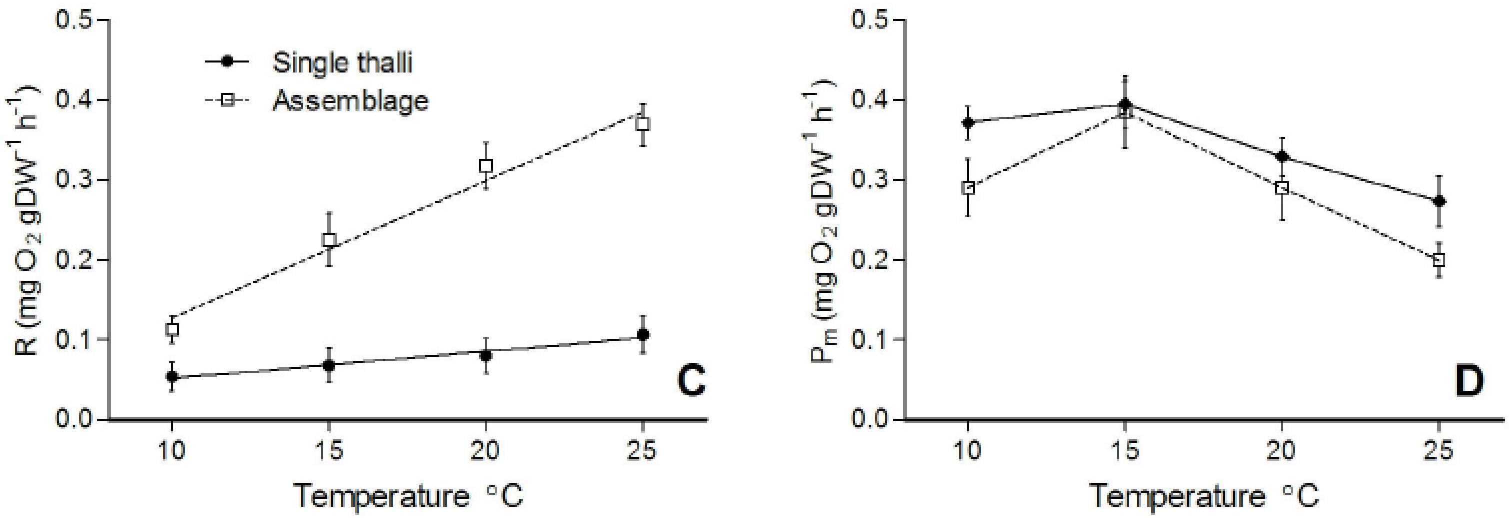
Ewers 2013



Similar temperature dependent pattern for photosynthesis and respiration in *Zostera marina,* Respiration rates *Hormosira banksia* dominated population with increasing temperature (Q_{10} ~ 2) whereas there was no significant increase in photosynthesis. Leads to a decrease in NPP with increasing temperatures. *Tait and Schiel 2013*

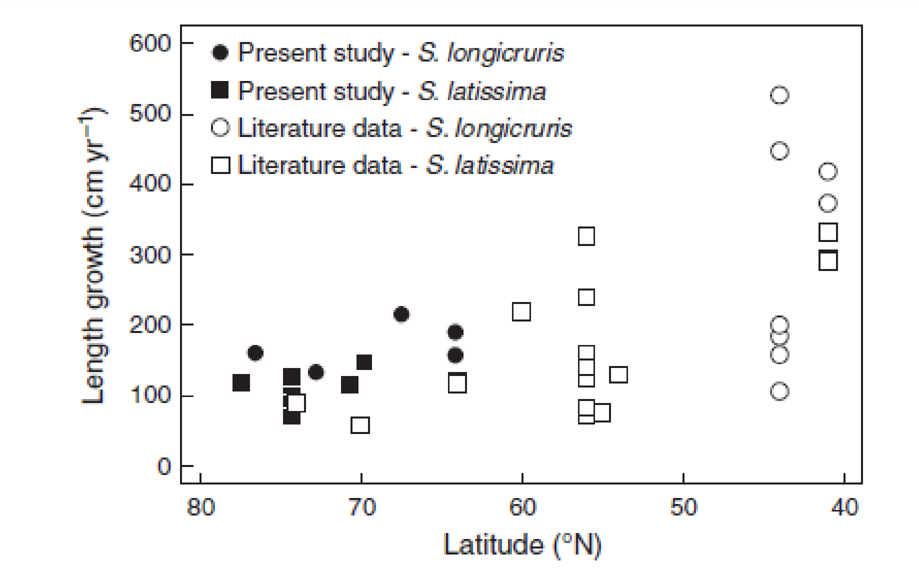
Temperature	*R* (mg O2 gDW^{-1} h^{-1})	P_m (mg O2 gDW^{-1} h^{-1})
8-12°C	0.12 (0.02)	0.57 (0.04)
13-17°C	0.16 (0.02)	0.6 (0.02)
18-22°C	0.24 (0.03)	0.58 (0.05)
ANOVA		
$F_{2,9}$	9.5	0.35
p	0.014	ns

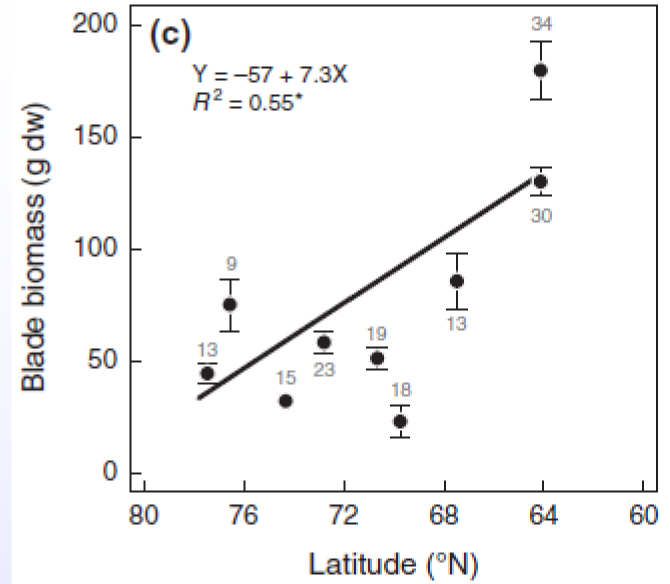
Tait and Schiel 2013

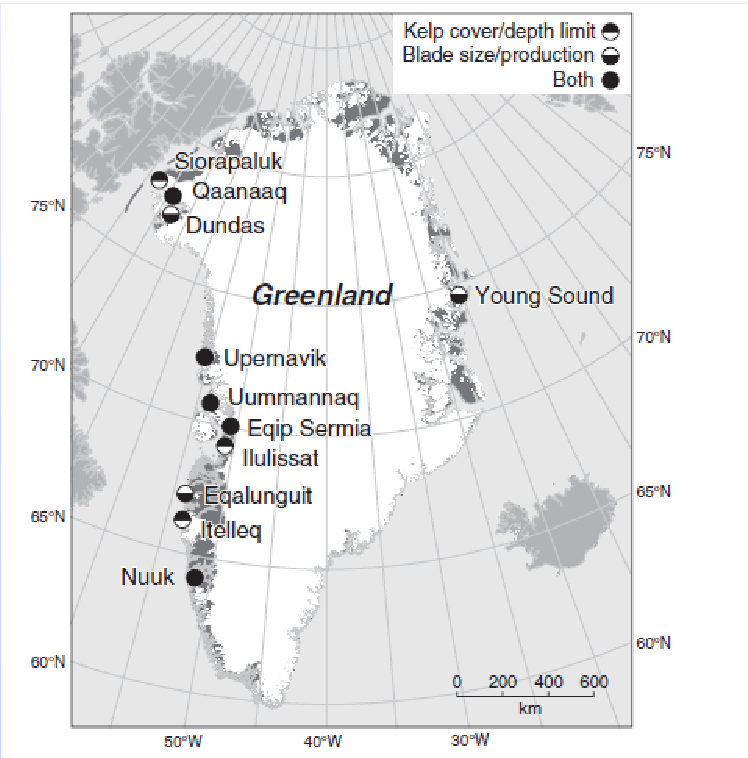


Increasing temperatures may affect macroalgal assemblages by increasing respiration and shifting the ratio of photosynthesis to respiration and decreasing NPP and reduced biomass accumulation.

Krause-Jensen et al 2012



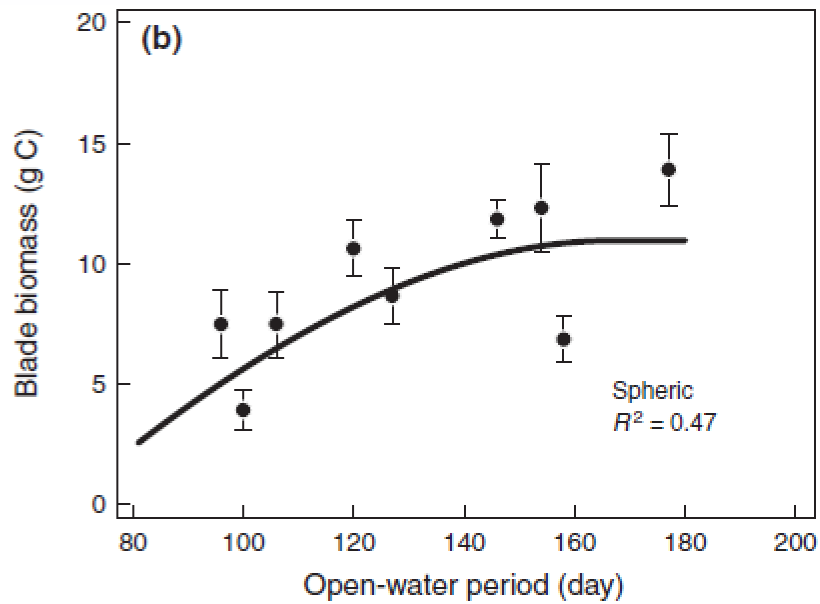


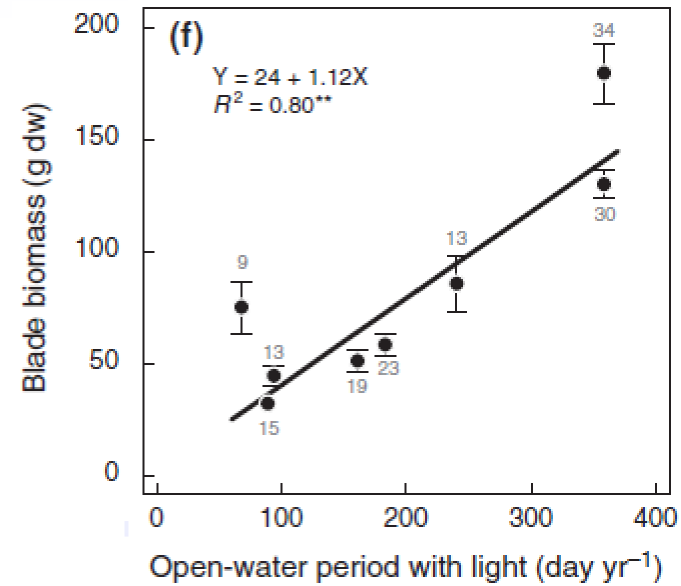


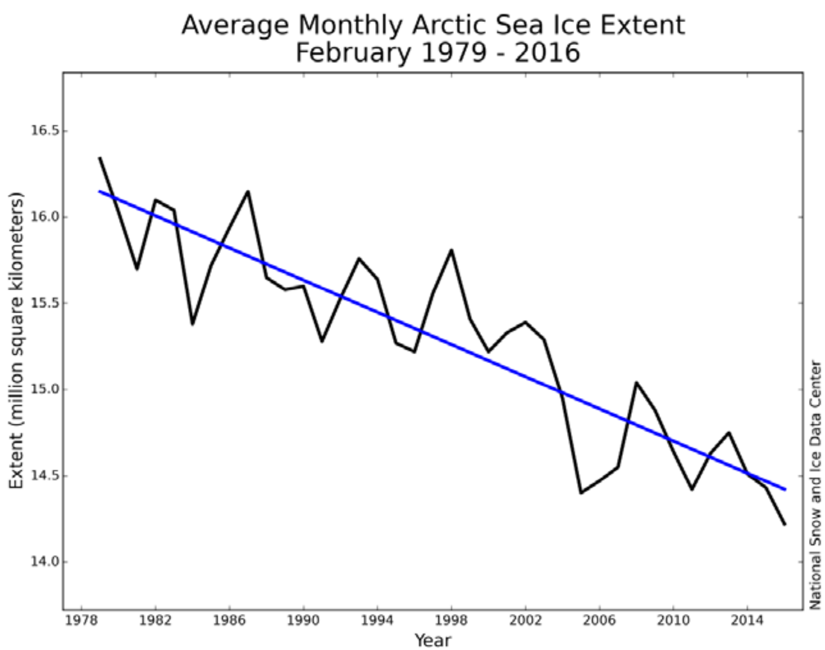
The distribution and production of kelp along the Greenland coast spanning from 78 ºN to 64 ºN.

Strong inverse relationship between latitude and both growth rate and biomass.

Krause-Jensen et al 2012







Strong and positive relationship between biomass and illuminated open water.

What is the impact of climate mediate reduction in ice cover?

Thank you for your attention