Using Ecogeomorphology Models to Scale Global Estimates of Biomass, Productivity and Carbon Dynamics in Mangrove Ecosystems

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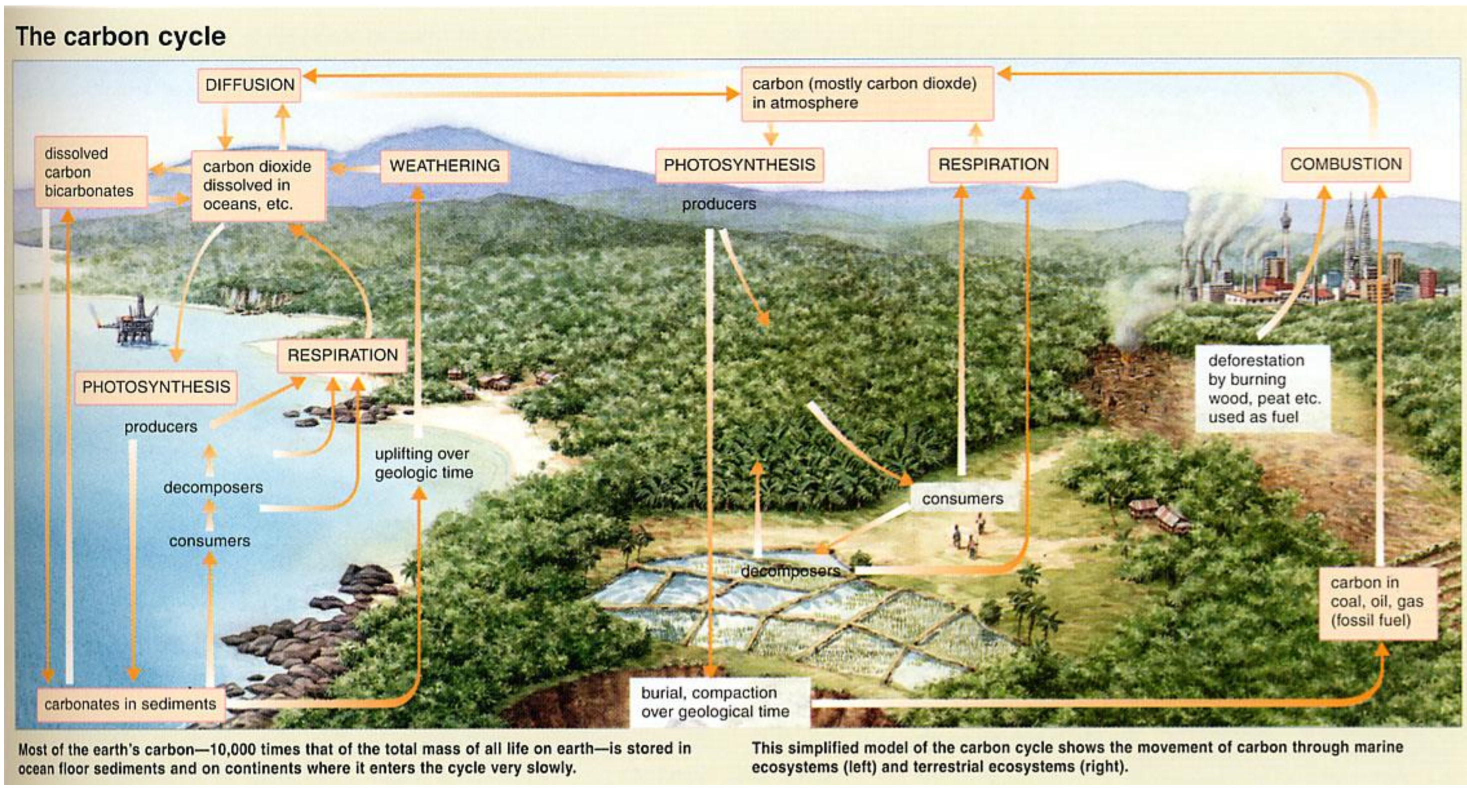
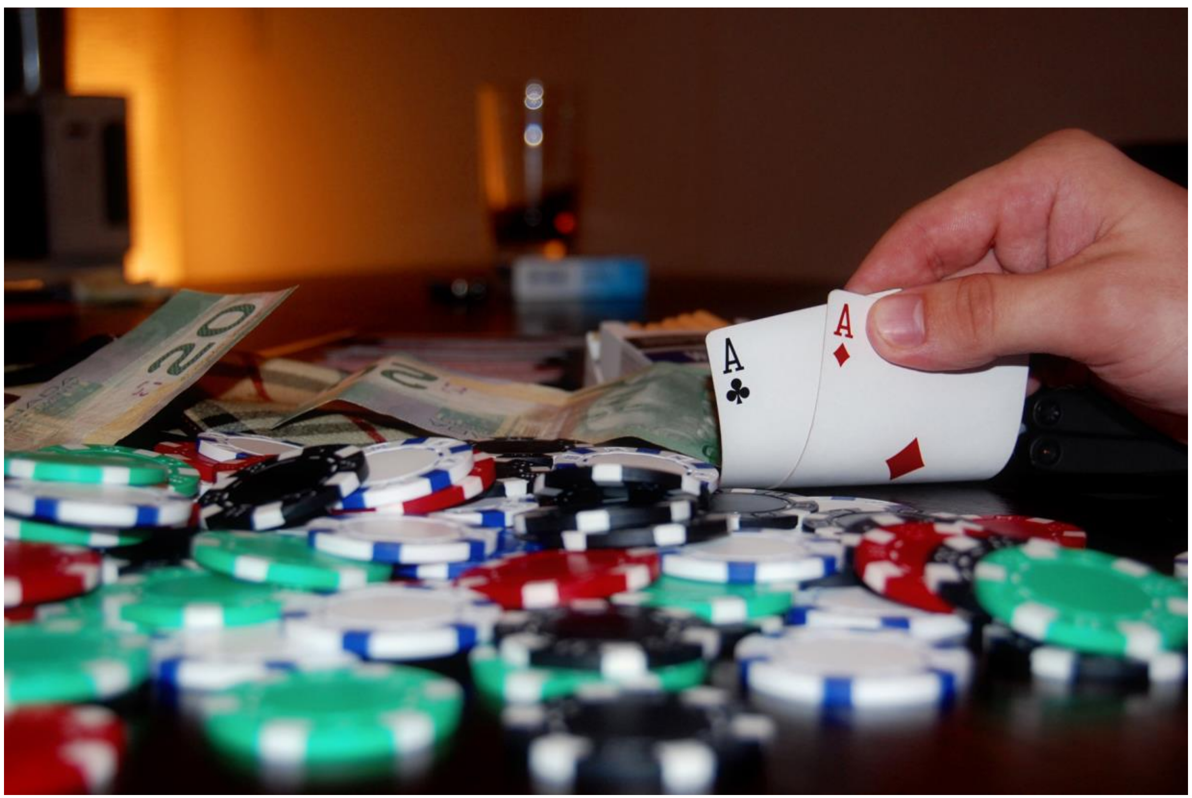


LSU

Mangrove and Macrobenthos Meeting (MM4) 2016

St. Augustine, Fla, July 20, 2016

1. Reflections on Mangrove Carbon – The carbon ‘ante’



Twilley, R.R., R.H. Chen, and T. Hargis. **1992**. Carbon sinks in mangroves and their implications to carbon budget of tropical coastal ecosystems.

Water, Air and Soil Pollution 64: 265-288.

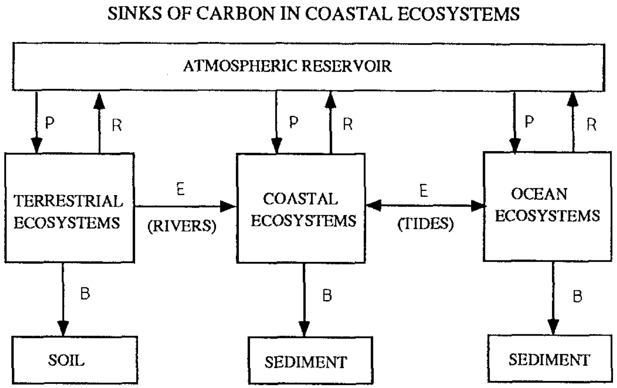


Figure 1. Conceptual diagram of the three major compartments of the biosphere that influence the global cycle of C. P = production, R = respiration, E = exchange, B = burial.

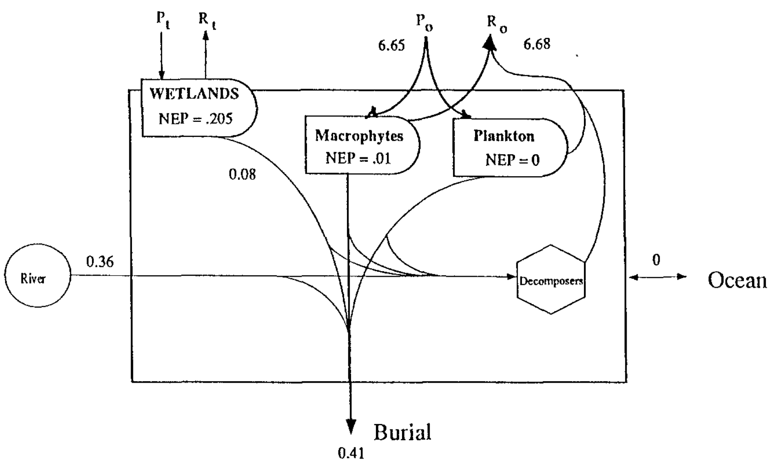


Figure 10. Mass balance of C for coastal ecosystems based on estimates of in situ net production and allochthonous inputs, minus losses associated with burial in coastal sediments. P and R represent net production and heterotrophic respiration, respectively, with exchange of CO_2 directly with atmosphere (t) or coastal waters (o).

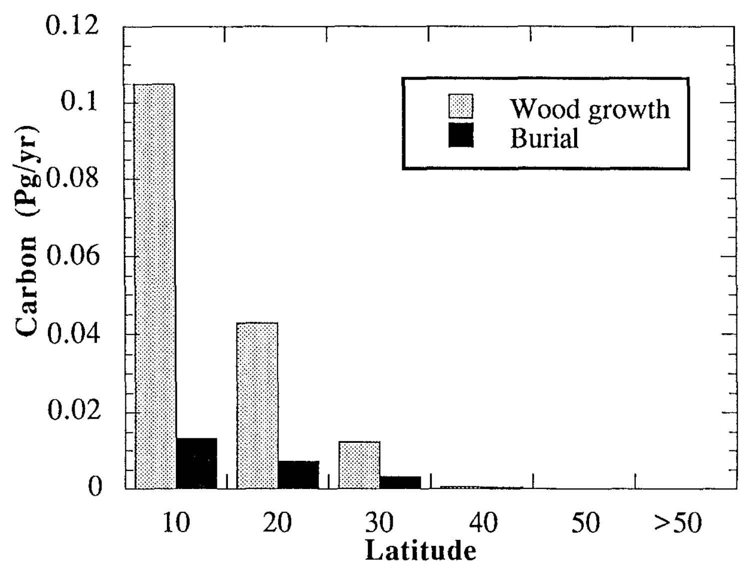
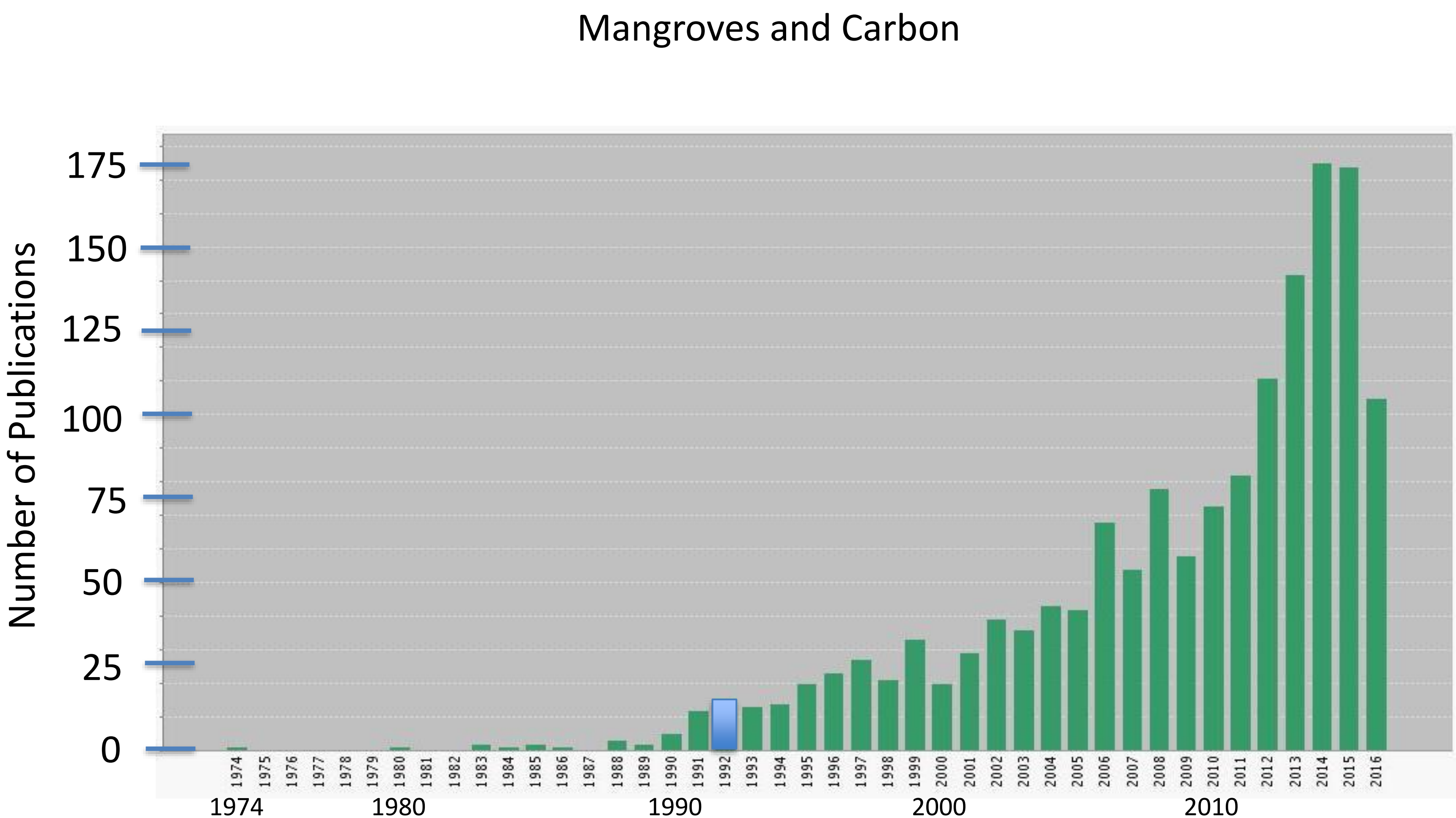


Figure 4. Estimates of annual carbon storage in mangrove wood and sediments.



Mangroves and Carbon
Number of Publications
175
150
125
100
75
50
25
0
1974
1980
1990
2000
2010

A blueprint for blue carbon

A blueprint for blue carbon

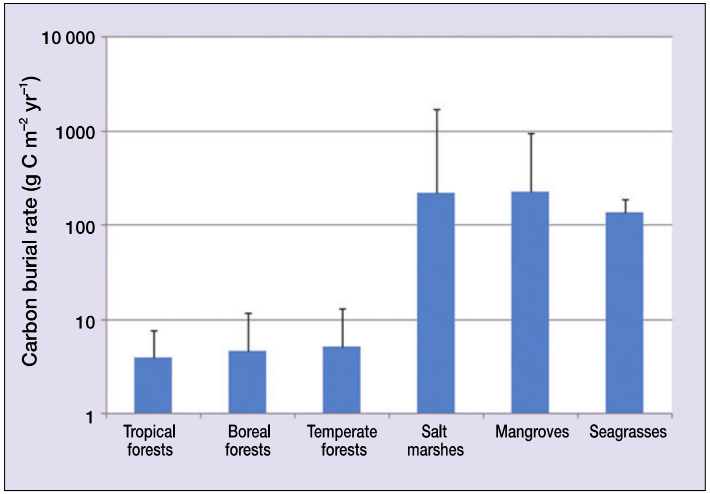
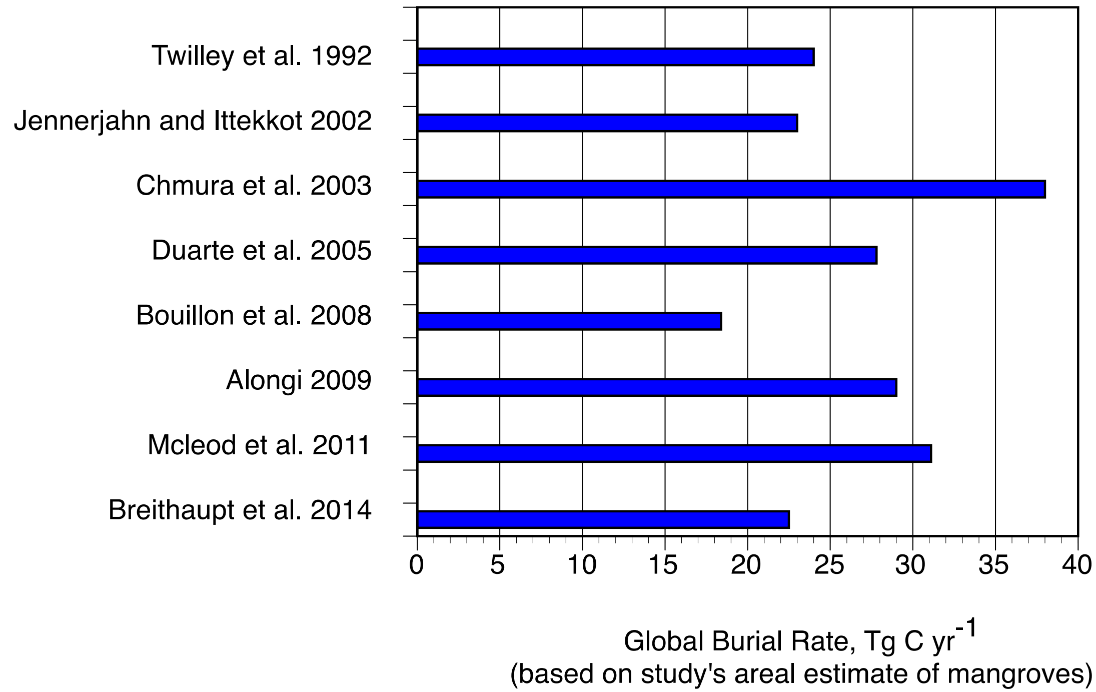


Figure 5. *Mean long-term rates of C sequestration (g C m^{-2} yr^{-1}) in soils in terrestrial forests and sediments in vegetated coastal ecosystems. Error bars indicate maximum rates of accumulation. Note the logarithmic scale of the y axis. Data sources are included in Tables 1 and 2.*



Mcleod, E., G. L. Chmura, S. Bouillon, R. Salm, M. Björk, C. M. Duarte, C. E. Lovelock, W. H. Schlesinger & B. R. Silliman, 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. Frontiers in Ecology and the Environment 9: 552-560

Breithaupt, J. L., J. M. Smoak, T. J. Smith, C. J. Sanders, and A. Hoare (2012), Organic carbon burial rates in mangrove sediments: Strengthening the global budget, Global Biogeochem. Cycles, 26, GB3011, doi:10.1029/2012GB004375

2. Developing Global Models of Carbon Sources and Sinks

(Setting the Context of Unidentified Carbon Flux – Carbon Mitigation)

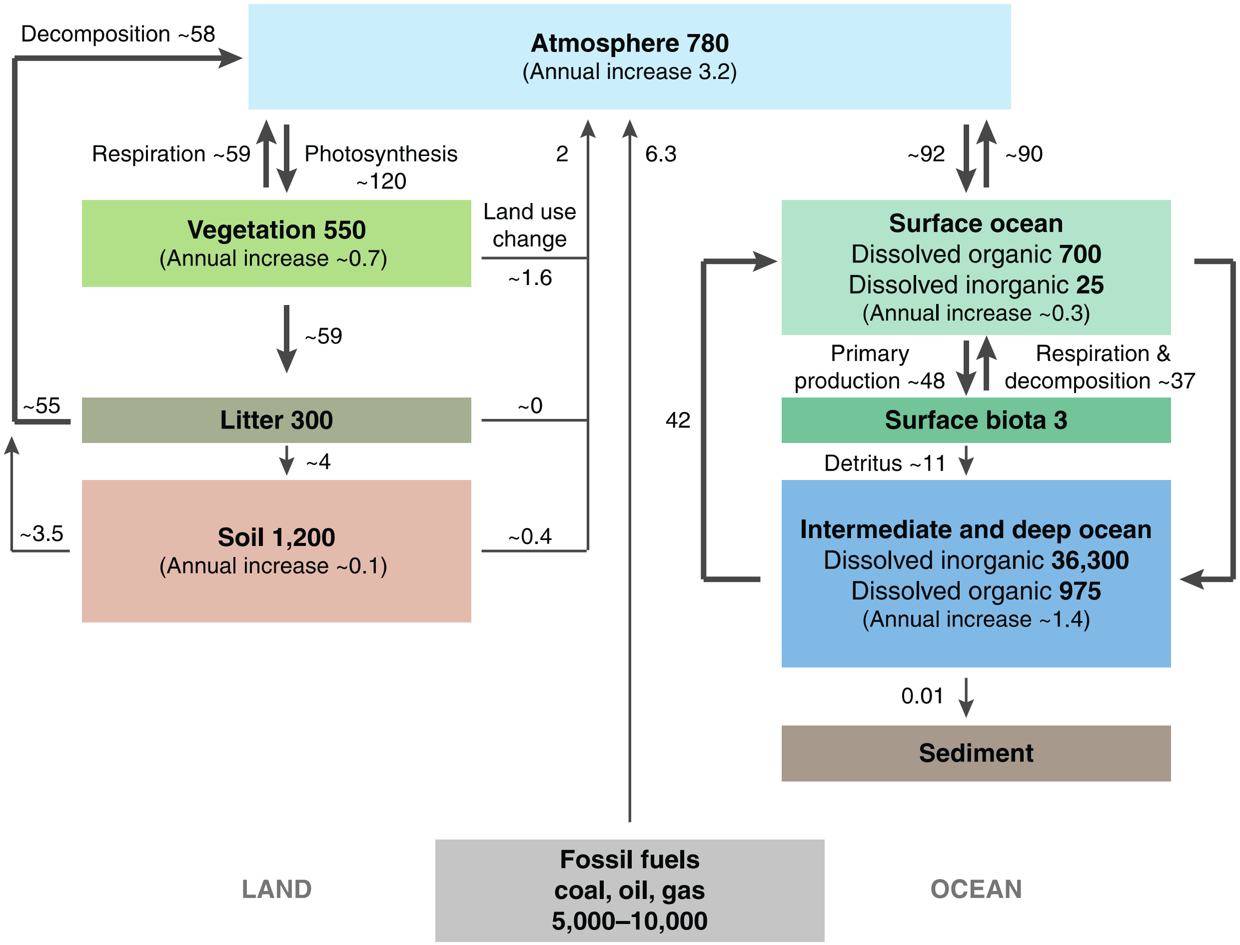
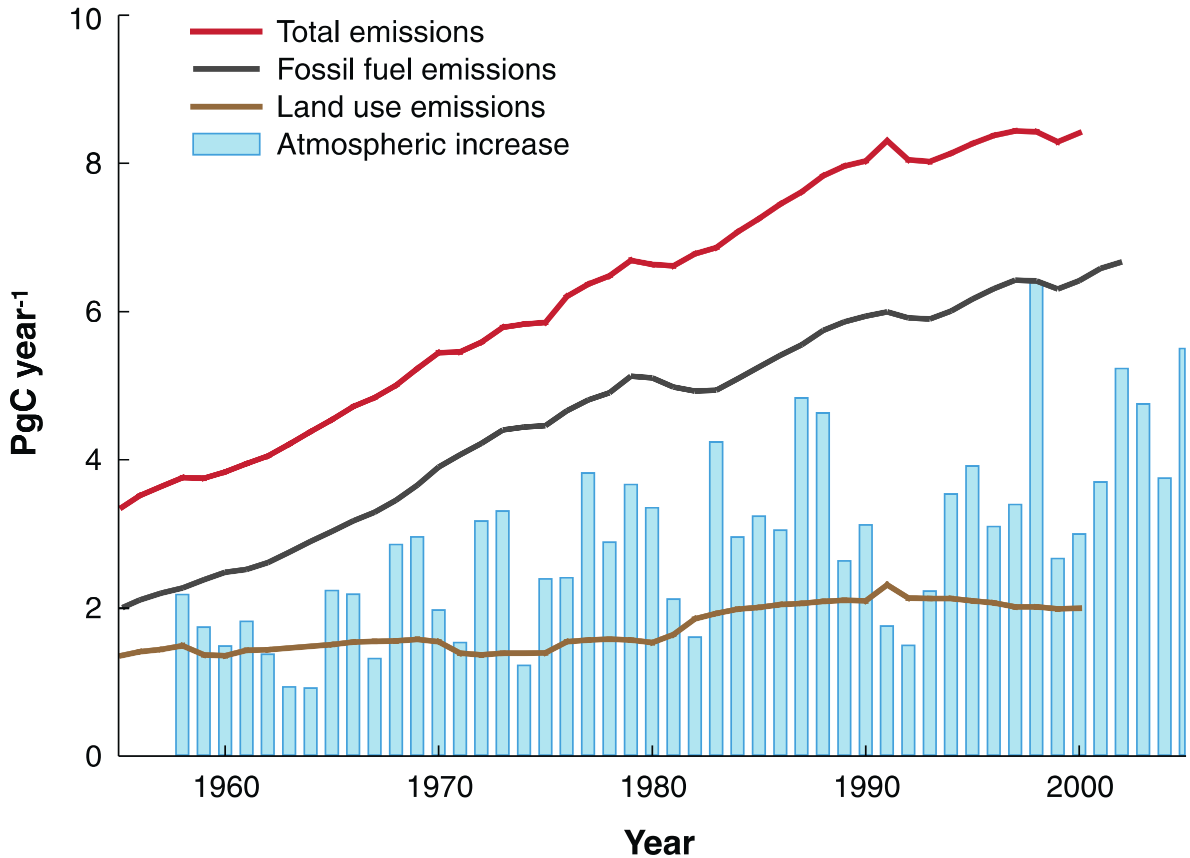


Figure 1

The global carbon cycle in the 1990s. Units are PgC or PgC year^{-1}.

Houghton, R.A. 1994. The worldwide extent of land-use change. Bioscience, 44(5), 305-313.

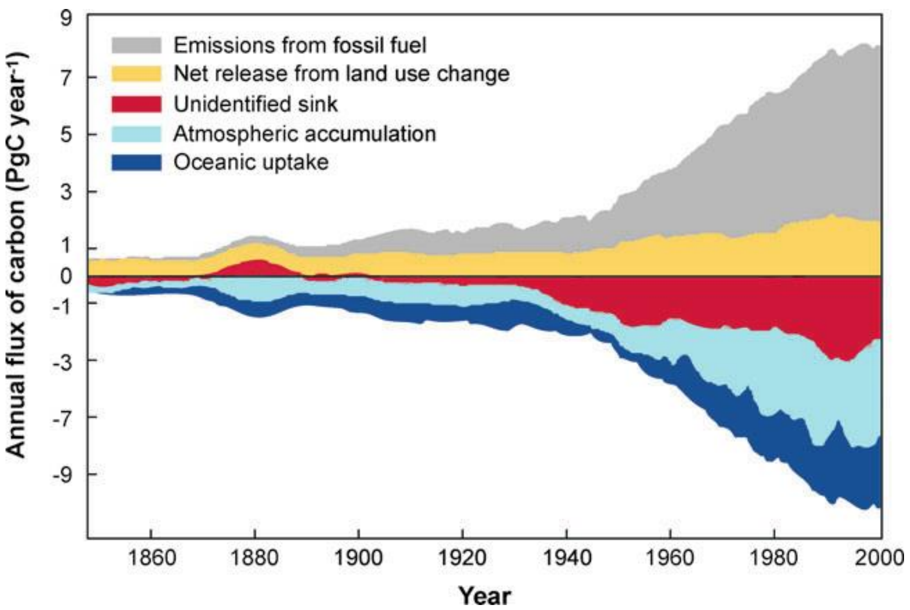
Houghton, R.A., 2007. Balancing the global carbon budget. Annu. Rev. Earth Planet. Sci., *35*, pp.313-347.



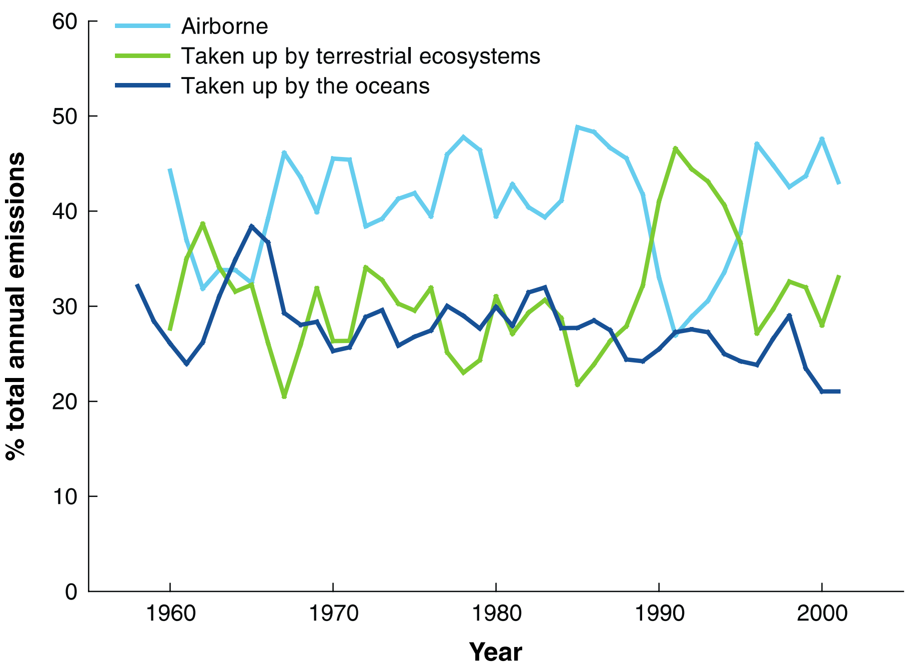
Annual emissions of carbon from the combustion of fossil fuels and from changes in land use, and the annual increase in atmospheric CO2 (in PgC) over the period 1958 to 2005.

Houghton, R.A., 2007. Balancing the global carbon budget. Annu. Rev. Earth Planet. Sci., *35*, pp.313-347.

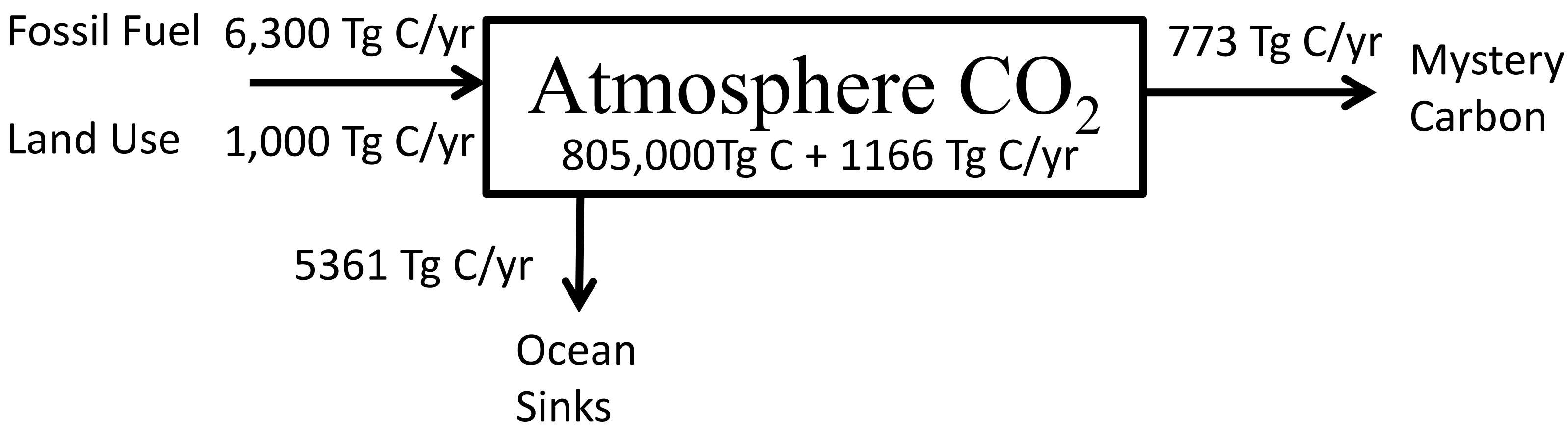
Annual sources and sinks of carbon from 1850 to 2000 for a balanced carbon budget (total sources are balanced by total sinks). The unidentified sink is the residual terrestrial sink.



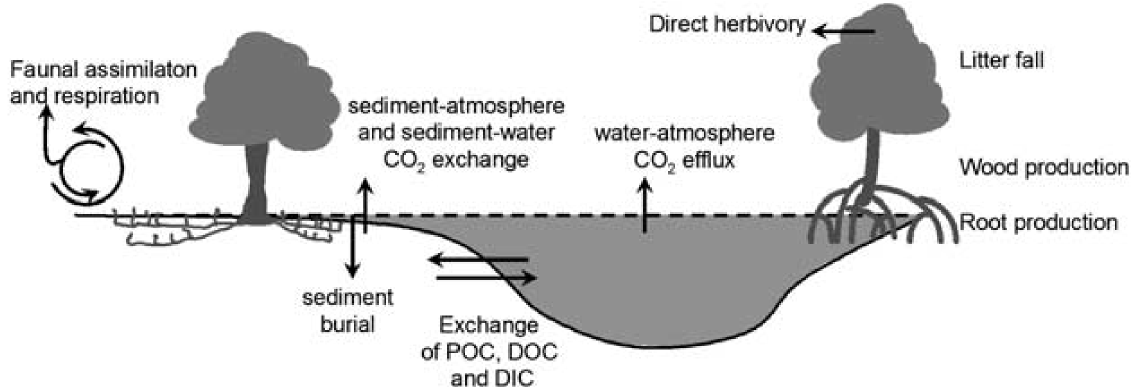
The fractions of total annual emissions (fossil fuel plus land-use change) accumulating in the atmosphere, oceans, and land (from Canadell et al. 2007). The anomaly in the early 1990s coincides with the eruption of Mt. Pinatubo in 1990. The values are 5-year running averages.

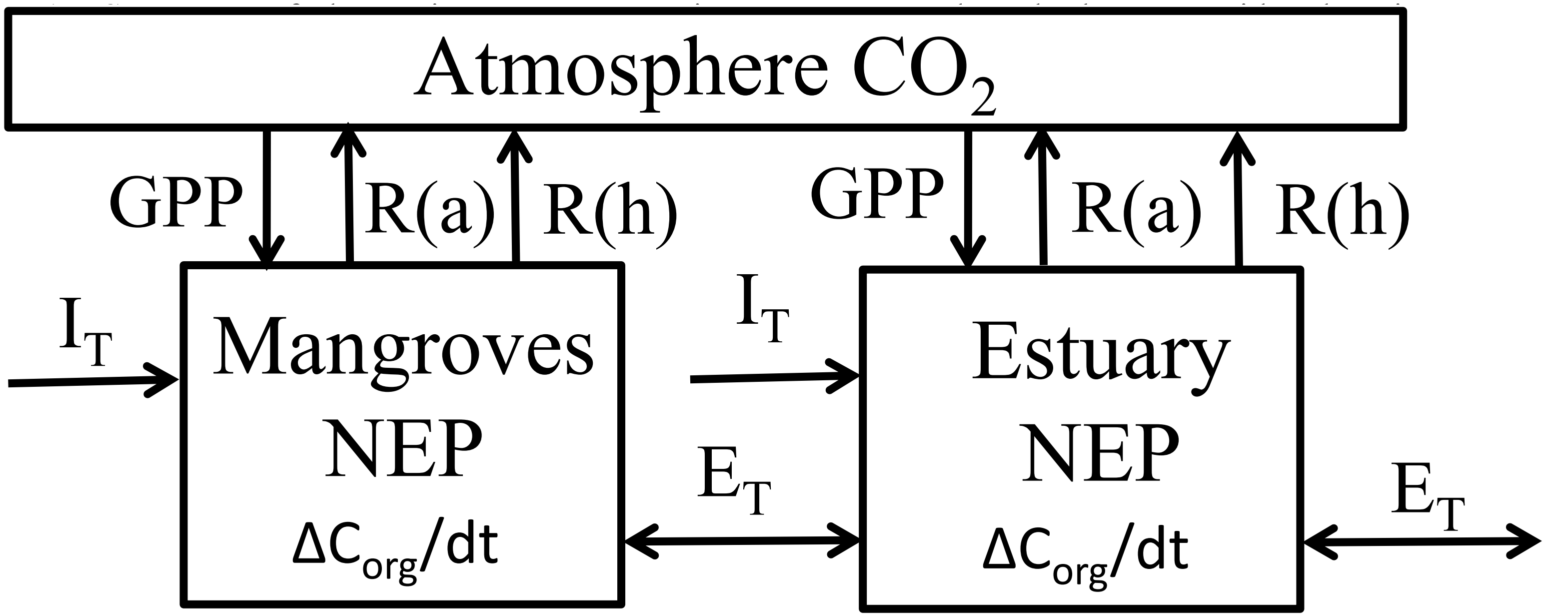


Houghton, R.A., 2007. Balancing the global carbon budget. Annu. Rev. Earth Planet. Sci., *35*, pp.313-347.


Fossil Fuel
6,300 Tg C/yr
Land Use
1,000 Tg C/yr
Atmosphere CO_2
805,000Tg C + 1166 Tg C/yr
773 Tg C/yr
Mystery Carbon
5361 Tg C/yr
Ocean Sinks

Bouillon, S., A.V. Borges, E. Castañeda-Moya, K. Diele, T. Dittmar, N.C. Duke, E. Kristensen, S.Y. Lee, C. Marchand, J.J. Middelburg, V.H. Rivera-Monroy, T.J. Smith, and R.R. Twilley. 2008. Mangrove production and carbon sinks: A revision of global budget estimates. Global Biogeochemical Cycles 22: 1-12



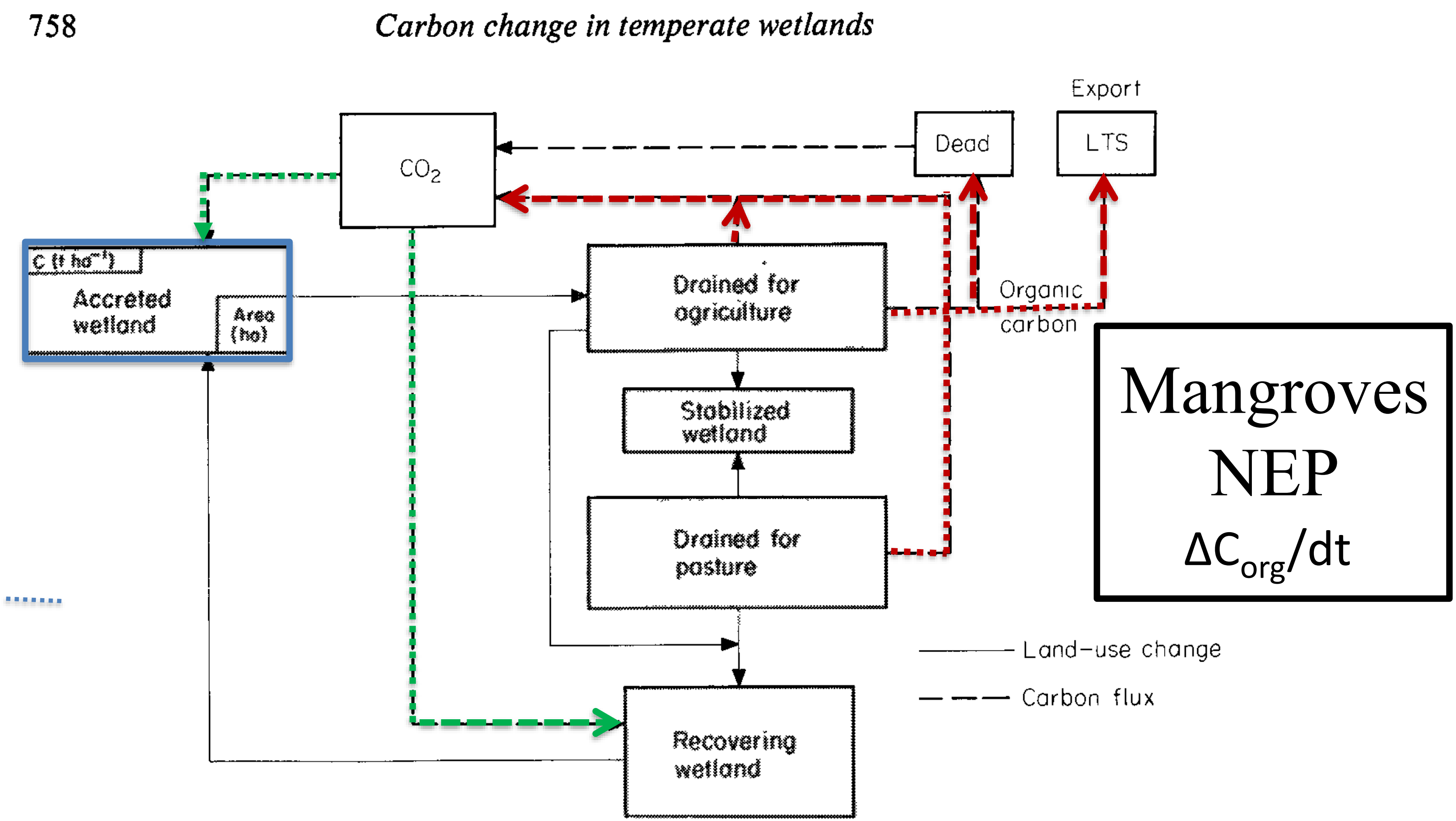


$$NEP = (GPP + I_T) - (Re + E_T)$$

$$E_T = DIC + DOC + PC \text{ (Surface and Ground Water)}$$

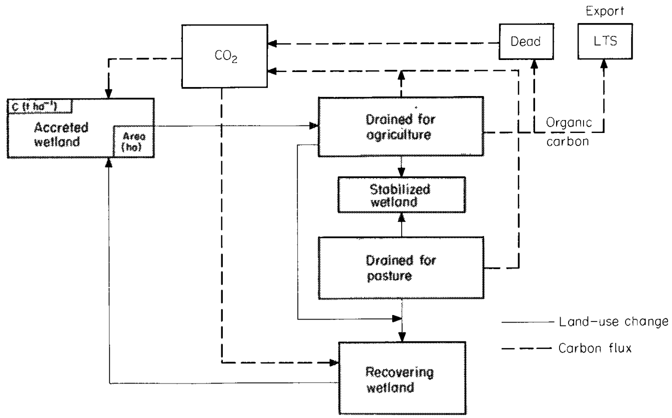
$$I_T = DIC + DOC + PC \text{ (Surface and Ground Water)}$$

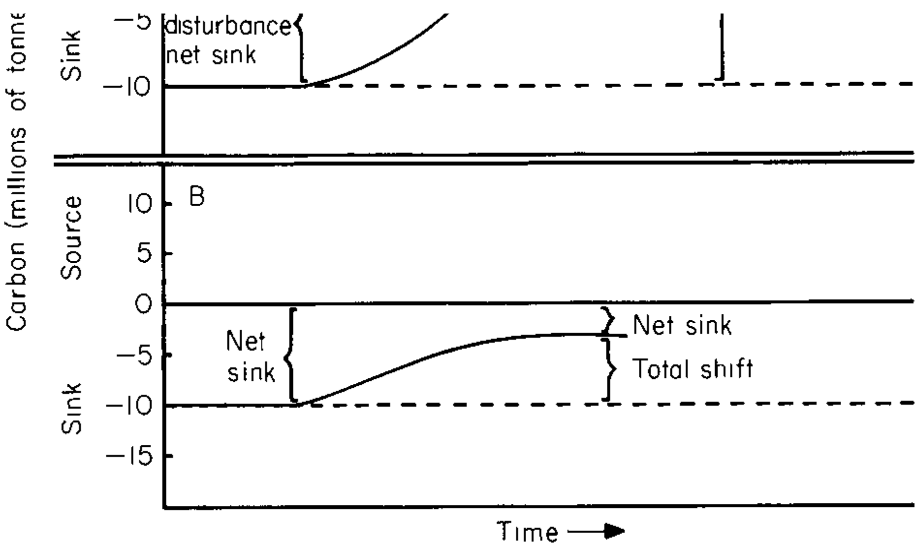
Land-use changes and carbon fluxes in simulation of wetland carbon exchange. Dead plant material is indicated as ‘Dead’ and long-term storage as reduced carbon (mostly exported in drainage waters) as LTS. Stabilized wetlands have depleted organic soils and no longer release carbon. (Armentano and Menges 1986)



Armentano, T.V. and Menges, E.S., 1986. Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. The Journal of Ecology, pp.755-774

758 *Carbon change in temperate wetlands*





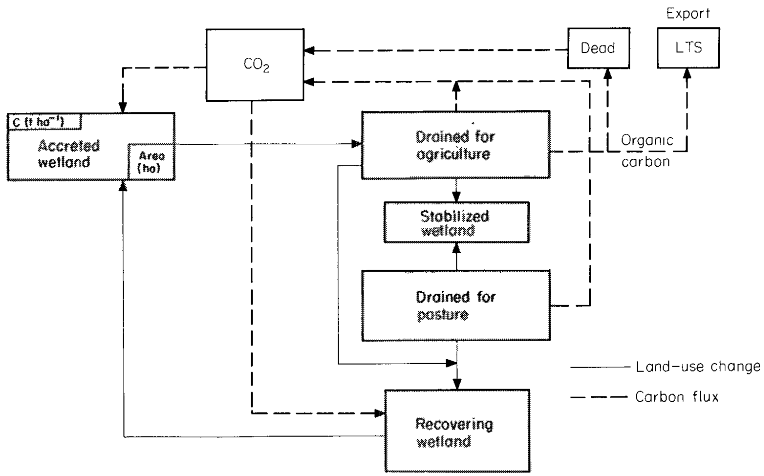
Definitions of carbon sources and sinks as exchanged with the atmosphere using two hypothetical wetland regions subject to disturbance. (A) The original net carbon sink is totally lost by the changes in ecosystem processes in response to disturbance, to condition where a net carbon source of carbon to atmosphere from the wetland has been created. (B) The wetland regionally currently functions as a diminished carbon sink because CO_2 release in disturbed wetlands is lower that net CO_2 fixation in undisturbed wetlands; with a modification to demonstrate that carbon sinks can actually increase in some scenarios following a disturbance by increasing NEP (net ecosystem production).

Carbon exchange in two hypothetical wetland regions subject to artificial drainage. In
al net carbon sink is totally lost, and a net carbon source has been created. In B, 1
rrently functions as a diminished carbon sink because CO_2 release in drained wetlan
is lower than net CO_2 fixation in undrained wetlands.

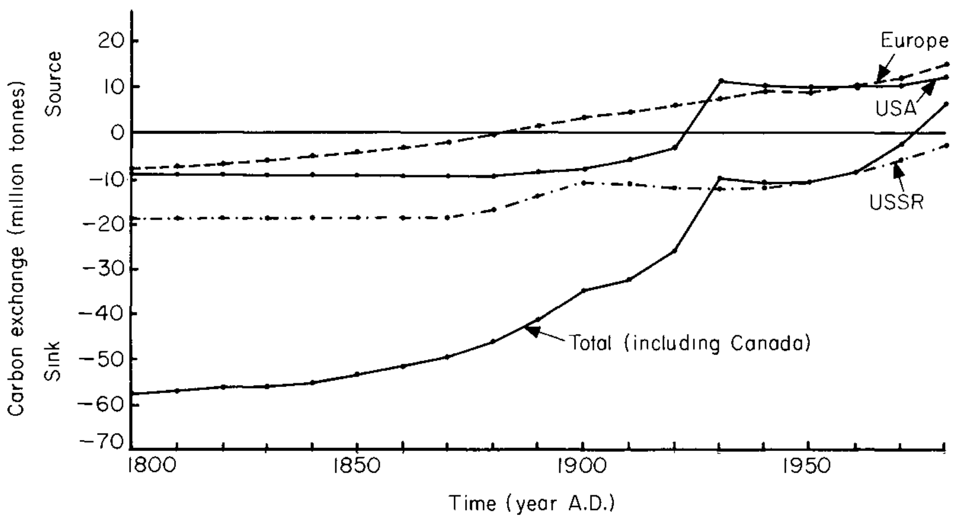
Net sink
Increase shift

Armentano, T.V. and Menges, E.S., 1986. Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. The Journal of Ecology, pp.755-774

758 *Carbon change in temperate wetlands*



Carbon change in temperate wetlands



Land-use changes and carbon fluxes in simulation of wetland carbon exchange. Dead plant material is indicated as ‘Dead’ and long-term storage as reduced carbon (mostly exported in drainage waters) as LTS. Stabilized wetlands have depleted organic soils and no longer release carbon. (Armentano and Menges 1986)

Change with time of CO2 exchange in temperate zone wetlands affected by agricultural drainage (Armentano and Menges 1986)

Armentano, T.V. and Menges, E.S., 1986. Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. The Journal of Ecology, pp.755-774

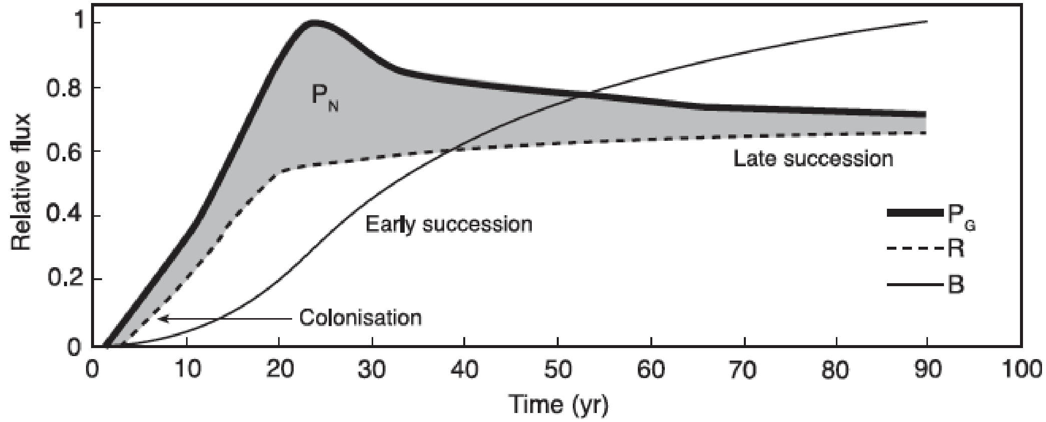
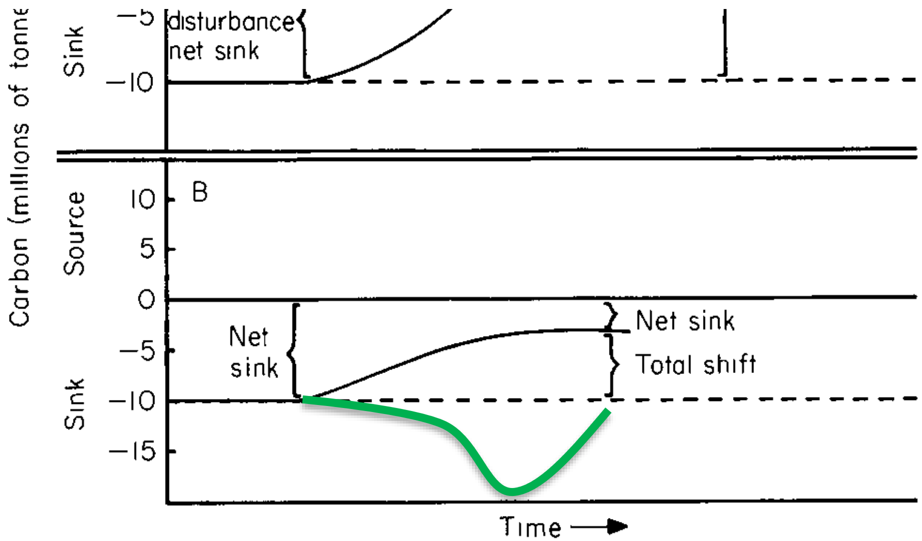


Fig. 1 – The original concept of ecosystem development over time.Modified from Odum (1969).



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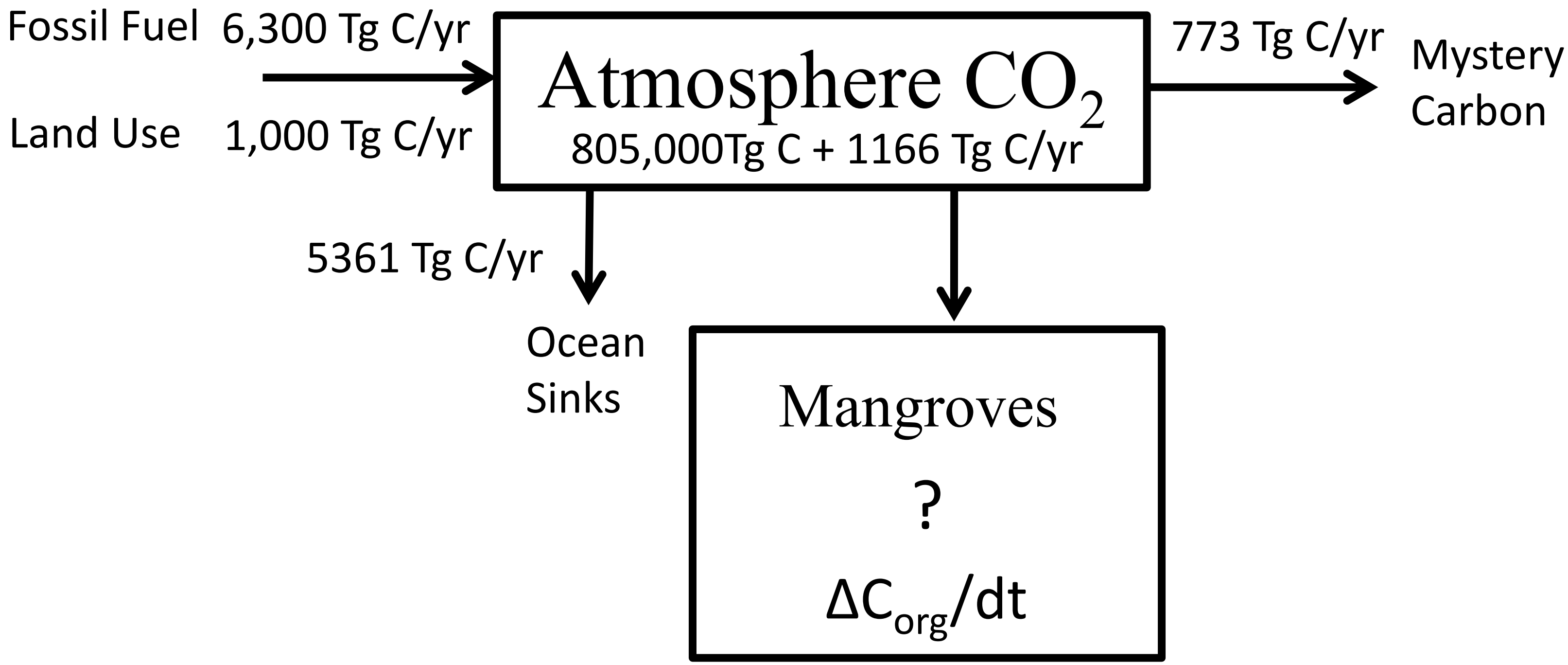
Net sink
Increase shift



Equation (1) subsumes, and partly omits, anthropogenic perturbations to carbon cycling in inland freshwaters, estuaries, and coastal areas that modify both lateral fluxes transported from land ecosystems to the open ocean, "vertical" CO_2 fluxes by outgassing in rivers and estuaries, and the air-sea net exchange of CO_2 in coastal areas. These flows are omitted in the absence of details on the natural versus anthropogenic terms of these facets of the carbon cycle.

Houghton, R.A., 2007. Balancing the global carbon budget. Annu. Rev. Earth Planet. Sci., *35*, pp.313-347.

3. Ecogeomorphology Models to Test Energy Signature Hypothesis


Roc
Mexico


Africa


Micronesia

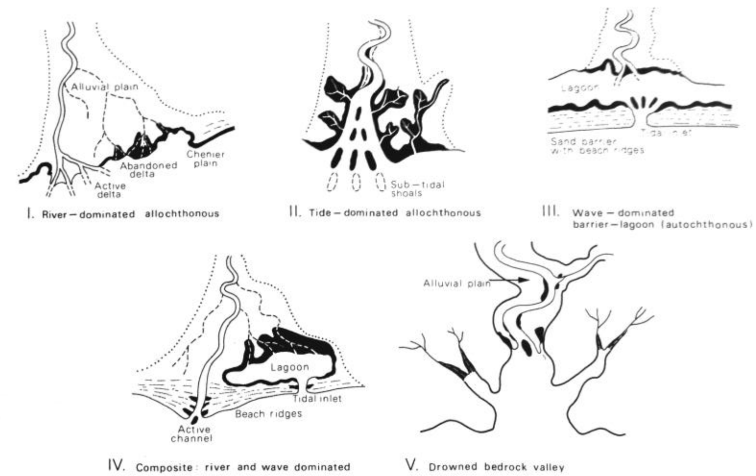
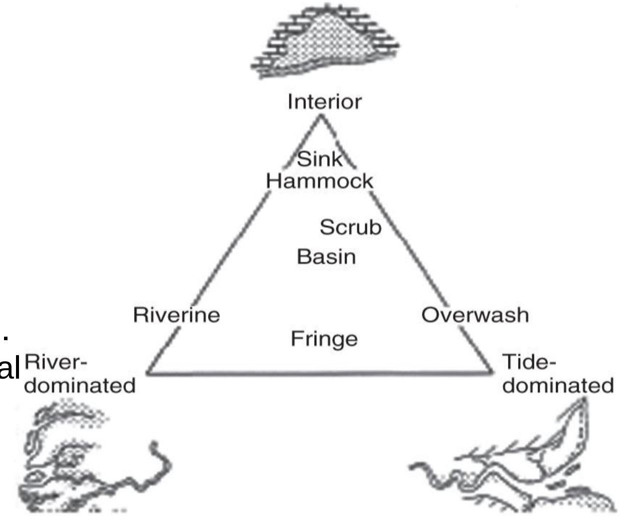


Fig. 1.1. Generalised environmental settings for mangrove colonisation and development (shaded). The five settings occur on coasts dominated by terrigenous deposition and reworking of sand, silt and clay sediments.

Woodroffe, C.D., 1992. Mangrove sediments and geomorphology, pp.7-41. In: A.I. Robertson and D.M. Alongi (eds.) Coastal and Estuarine Studies. American Geophysical Union, Washington, D.C



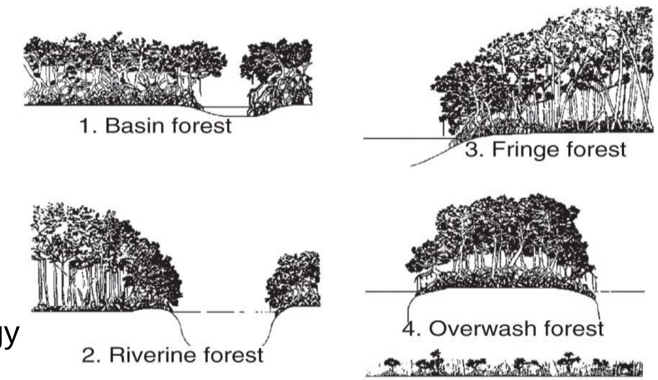
(a)

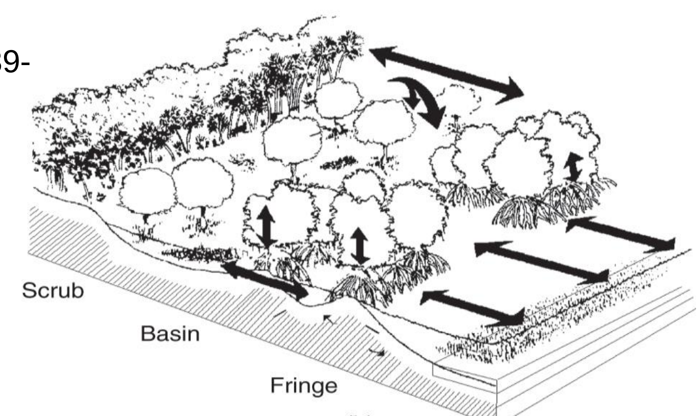
Table 1.1 **Geomorphic and ecologic responses to varying combinations of environmental process variables. Some attempt is made to quantify these variables for large river and open-ocean wave energy conditions (H = high; M = moderate; L = low).**

SETTING	PROCESSES Tide	Rainfall	River discharge	Turbidity	Wave power	GEOMORPHIC RESPONSE Landform diversity	Shoreline stability	ECOLOGIC RESPONSE Zonation diversity	Community stability	EXAMPLE
I	L	H	H	H	L	H	L	H	L	Mississippi
	M	H	H	H	L	H	L	H	L	Orinoco
II	H	H	H	H	L	M	M	M	M	Ganges
	H	L	M	H	L	L	L	L	H	Ord
III	M	M	L	L	H	L	H	L	H	El Salvador
	M	L	L	L	H	L	M	L	M	Senegal
IV	L	H	H	H	M	H	L	H	L	Grijalva
	M	H	H	H	M	M	M	M	L	Burdekin
V	M	M	M	M	H	L	H	L	H	Broken Bay

Tide	H > 4m M 2-4m L < 2m	Rainfall	H > 1500mm M 700-1500mm L < 700mm
River discharge in m³/sec	H > 10000 M 3000 to 10000 L < 3000	Wave power in X10⁷ ergs/sec	H < 100 M 10-100 L > 10

Lugo, A.E. & Snedaker, S.C. (1974) The Ecology of Mangroves, *Annual Review of Ecology and Systematics*, 5, 39-64.

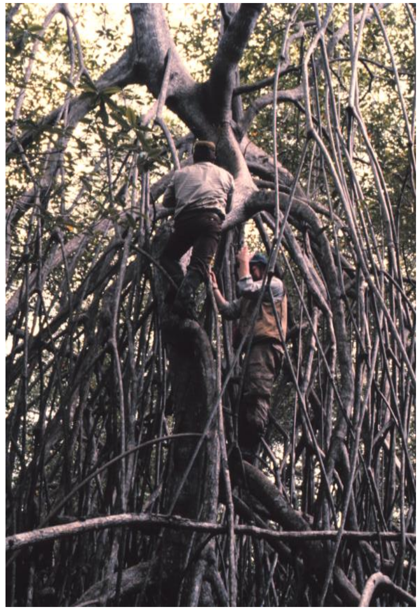


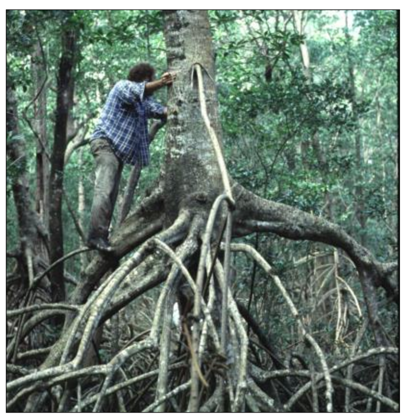


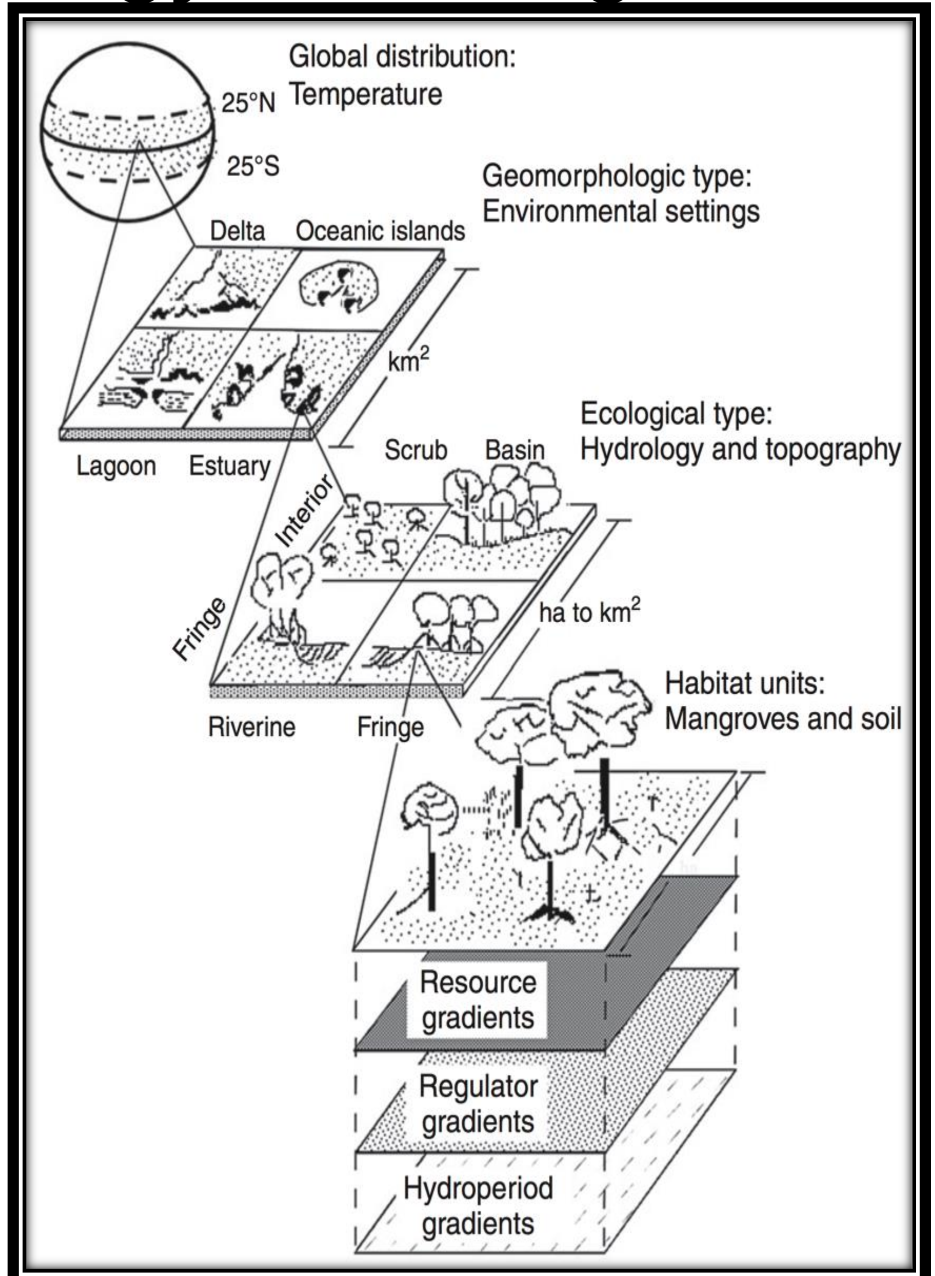
(b)

Thom, B.G. (1982) Mangrove ecology: A geomorphological perspective. *Mangrove ecosystems in australia: Structure, function and management* (ed. by B.F. Clough), pp. 3–17. Australian Institute of Marine Science, Canberra

The Ecogeomorphology of Mangroves







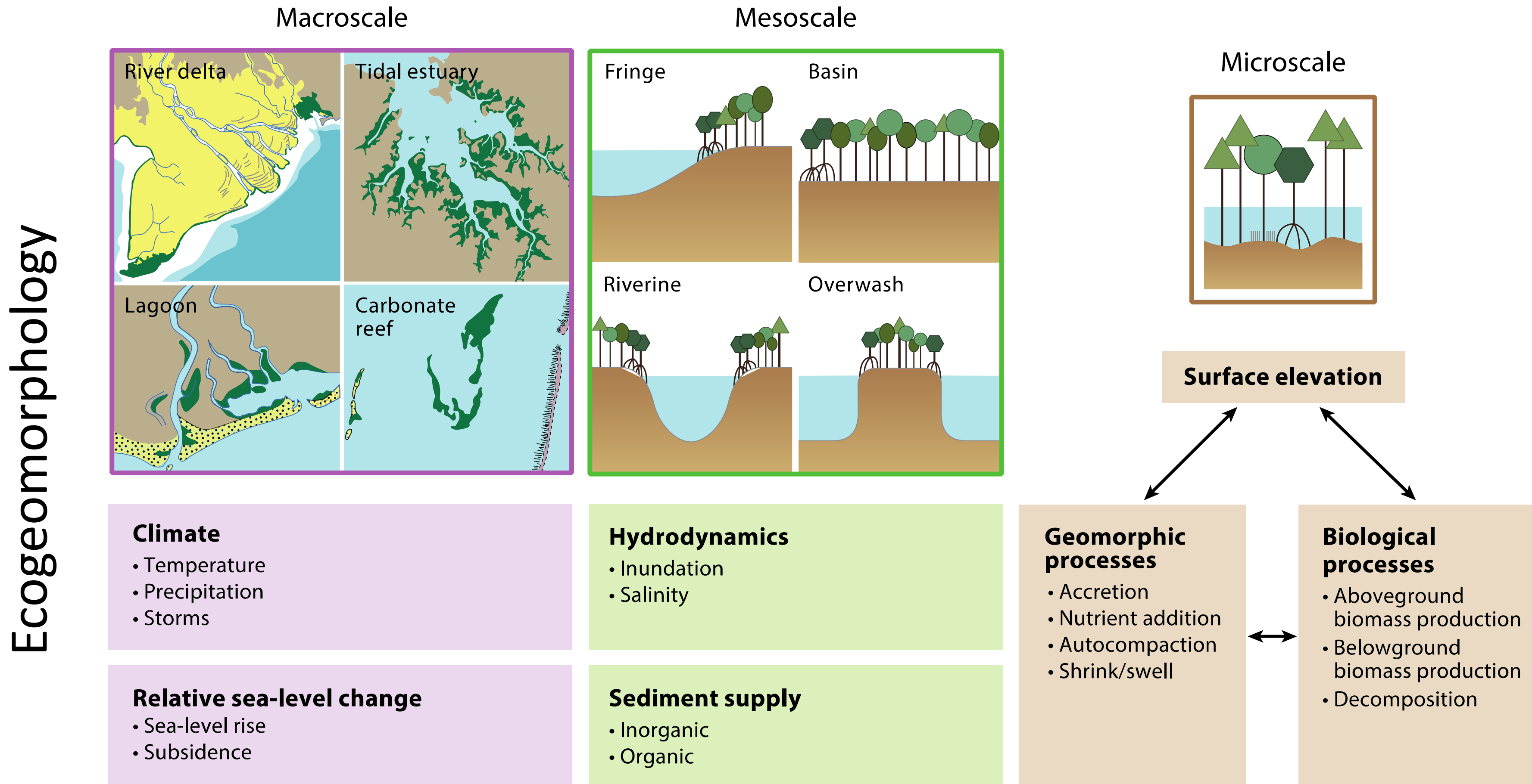
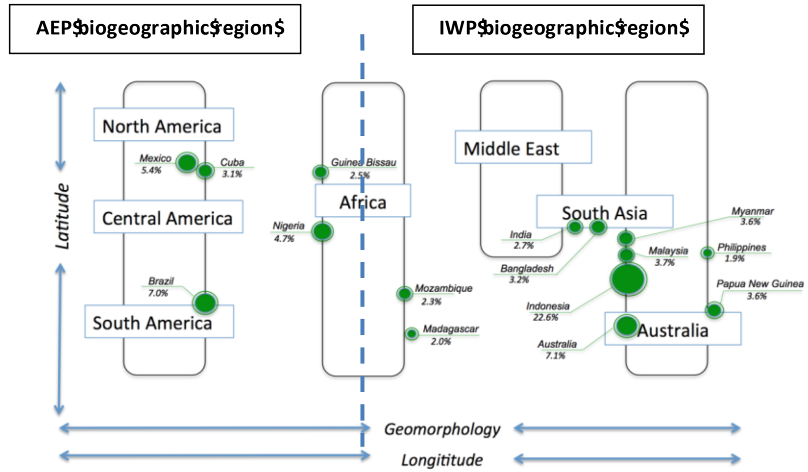


Figure 3

A scale-based framework within which to view mangrove systems, comprising macroscale regional boundary conditions (climate and relative sea-level change, which includes both subsidence and sea-level rise); mesoscale processes, in which hydrodynamics and sediment supply are important influences on mangrove systems; and microscale at-a-site interactions within a mangrove stand, including surface and subsurface processes.

Woodroffe, C, K. Rogers, K.L. McKee, C.E. Lovelock, I.A. Mendelssohn, and N. Saintilan, 2016. Mangrove Sedimentation and Response to Relative Sea-Level Rise. Annu. Rev. Mar. Sci. 8:243–66

Atlantic/Eastern Pacific (AEP) Indo/West Pacific (IWP)



C. Giri *et al.*

Figure 1. The biogeographic and regional dimensions scales considered in the comparative analysis of ecological and socioeconomic mangrove processes discussed in this book. The circles represent the 15 countries contributing 75.3% of the total global mangrove area in 2000 (Data from Giri *et al.*, 2011).

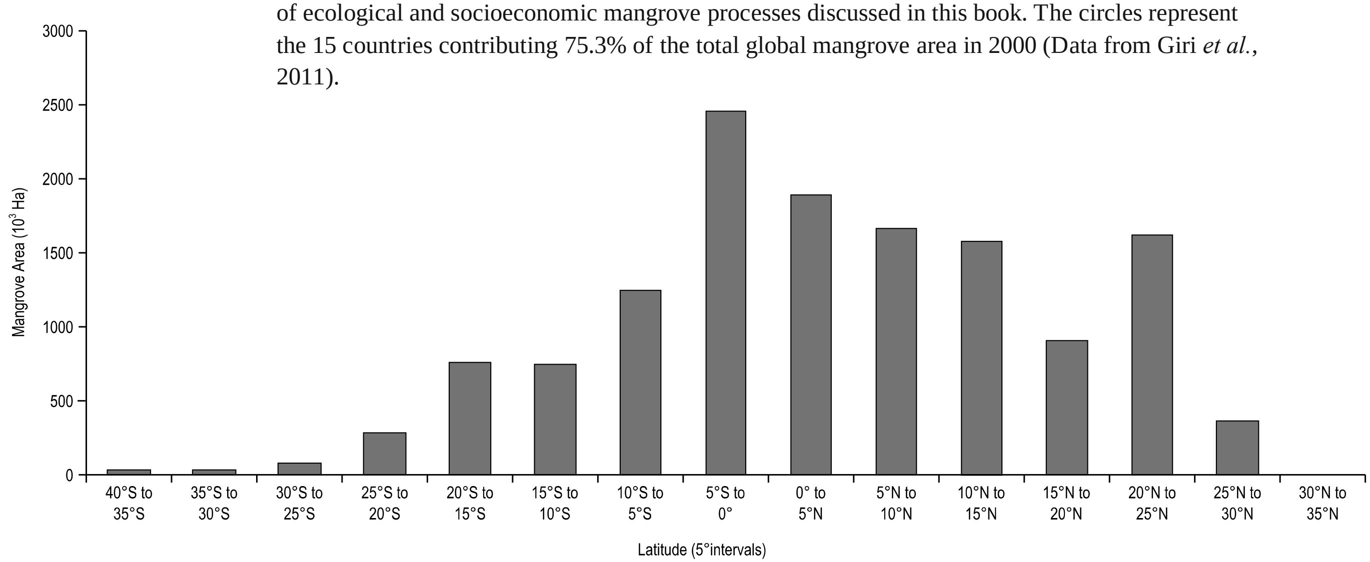
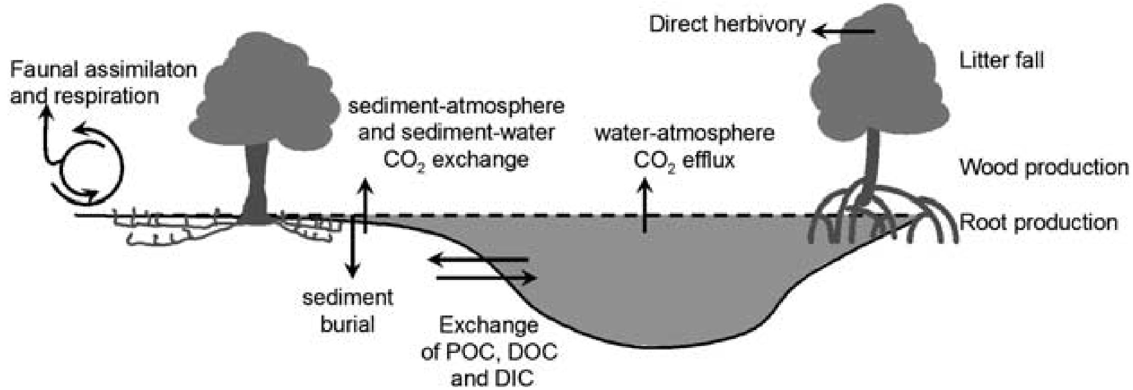


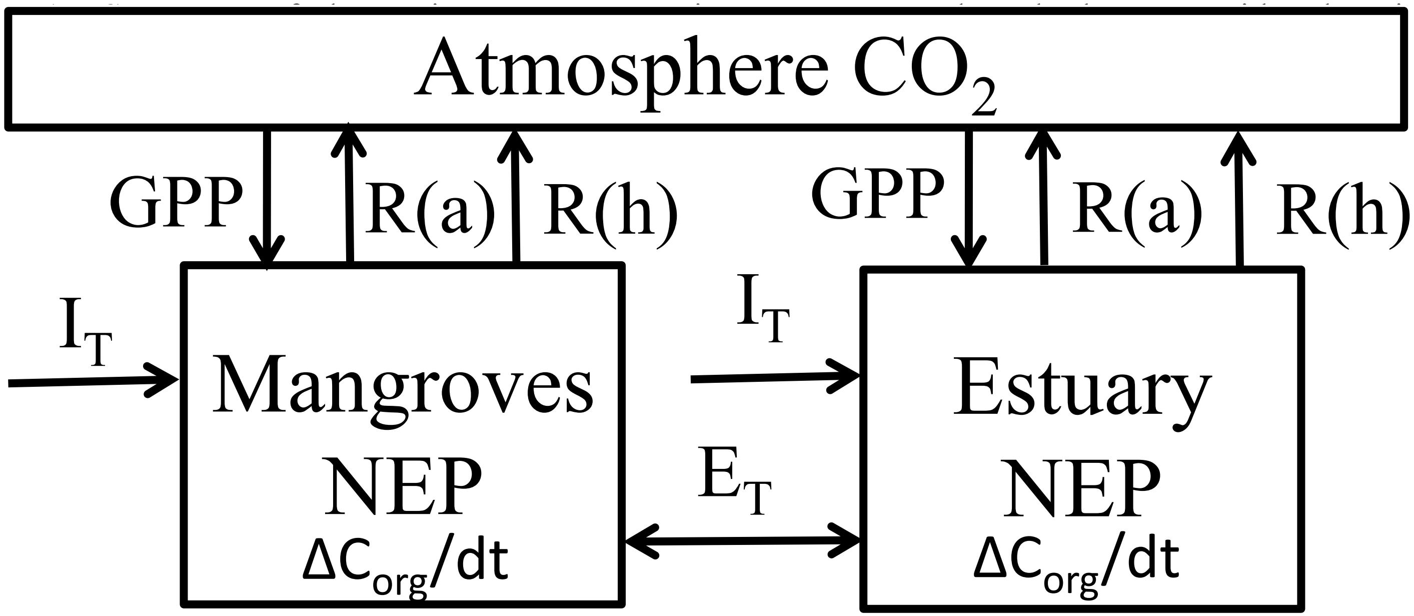
Figure 3 Latitudinal distribution of mangrove forest of the world.

Giri, C., E. Ochieng, L.L. Tieszen, Z. Zhu, A. Singh, T. Loveland, J. Masek, and N. Duke. 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography* 20: 154-159

4. Using Net Ecosystem Production (NEP) to Estimate Carbon Sequestration

Bouillon, S., A.V. Borges, E. Castañeda-Moya, K. Diele, T. Dittmar, N.C. Duke, E. Kristensen, S.Y. Lee, C. Marchand, J.J. Middelburg, V.H. Rivera-Monroy, T.J. Smith, and R.R. Twilley. 2008. Mangrove production and carbon sinks: A revision of global budget estimates. Global Biogeochemical Cycles 22: 1-12



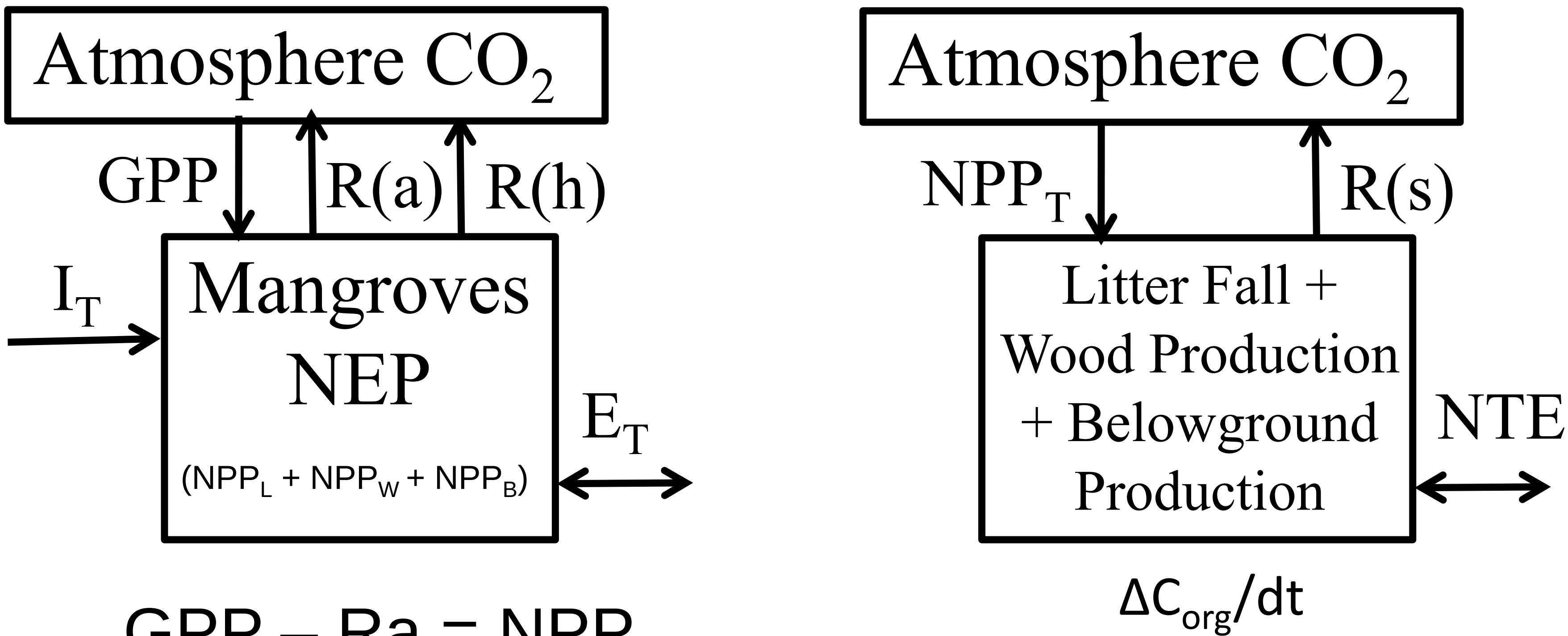


NEP = Net Ecosystem Productivity = $(GPP + I_T) - (Re + E_T)$

E_T = DIC + DOC + PC (Surface and Ground Water)

I_T = DIC + DOC + PC (Surface and Ground Water)

Net Ecosystem Production (NEP) = Organic Carbon



$$GPP – Ra = NPP_T$$

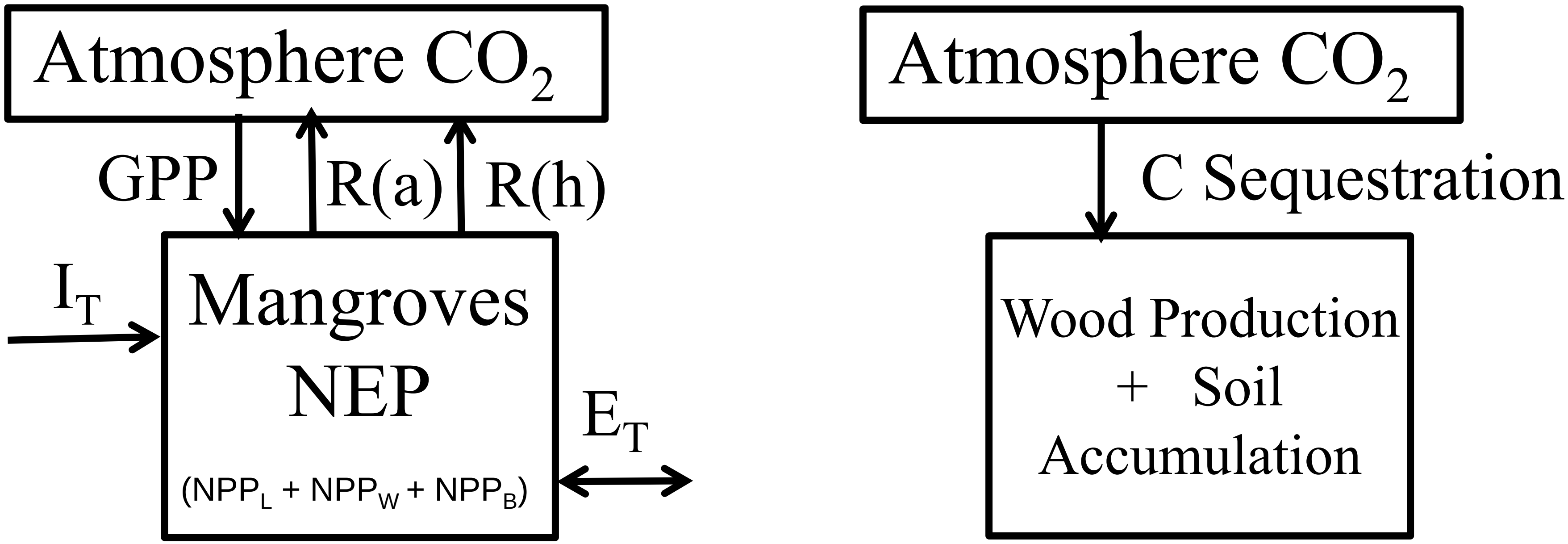
$$NPP_T = (NPP_L + NPP_W + NPP_B)$$

$$NTE = I_T + E_T$$

$$Rh = Rs$$

$$NEP = (NPP_L + NPP_W + NPP_B) – (Rs + NTE)$$

Net Ecosystem Production (NEP) = Organic Carbon



$\Delta C_{org}/dt$

$$GPP - Ra = NPP_T$$

$$NPP_T = (NPP_L + NPP_W + NPP_B)$$

$$NTE = I_T + E_T$$

$$Rh = Rs$$

$$NEP = (NPP_L + NPP_W + NPP_B) - (Rs + NTE)$$

$$\Delta S_{org} = (NPP_L + NPP_B) - (Rs + NTE)$$

$$NEP = NPP_W + \Delta S_{org}$$

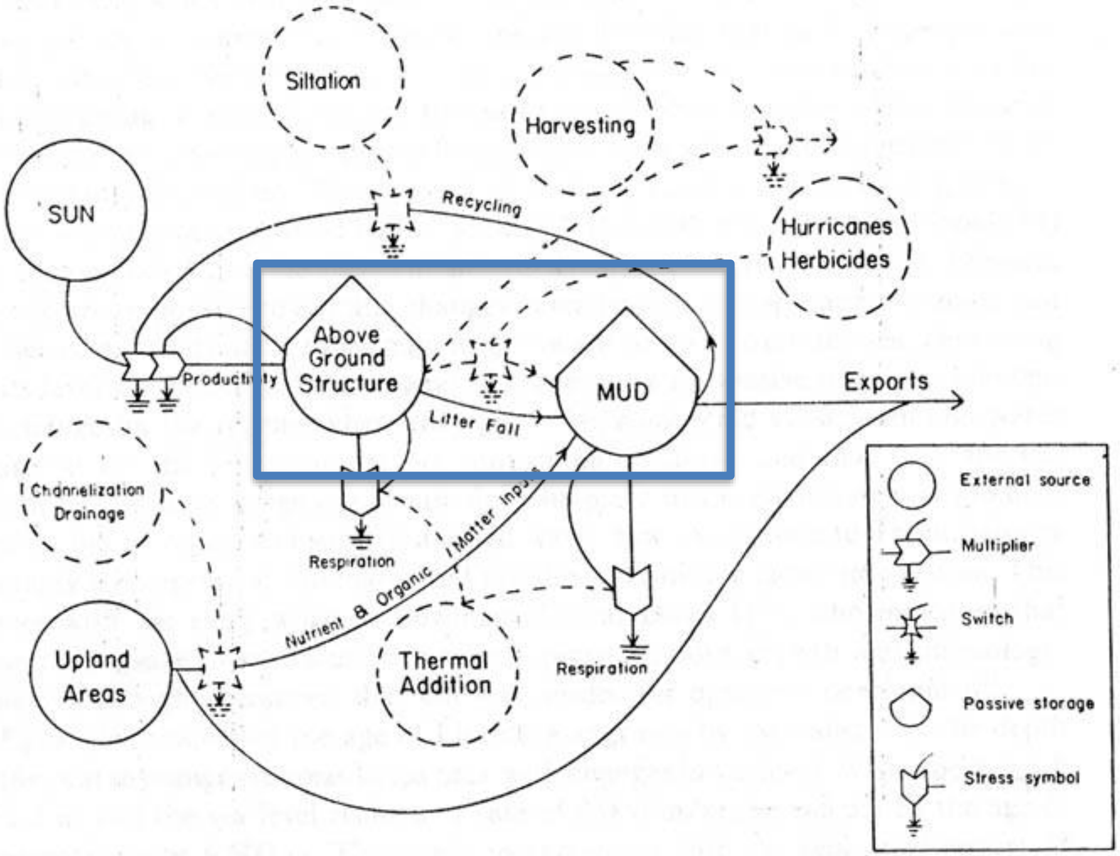


Figure 1 A simple energy model illustrating the major storages and flows in a mangrove ecosystem. Potential stresses are distinguished by dashed lines. In essence, the model is a series of differential equations graphically depicted using the ecological circuit language created by H. Odum (65).

THE ECOLOGY OF MANGROVES

✦4068

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INTRODUCTION

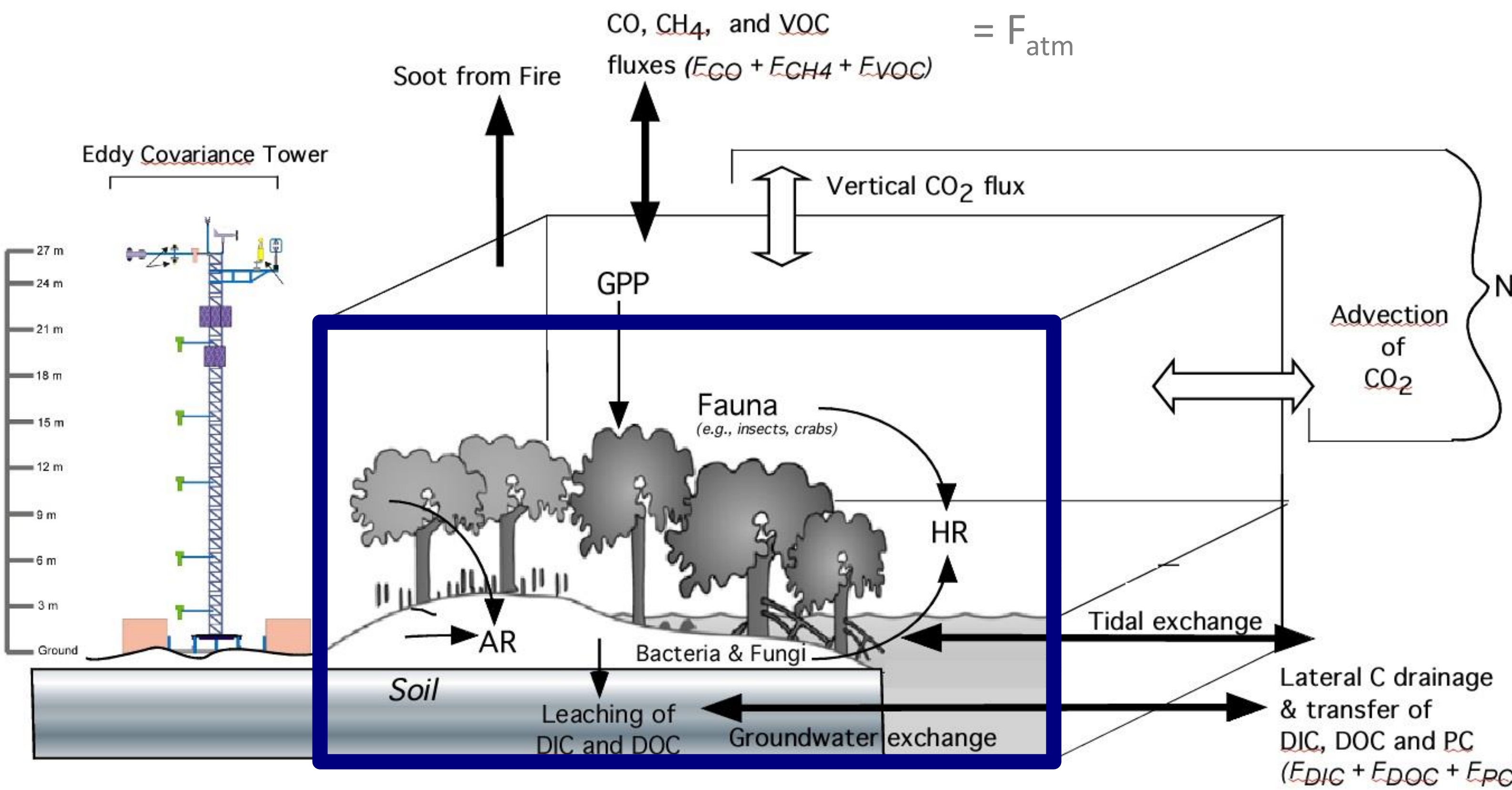
The Historical Perspective

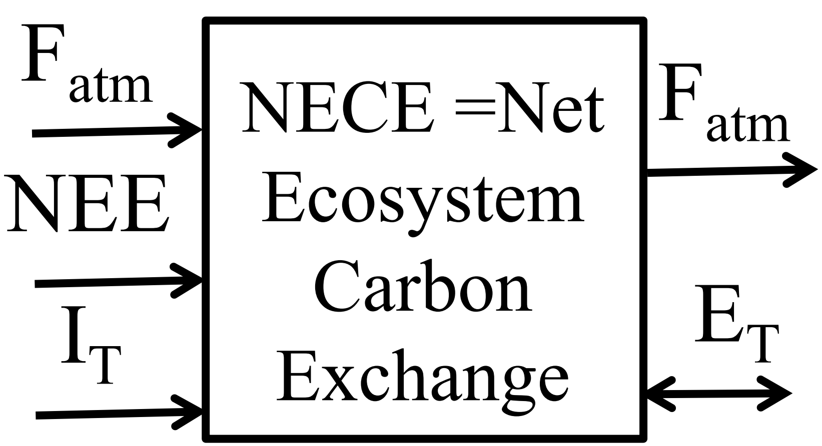
Probably no other distinct plant community has attracted as much curiosity and scientific attention for as long as have the mangrove forests of the tropical and subtropical tidelands; a general bibliography would list some 1200 titles (L. Wilcox, personal communication). The first written account is reported by Bowman (7) from the Chronicle of Nearchus, dating back to the Greek mariners of 325 BC. The historical interest has been largely engendered by the unique adaptations (e.g. prop roots, pneumatophores, and viviparous seeds) of certain mangrove species and by their ubiquitous ability to function in a saline environment.

Unlike other terrestrial communities that can be lived in, managed, or exploited by man, mangroves offer only a few direct uses [tannin, construction timber, and charcoal (3, 69)], which may account for man's historical ambivalence concerning their value. This is revealed in the literature as attitudes that consider mangroves an academic curiosity at best, a nuisance at worst, and, in general, of little value to man and his works. In 1667, Du Terte (in 7) admonished travelers: "Wild boars and other savage beasts live in them . . . who lie in wait to surprise a person." Equally ominous were two Florida newspaper accounts[1] that reported "300 homes blackened" and "two men killed" by "mangrove root gas" in Miami, Florida. In 1938, Davis, whose mangrove research papers (17–20) are considered classics, referred to

[1]Respectively, the *Miami Herald*, Nov. 15, 1951, and the *Miami News*, Jul. 28, 1961.

' The basic mangrove ecosystem is depicted as two coupled storages (above-ground structure and muds) linked by cycling of matter and powered by the interaction of sunlight and matter through photosynthesis'



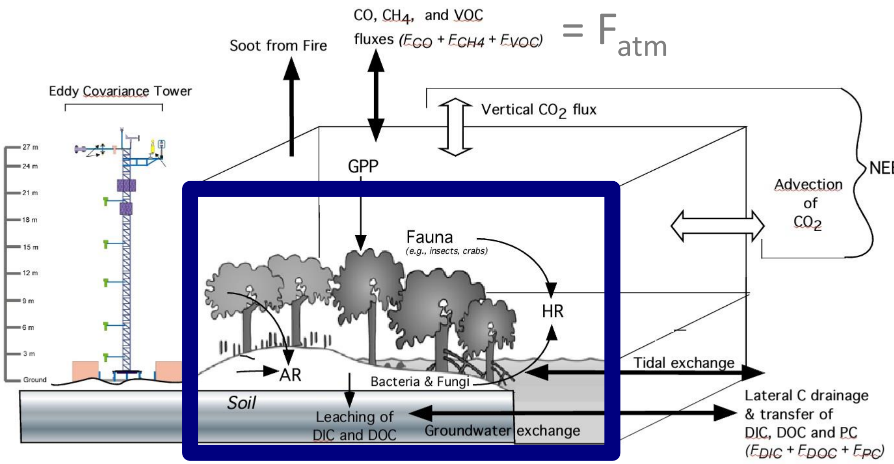


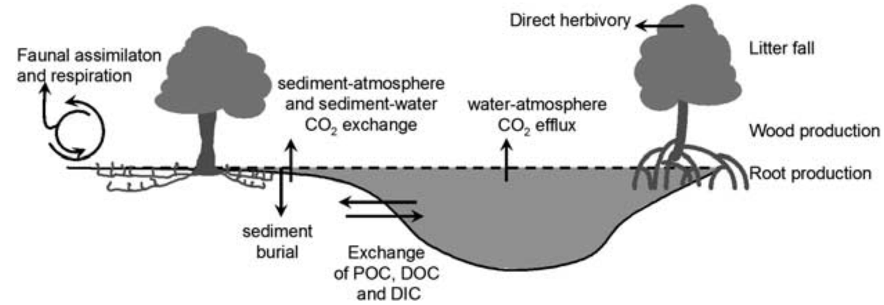
$$NECE = (NEE + I_T + F_{atm}) - (F_{atm} + E_T)$$

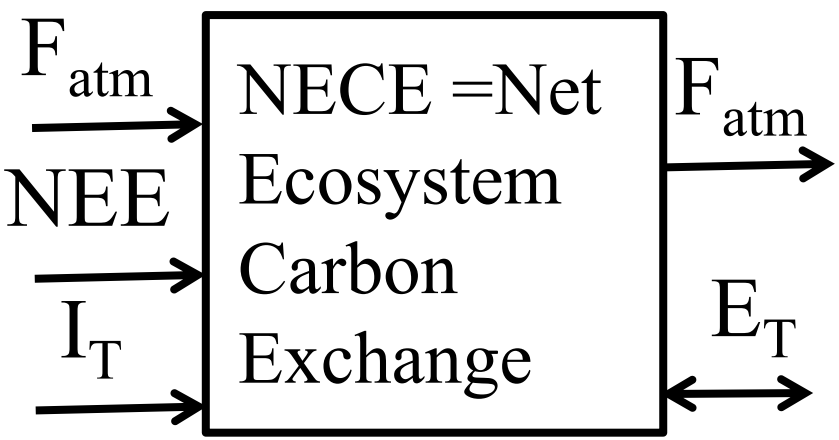
$$E_T = DIC + DOC + PC$$

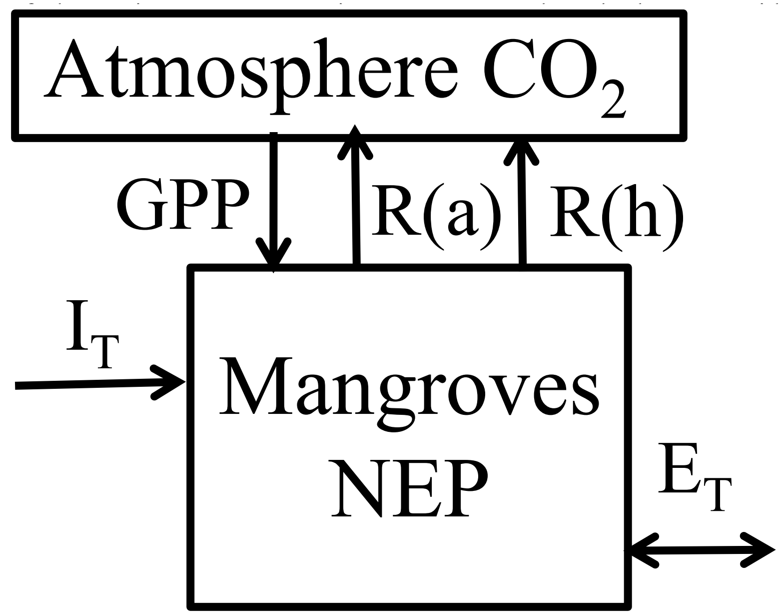
$$I_T = DIC + DOC + PC$$

Surface and Ground Water







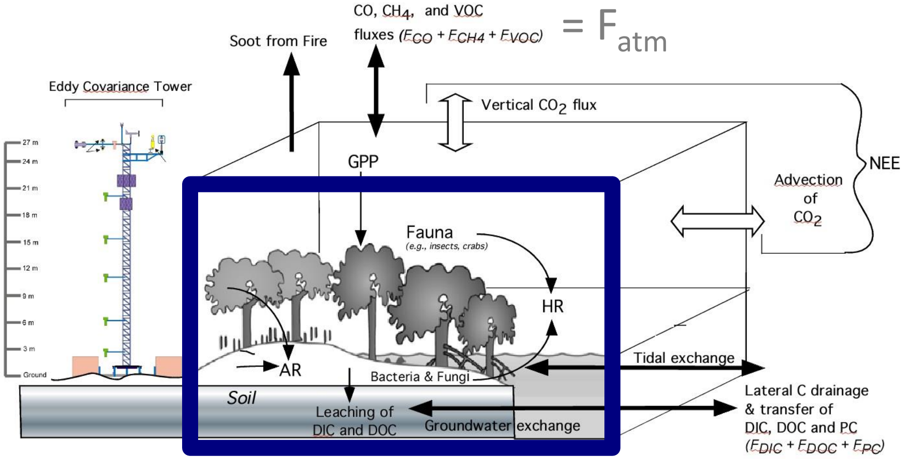


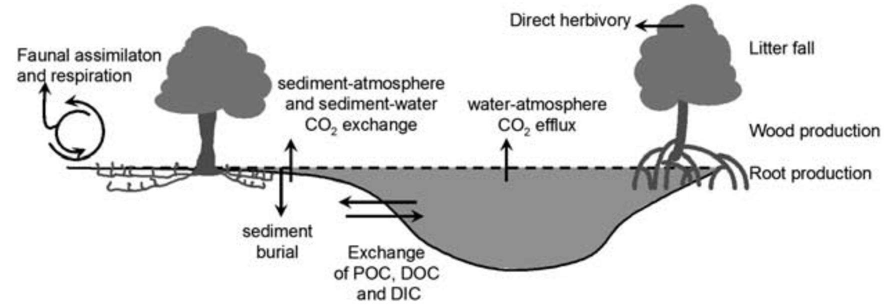
NECE = NEE + NTE

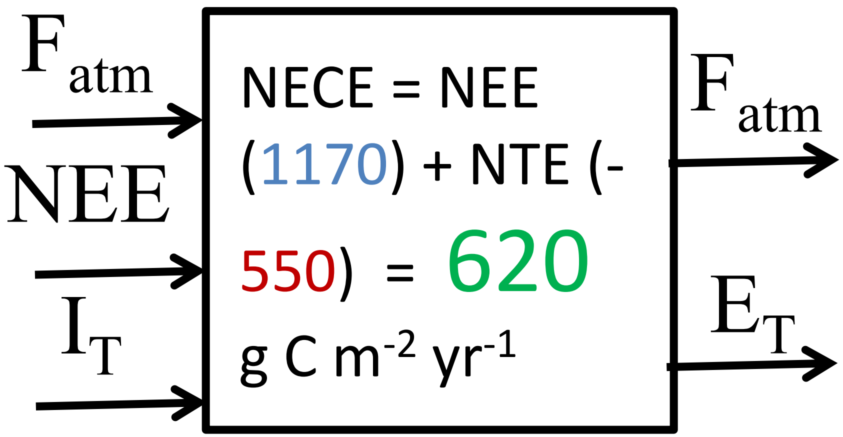
NTE (IT + ET) = DIC + DOC + PC

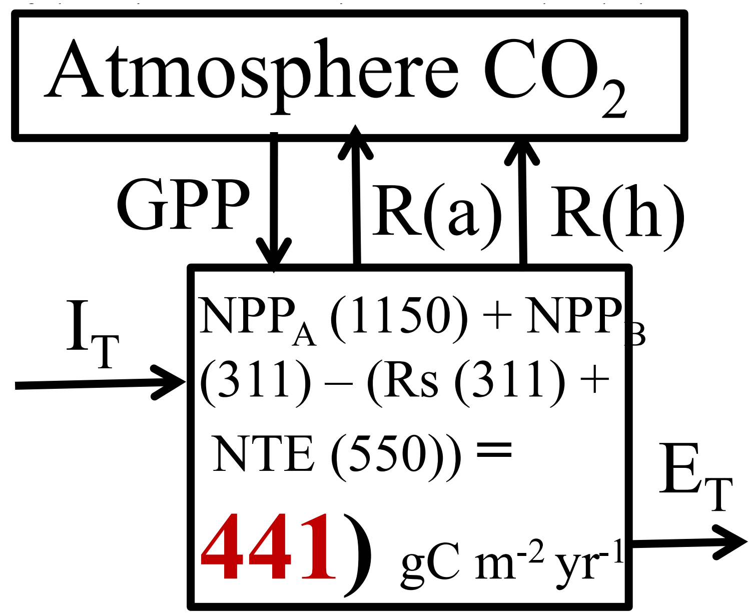
$NEP = (NPP_L + NPP_W + NPP_B) – (Rs + NTE)$

$NEP = NPP_W + \Delta S_{org}$







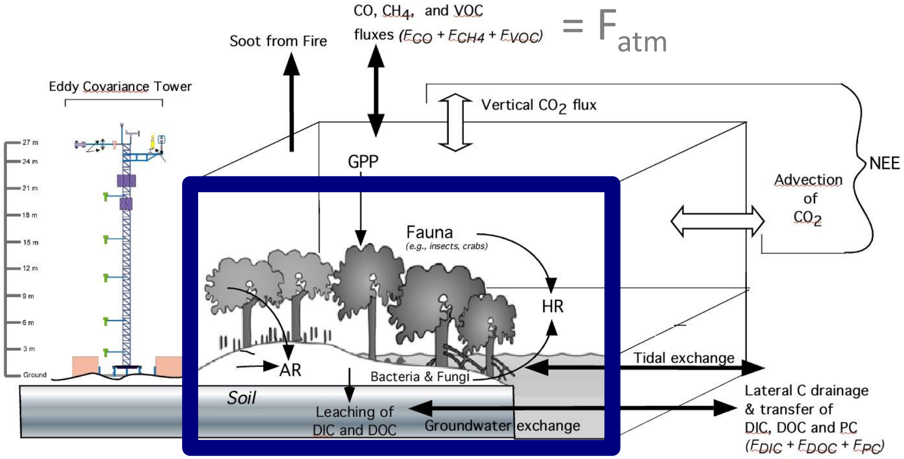


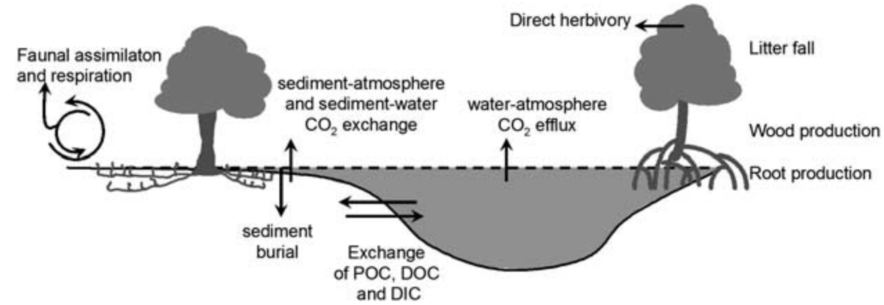
NECE = NEE + NTE

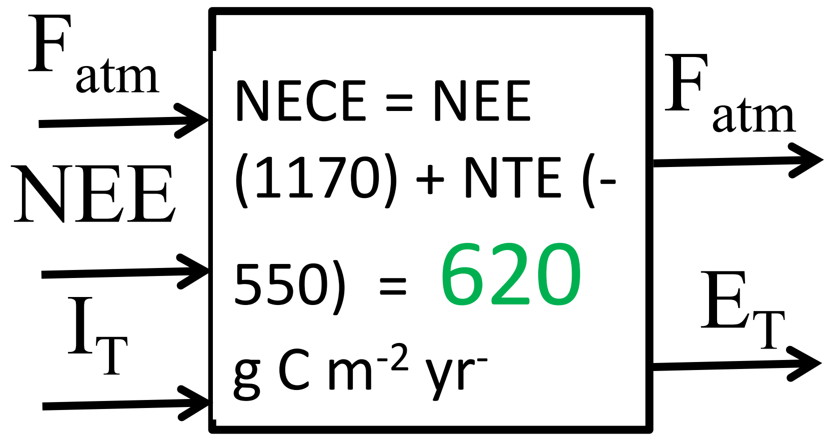
NTE (IT + ET) = DIC + DOC + PC

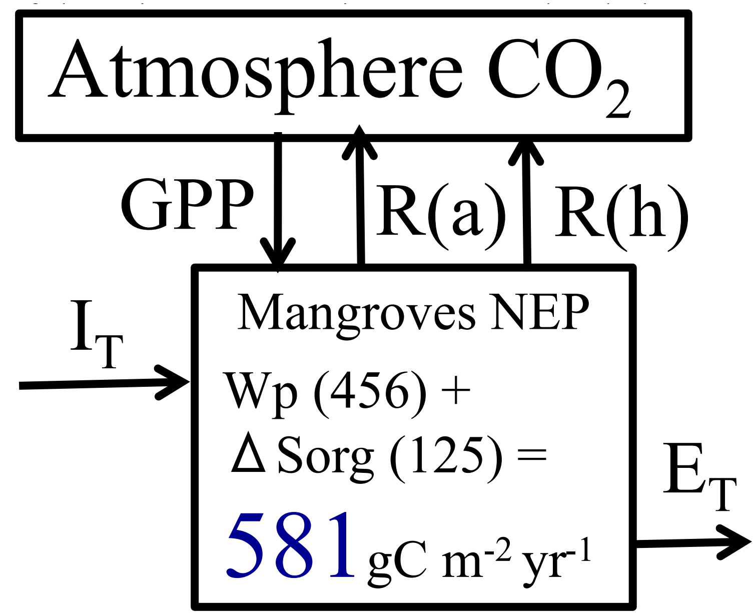
$NEP = (NPP_L + NPP_W + NPP_B) - (Rs + NTE)$

Barr, J.G., V. Engel, J.D. Fuentes, J.C. Zieman, T.L. O'Halloran, T.J. Smith, and G.H. Anderson. 2010. Controls on mangrove forest-atmosphere carbon dioxide exchanges in western Everglades National Park. *Journal of Geophysical Research* 115: G0202





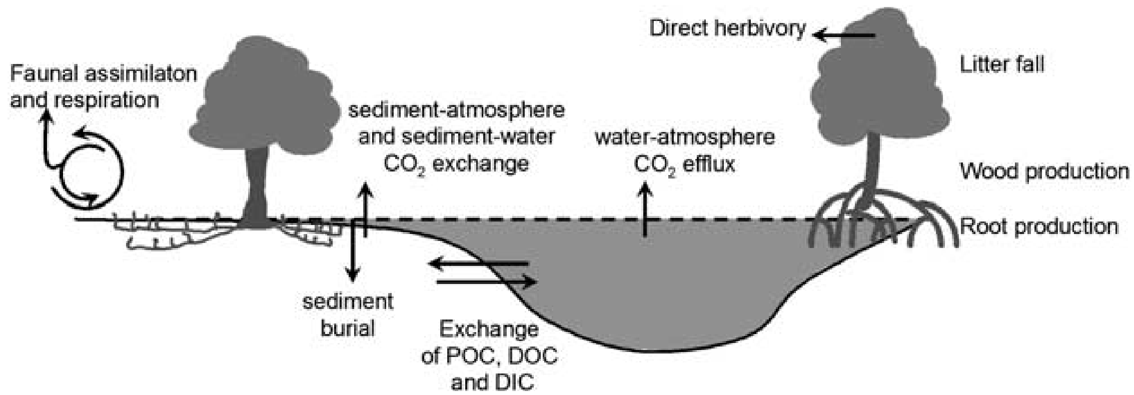




$$NECE = NEE + NTE$$

$$NTE\ (IT + ET) = DIC + DOC + PC$$

$$NEP = NPP_W + \Delta S_{org}$$



(1) NECE = NEE + NTE — 620 gC m^{-2} yr^{-1}

(2) NEP = (NPP_L + NPP_W + NPP_B) – (Rs + NTE) — 441 gC m^{-2} yr^{-1}

(3) NEP = NPP_W + ΔS_{org} — 581 gC m^{-2} yr^{-1}

(4) NEP = ALONGI 2014 — 651 (NEP) – 200 (NTE) = 451 gC m^{-2} yr^{-1}

(NOTE: Dissolved Organic Carbon Export measured = 56 gC m^{-2} yr^{-1} that is increased to 550 gC m^{-2} yr^{-1} by including assumed values for DIC and POC).

5. NEP Variation (Wood Production and Soil Sequestration) linked to Coastal Environmental Settings

Environmental Signature Hypothesis of Carbon Dynamics in Mangrove Ecosystems

Robert R. Twilley[1]
Andre S. Rovai[2]
Paulo R. Pagliosa[2]
Alessandra Larissa Fonseca[3]
Edward Castaneda[1]

[1]Department of Oceanography and Coastal Sciences, College of Coast and Environment
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[2]Núcleo de Estudos do Mar - NEMAR
Centro de Ciências Biológicas - CCB
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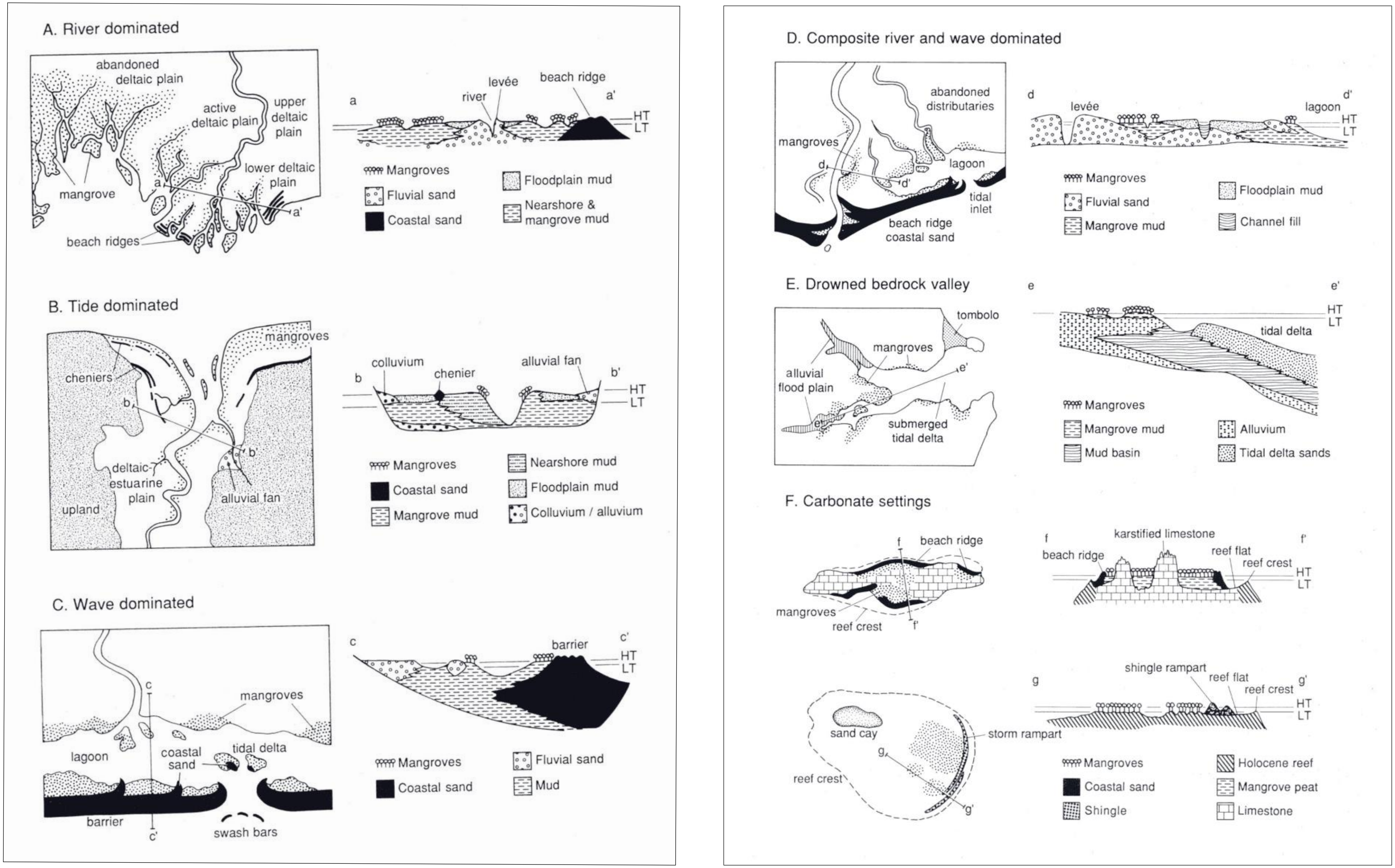
Campus Universitário - Trindade
Florianópolis, SC, Brasil

[2]Universidade Federal de Santa Catarina
Centro de Filosofia e Ciências Humanas
Departamento de Geociências
Florianópolis - SC, Brasil

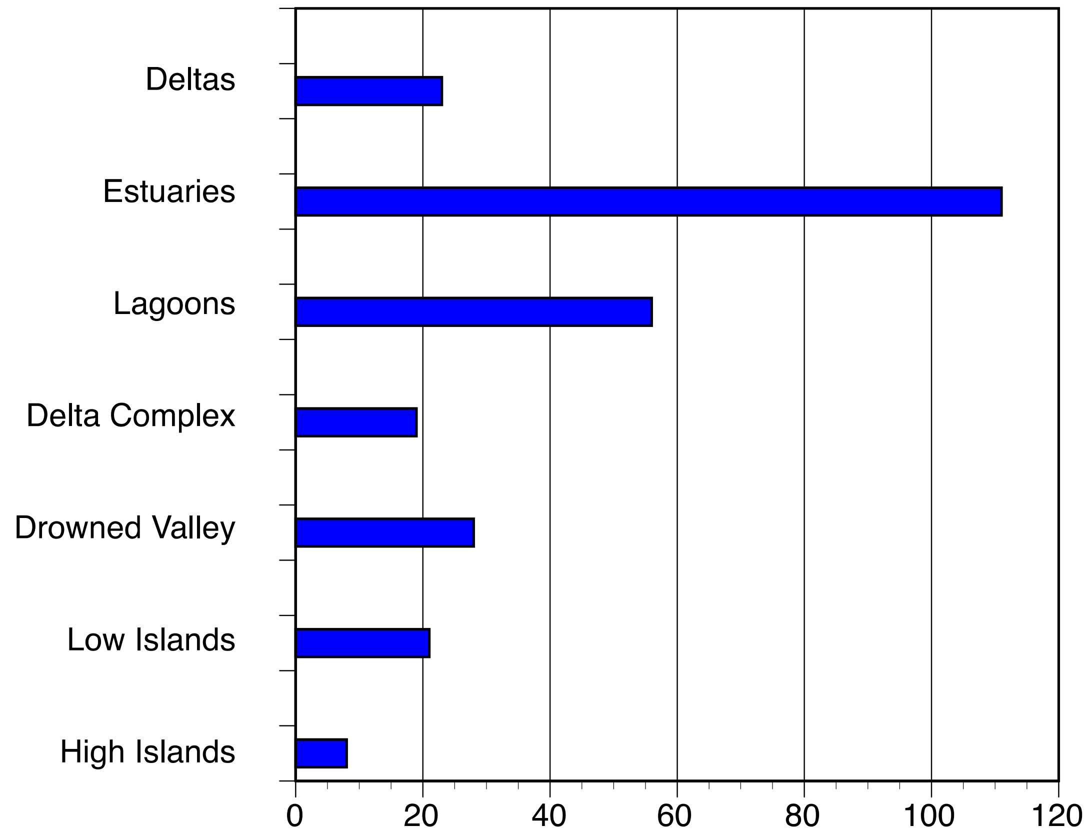
[3]Universidade Federal de Santa Catarina
CFH/Departamento de Geociências
Campus Universitário
Trindade,Florianópolis/SC



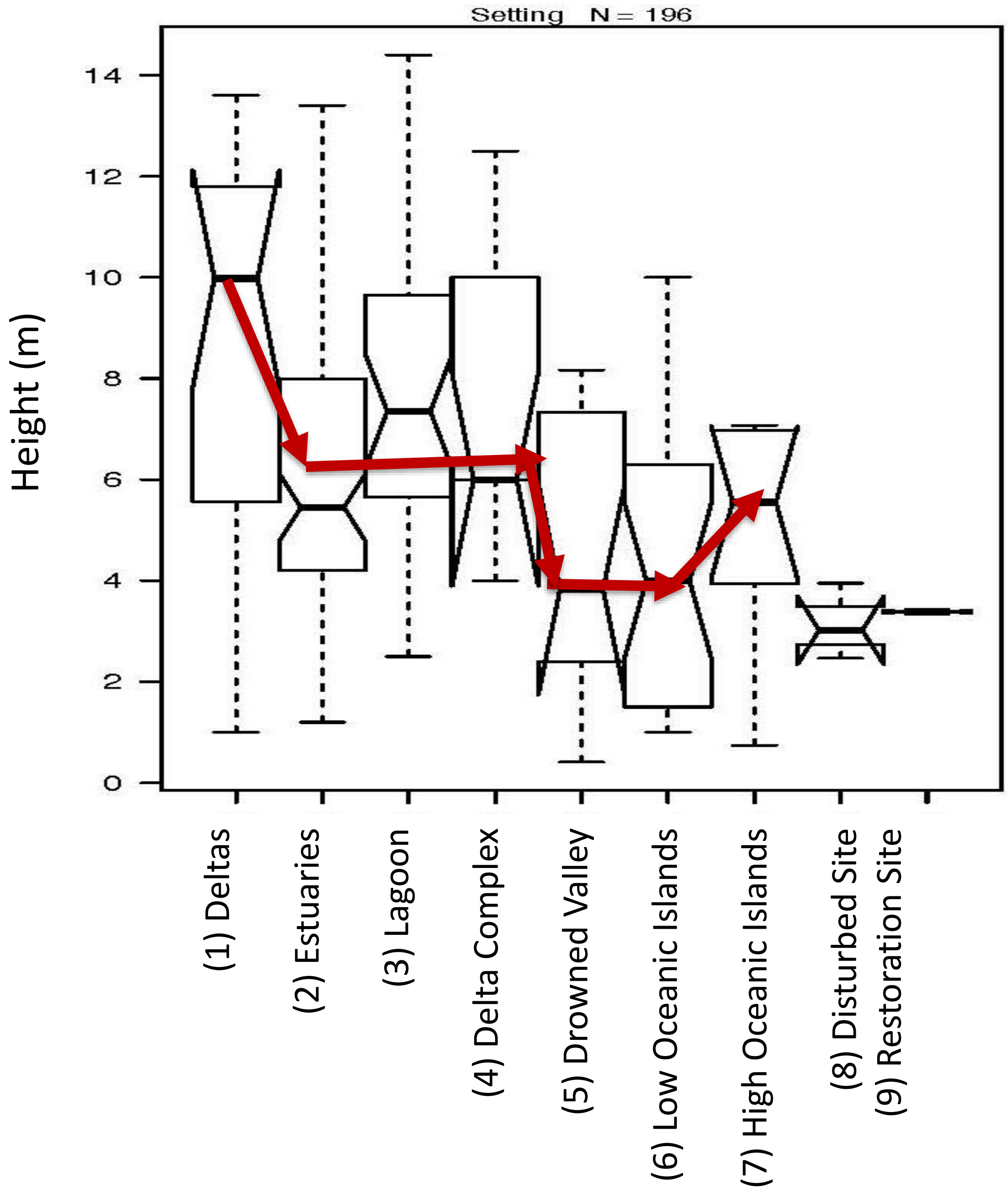
Woodroffe, C. D., 2002. Coasts: form, process, evolution. Cambridge University Press. Cambridge, U.K.

Literature Survey of 260 Mangrove Sites

Twilley, R.R., R.H. Chen, and T. Hargis. **1992**. Carbon sinks in mangroves and their implications to carbon budget of tropical coastal ecosystems. *Water, Air and Soil Pollution* 64: 265-288.

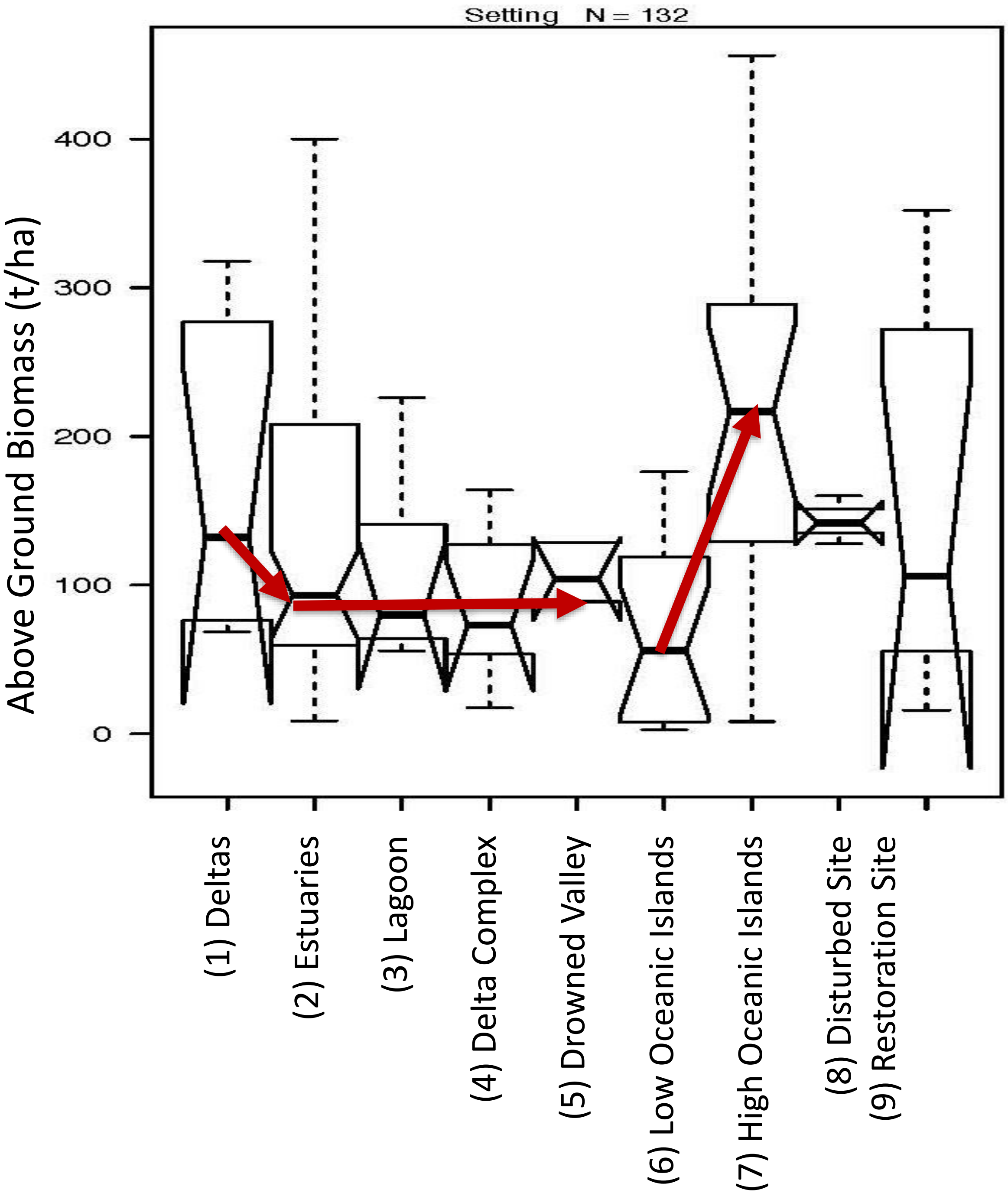


Plot of the frequency of sites in each ecogeomorphic setting for each ecological attribute



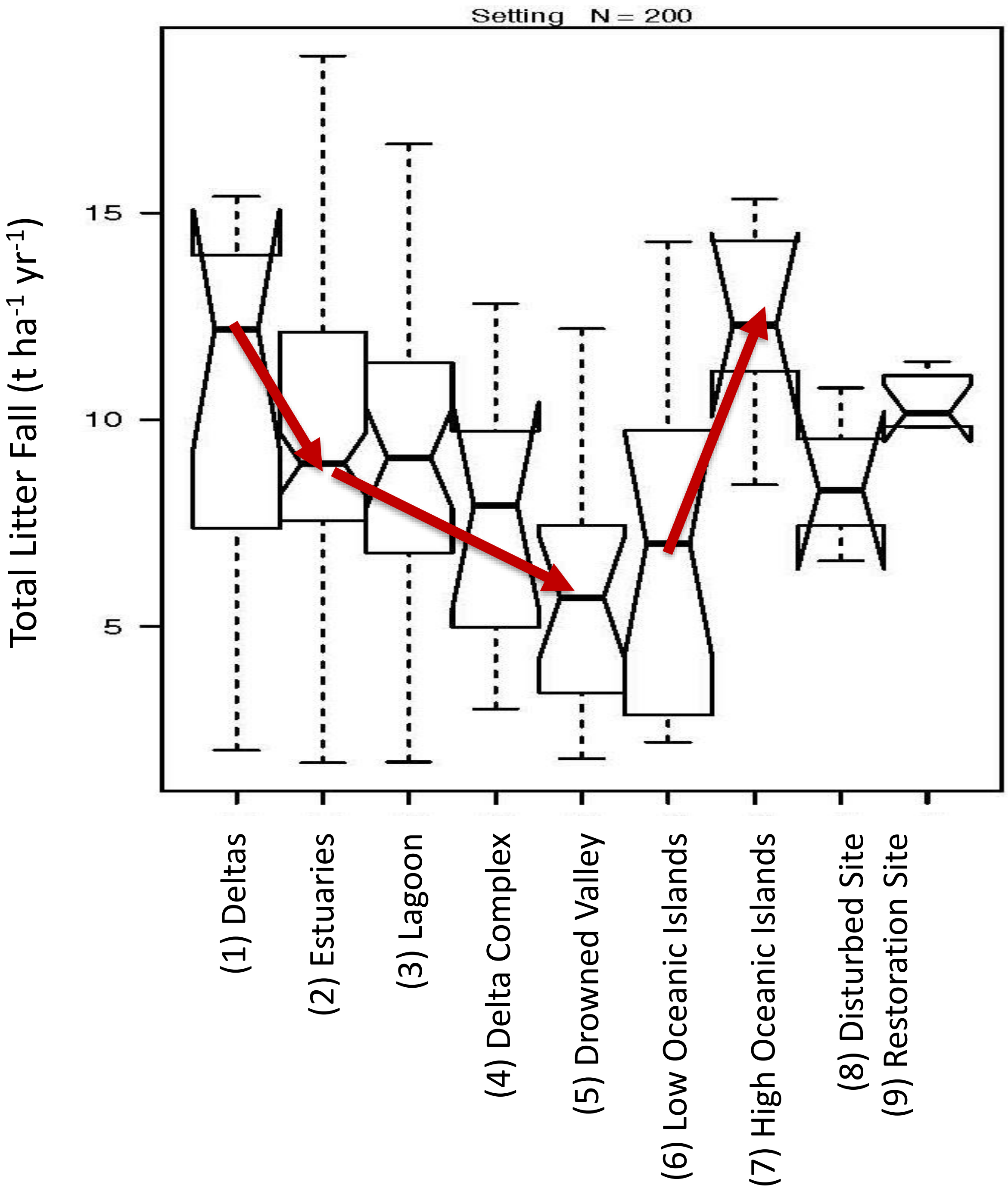
Summary

1. No sites = 196
    a. Estuaries (80)
    b. Lagoons (32)
    c. Low islands (25)
    d. Deltas (21)
    e. Drowned valleys (14)
    f. Delta complex = High Islands (10)
2. Deltas have greater heights at 10 m avg;
3. Low islands and drowned valley have lowest heights
4. High islands > low islands in height



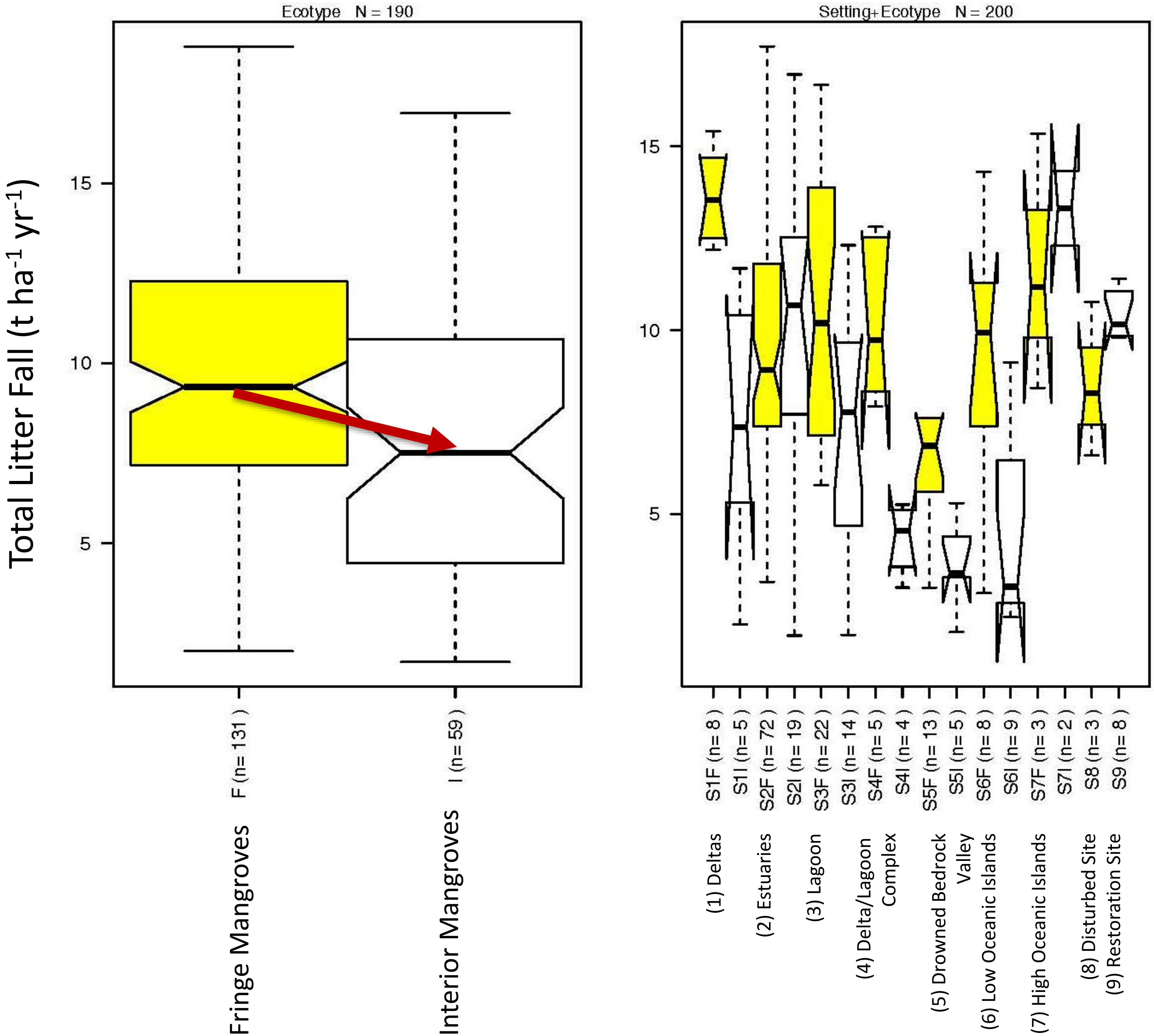
Summary

1. No sites = 132
   a. Estuaries (61)
   b. High Islands (18)
   c. Low islands (17)
   d. Deltas (8)
   e. Delta complex (7)
   f. Lagoons (6)
   g. Drowned valleys (5)
2. High islands have greatest AGB at 210 t/ha avg;
3. Low islands have lowest AGB
4. Estuaries = Lagoons = Delta complex



Summary

1. No sites = 200
    a. Estuaries (91)
    b. Lagoons (36)
    c. Drowned valleys (18)
    d. Low islands (17)
    e. Deltas (13)
    f. Delta complex (9)
    g. High Islands (5)
2. Deltas and High islands have greatest Litter Fall at 13 t ha^{-1} yr^{-1}avg;
3. Drowned valleys and Low islands have lowest litter fall (6 t ha^{-1} yr^{-1}
4. Estuaries = Lagoons = Delta complex

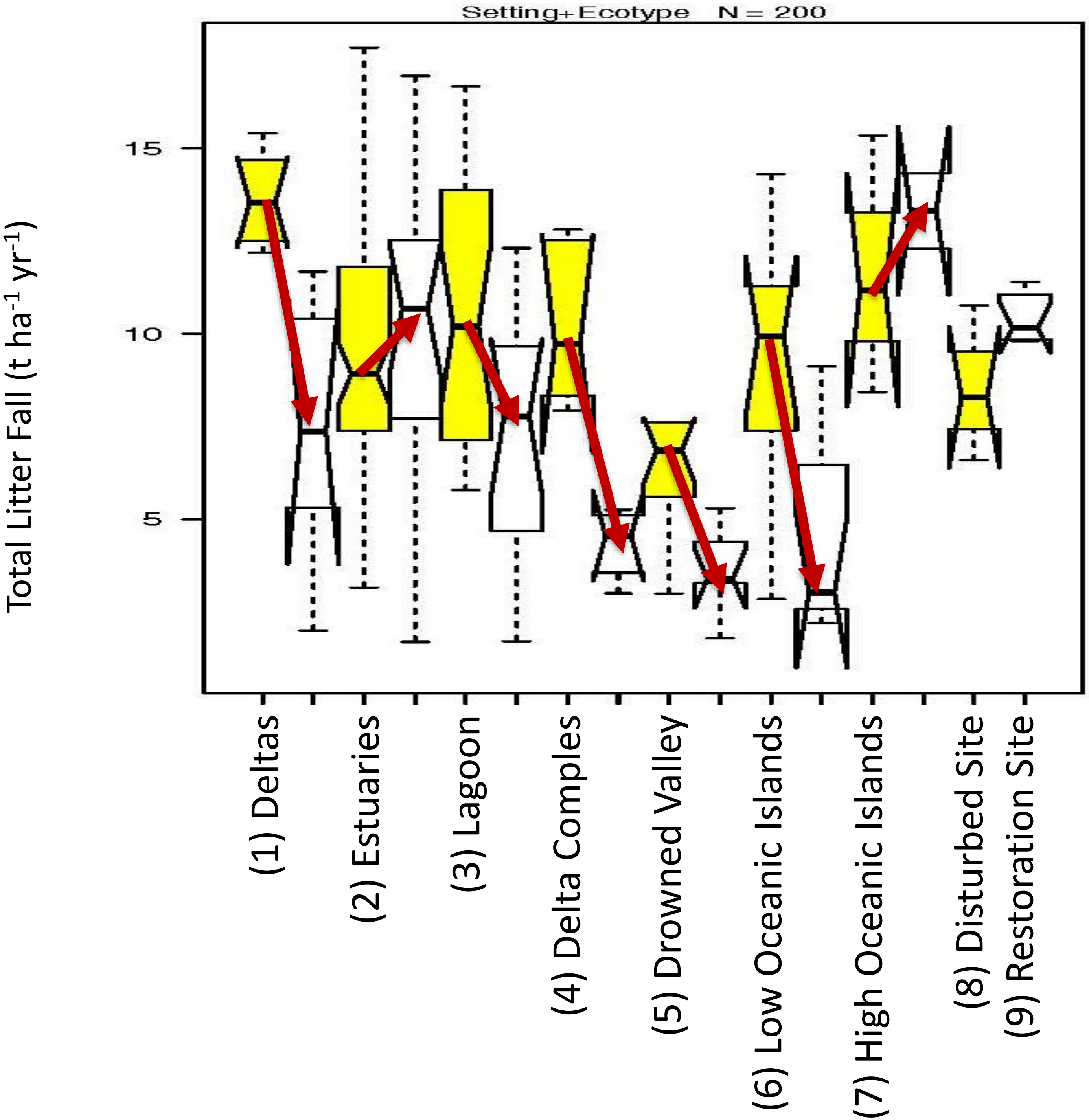


Summary

Fringe > Interior (but not sign)

Fringe > Interior
- Deltas
- Lagoons
- Delta complex
- Bedrock valley
- Low islands

Fringe < Interior
- Estuaries
- High Islands

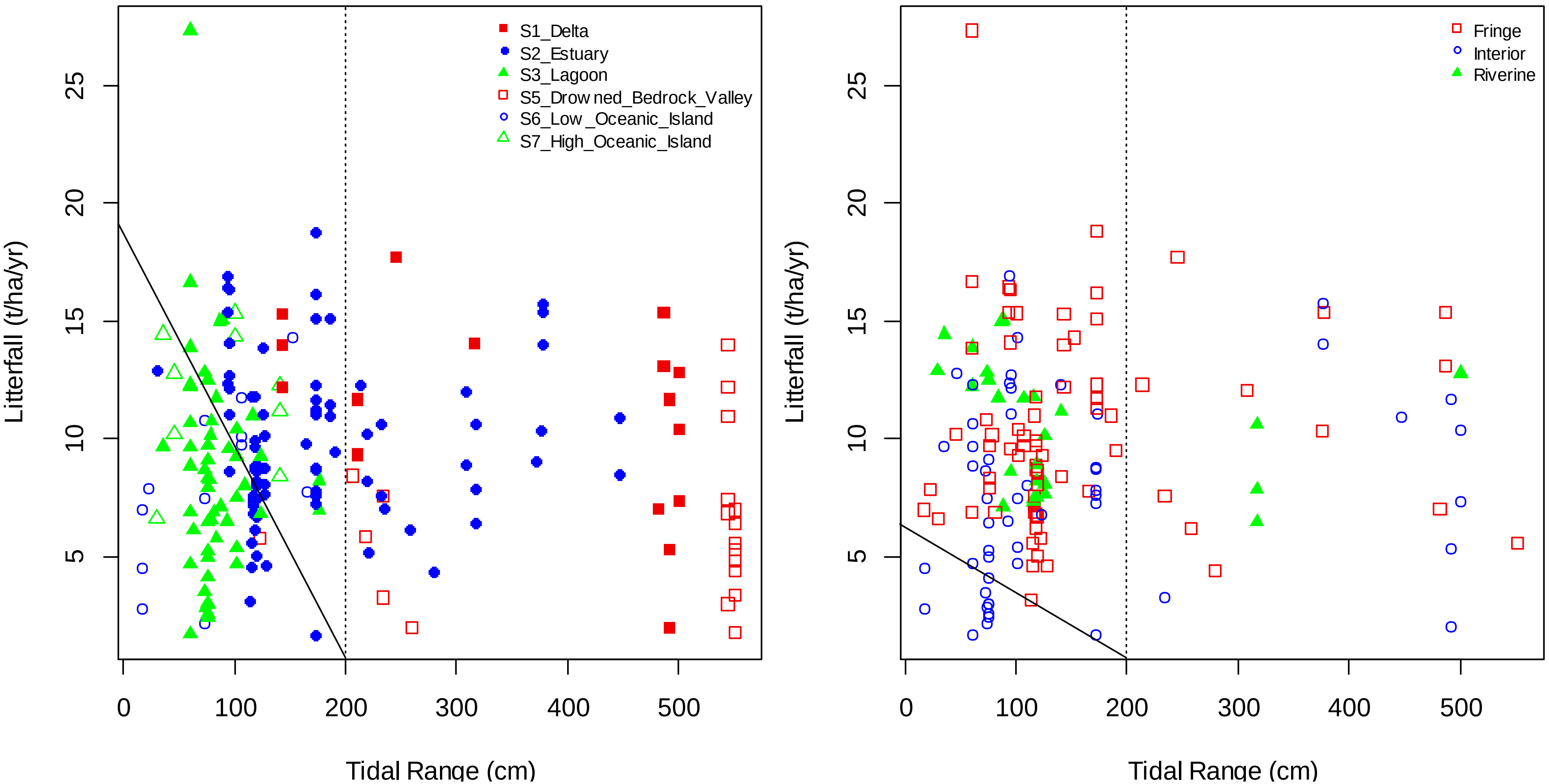


Summary

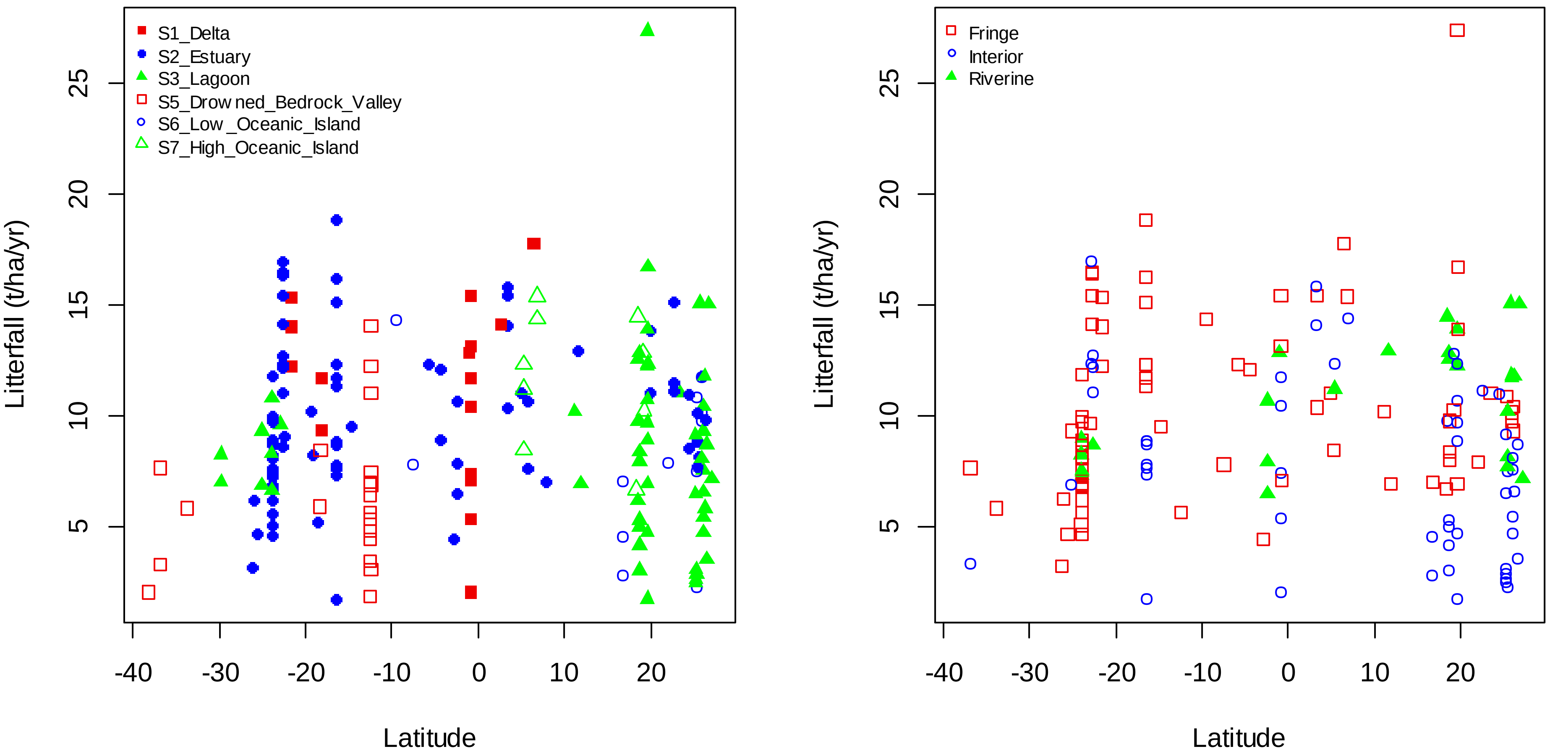
Fringe > Interior (but not sign)

Fringe > Interior
- Deltas
- Lagoons
- Delta complex
- Bedrock valley
- Low islands

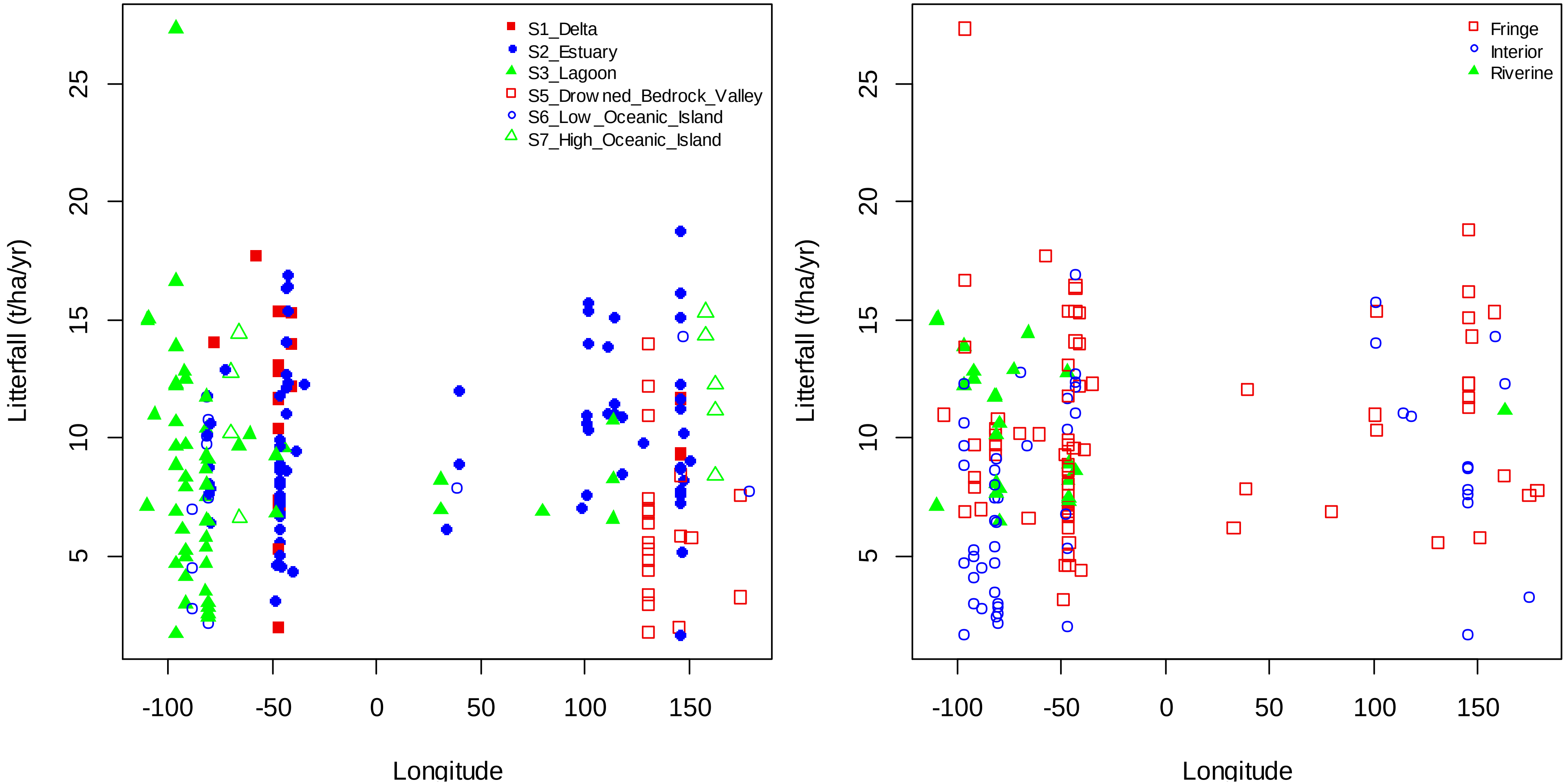
Fringe < Interior
- Estuaries
- High Islands



S1_Delta
S2_Estuary
S3_Lagoon
S5_Drowned_Bedrock_Valley
S6_Low_Oceanic_Island
S7_High_Oceanic_Island
Fringe
Interior
Riverine
Litterfall (t/ha/yr)
Tidal Range (cm)
0
100
200
300
400
500
5
10
15
20
25

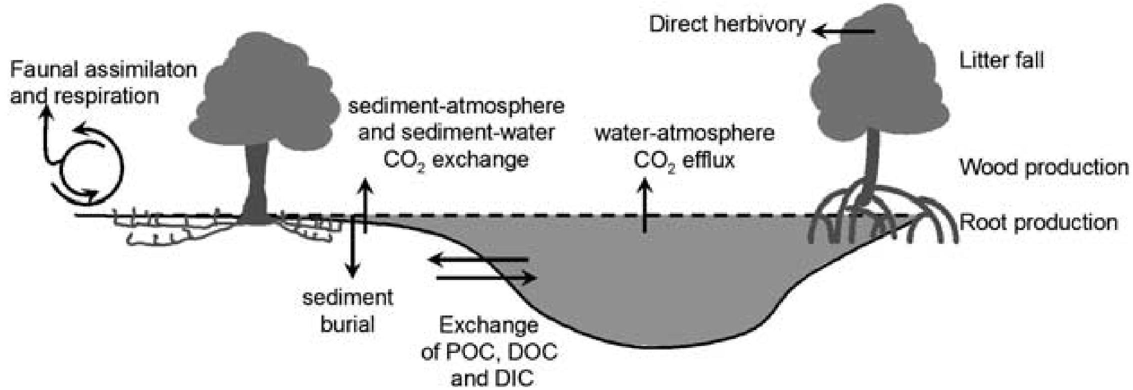


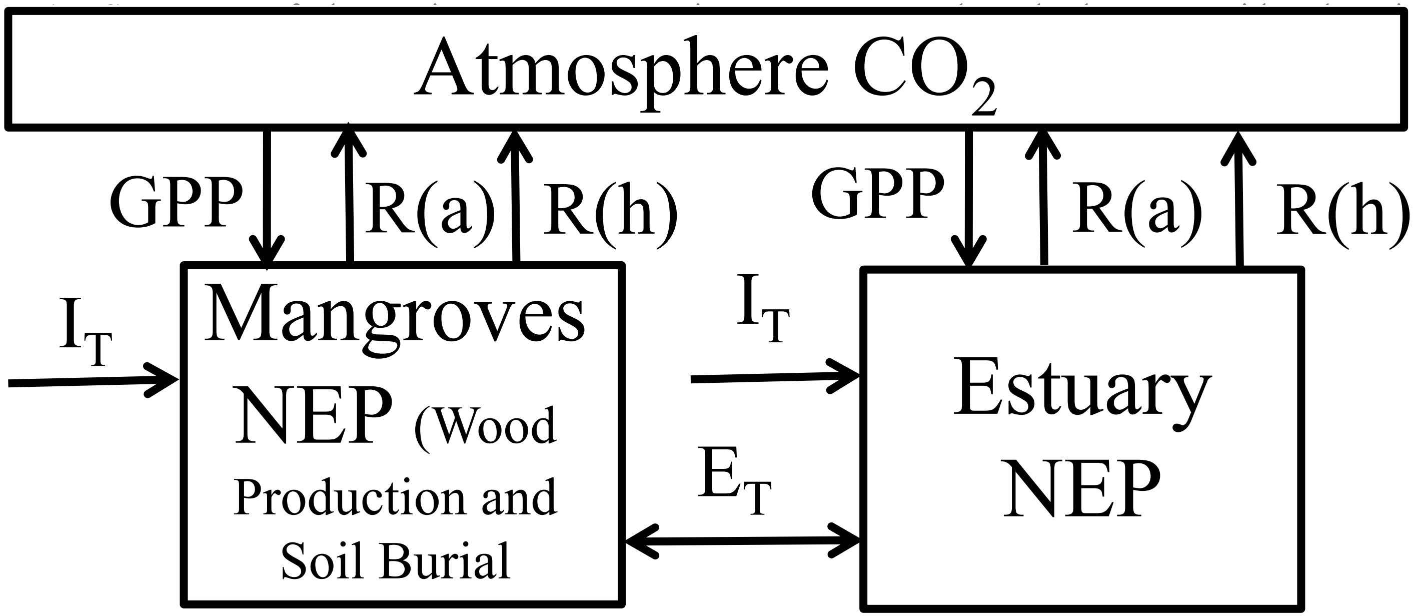
S1_Delta
S2_Estuary
S3_Lagoon
S5_Drowned_Bedrock_Valley
S6_Low_Oceanic_Island
S7_High_Oceanic_Island
Litterfall (t/ha/yr)
Latitude
Fringe
Interior
Riverine
Litterfall (t/ha/yr)
Latitude



S1_Delta
S2_Estuary
S3_Lagoon
S5_Drowned_Bedrock_Valley
S6_Low_Oceanic_Island
S7_High_Oceanic_Island
Litterfall (t/ha/yr)
25
20
15
10
5
-100
-50
0
50
100
150
Longitude
Fringe
Interior
Riverine
Litterfall (t/ha/yr)
25
20
15
10
5
-100
-50
0
50
100
150
Longitude

6. Expanding Global Estimates (Models) of NEP Using ESH - Above Ground Biomass





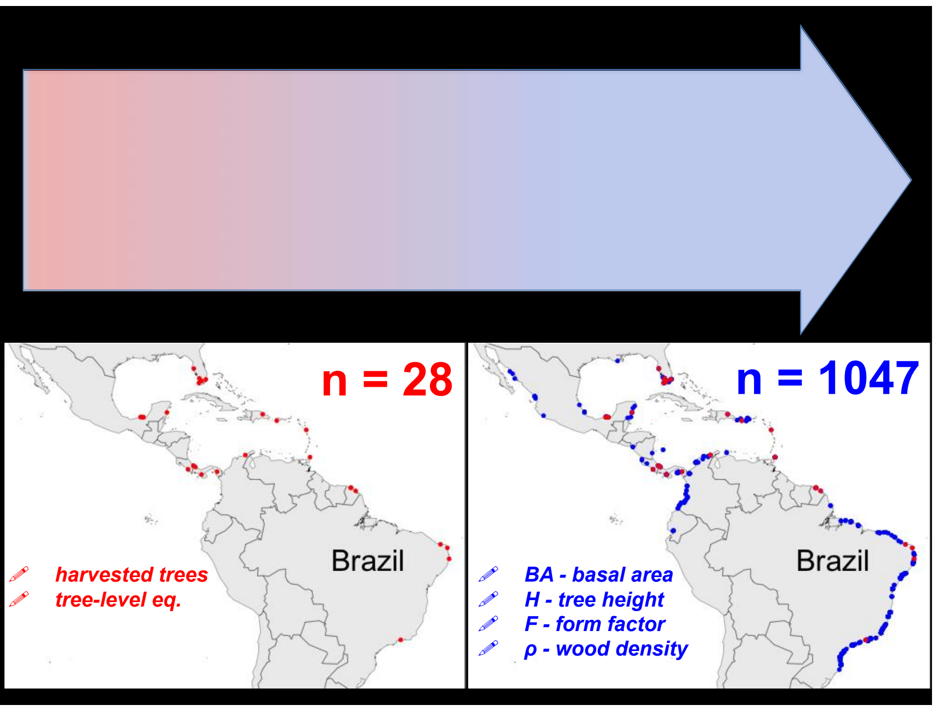
$$NEP = NPP_W + \Delta S_{org}$$

Global Ecology and Biogeography
A Journal of Macroecology

RESEARCH PAPER

Scaling mangrove aboveground biomass from site-level to continental-scale

A. S. Rovai[1*], P. Riul[2], R. R. Twilley[3], E. Castañeda-Moya[3], V. H. Rivera-Monroy[3], A. A. Williams[3], M. Simard[4], M. Cifuentes-Jara[5], R. R. Lewis[6], S. Crooks[7], P. A. Horta[1,8], Y. Schaeffer-Novelli[9], G. Cintrón[10], M. Pozo-Cajas[11] and P. R. Pagliosa[1,12]

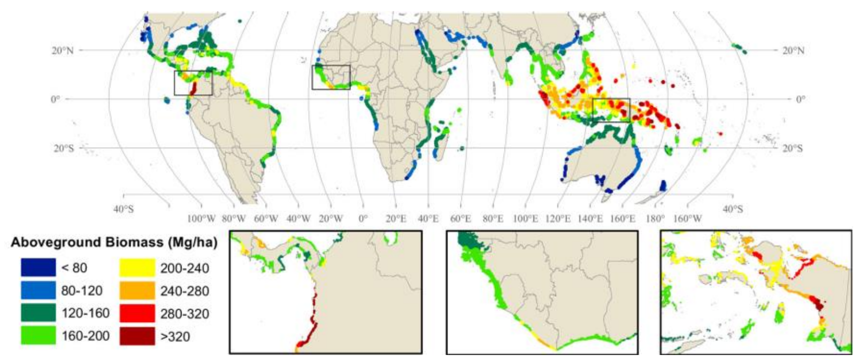


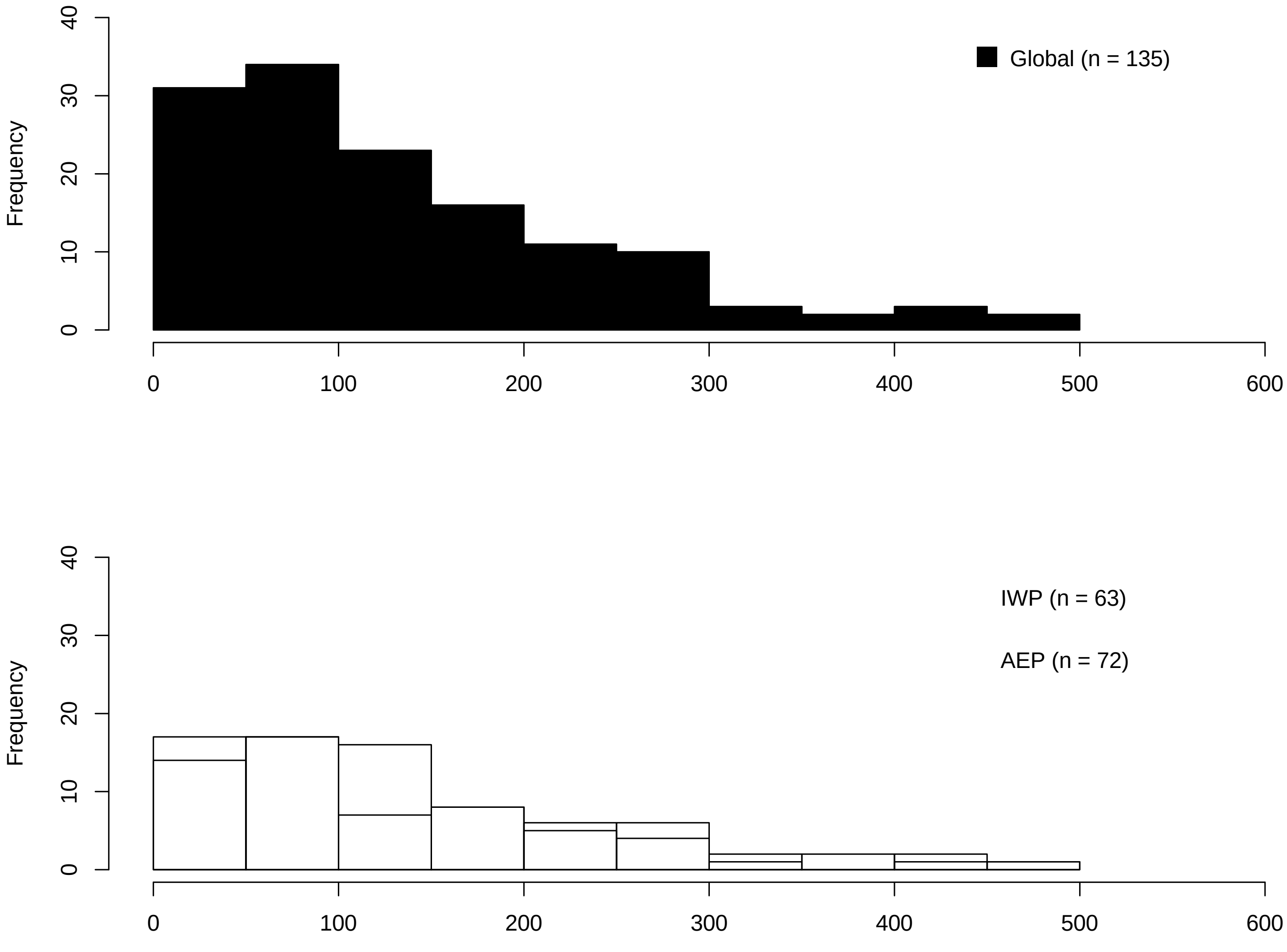
LETTER

Predicting Global Patterns in Mangrove Forest Biomass

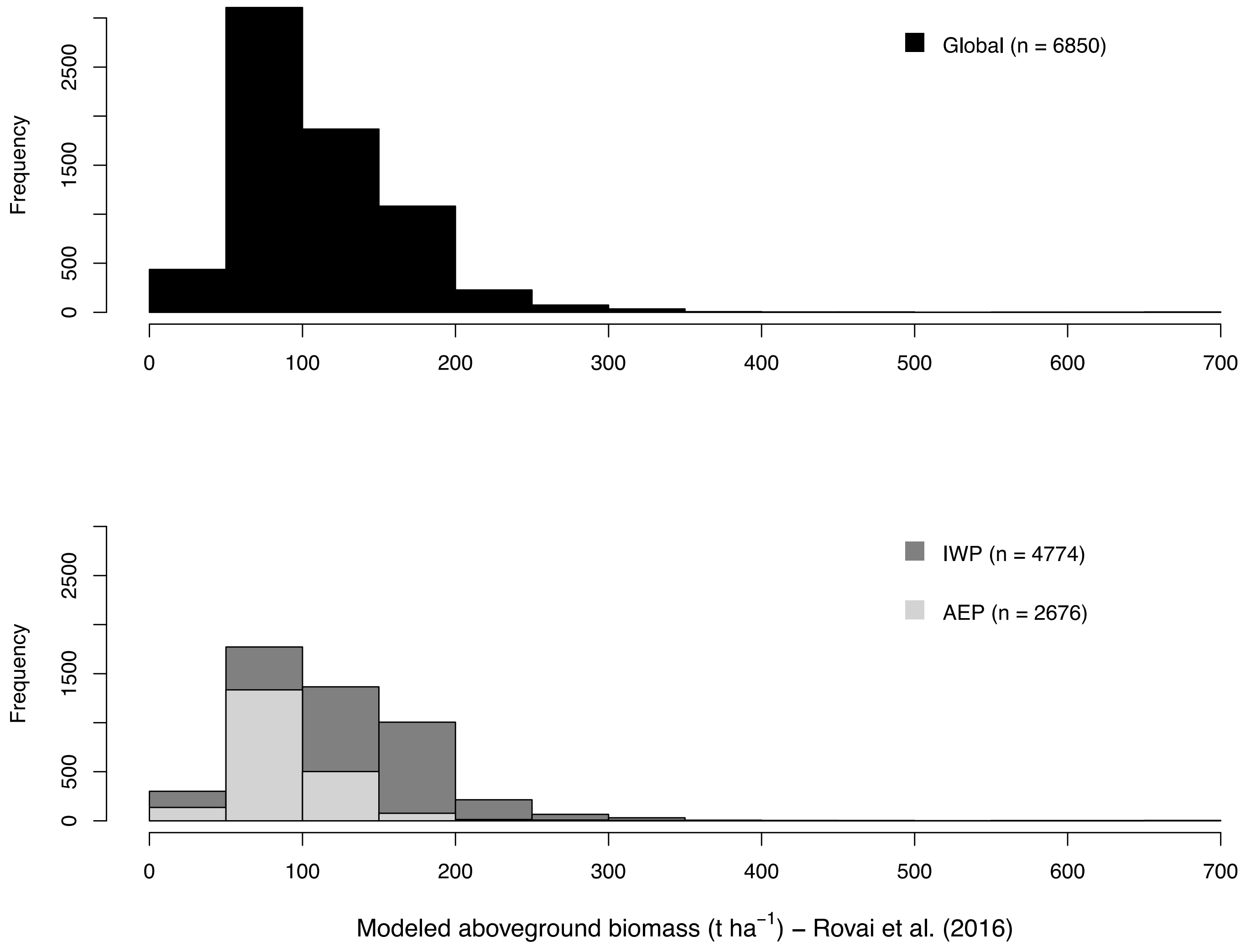
James Hutchison[1], Andrea Manica[1], Ruth Swetnam[2], Andrew Balmford[1], & Mark Spalding[3]

$$AGB\,(t\,ha^{-1}) = 0.295BIO10 + 0.658BIO11 + 0.0234BIO16 + 0.195BIO17 - 120.3.$$

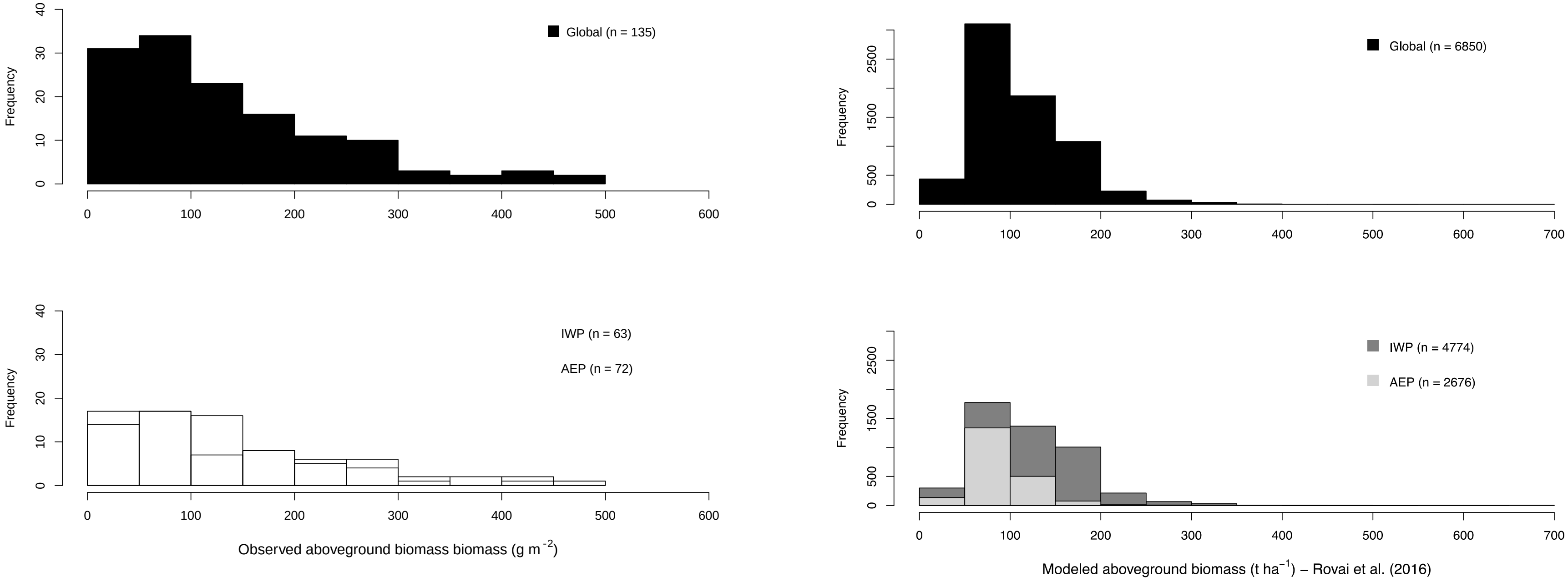




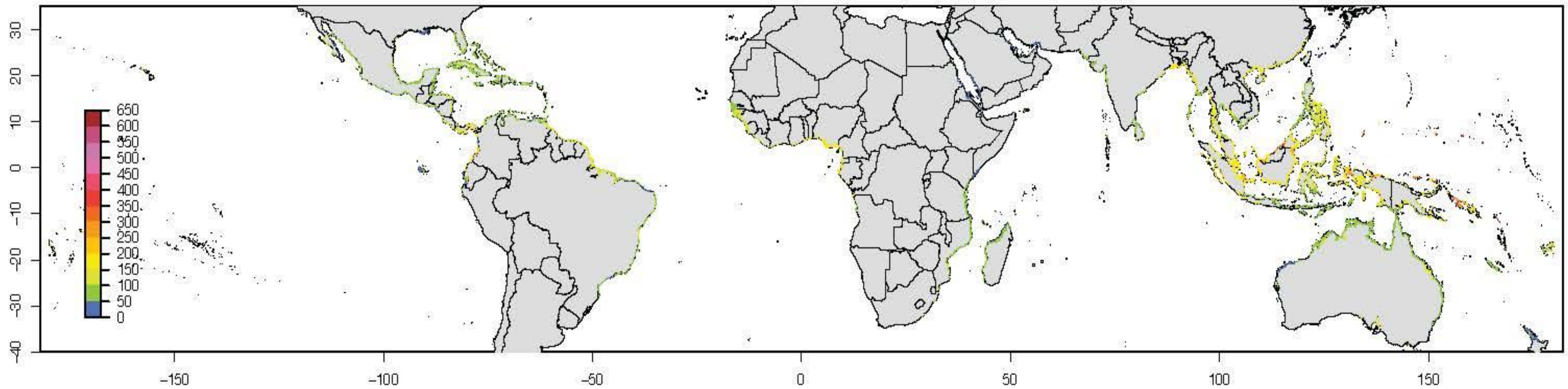
Observed aboveground biomass (t/ha)

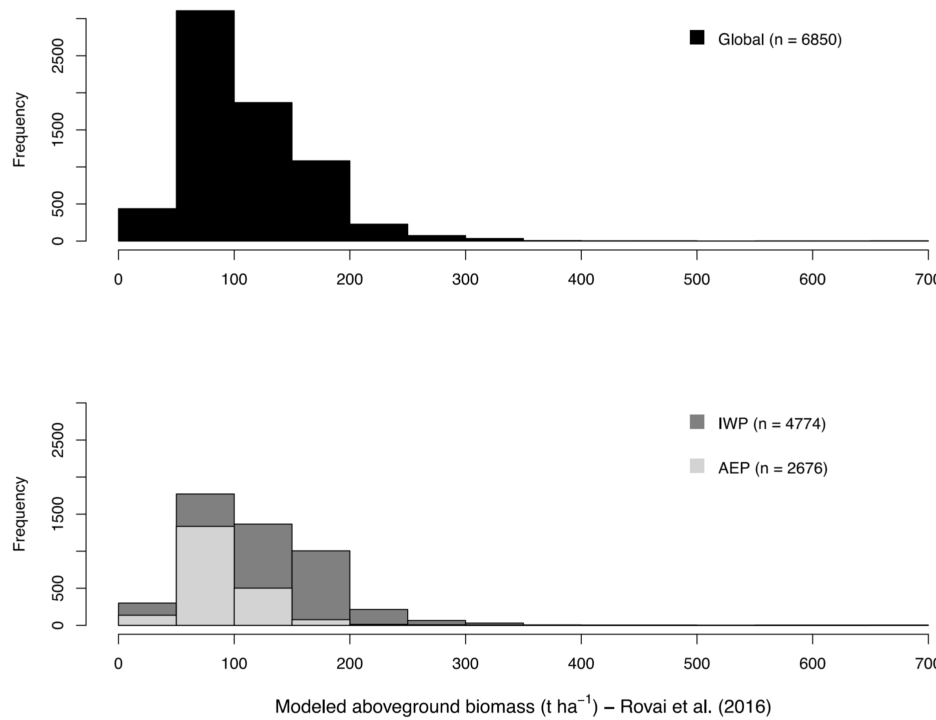


Rovai AS, Riul P, Twilley RR, Castañeda-Moya E, Rivera-Monroy VH, Williams AA, Simard M, Cifuentes-Jara M, Lewis RR, Crooks S, Horta PA[h], Schaeffer-Novelli Y, Cintrón G, Pozo-Cajas M, Pagliosa PR 2015. Scaling mangrove aboveground biomass from site-level to continental-scale. Global Ecology and Biogeography 25:286-298

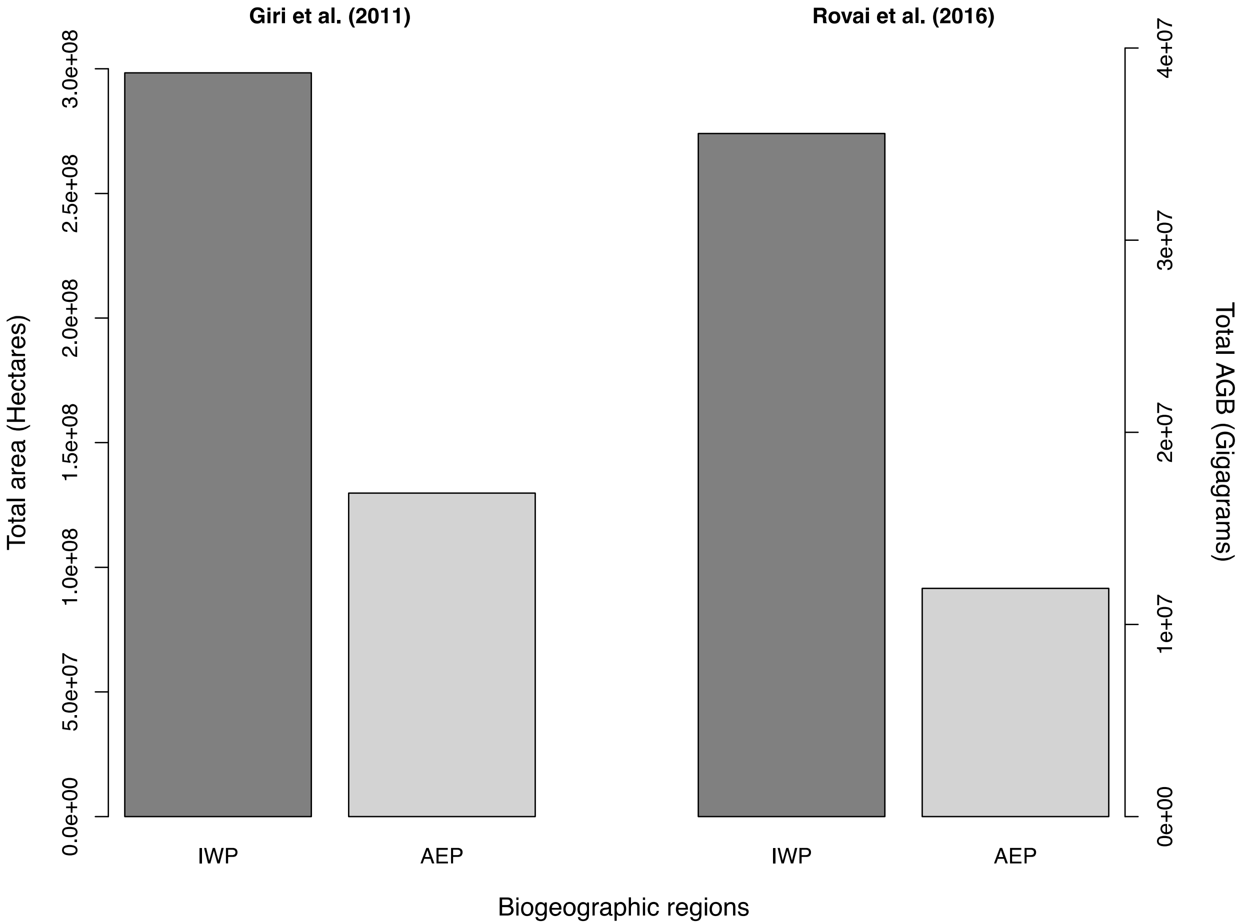


Rovai AS, Riul P, Twilley RR, Castañeda-Moya E, Rivera-Monroy VH, Williams AA, Simard M, Cifuentes-Jara M, Lewis RR, Crooks S, Horta PA[h], Schaeffer-Novelli Y, Cintrón G, Pozo-Cajas M, Pagliosa PR 2015. Scaling mangrove aboveground biomass from site-level to continental-scale. Global Ecology and Biogeography 25:286-298



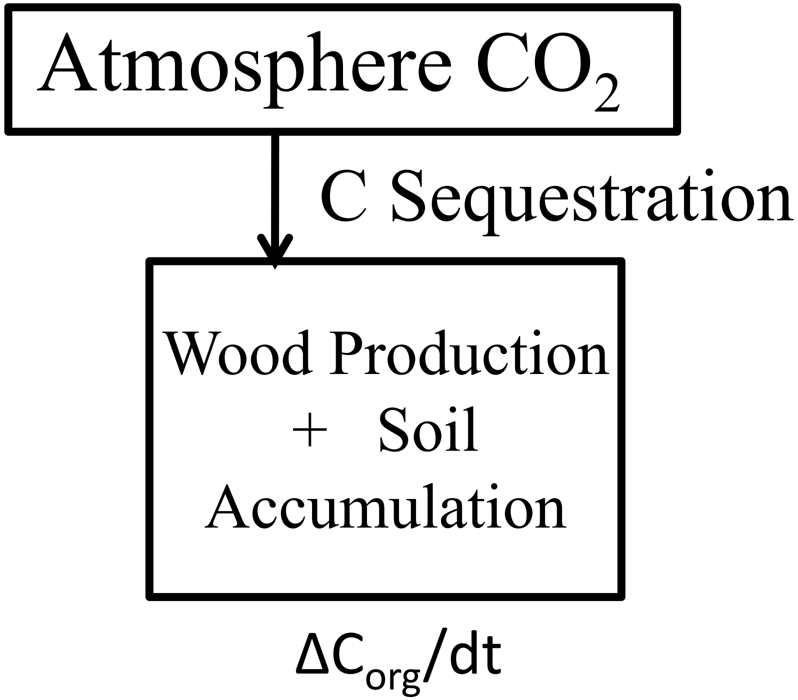


Rovai AS, Riul P, Twilley RR, Castañeda-Moya E, Rivera-Monroy VH, Williams AA, Simard M, Cifuentes-Jara M, Lewis RR, Crooks S, Horta PA[h], Schaeffer-Novelli Y, Cintrón G, Pozo-Cajas M, Pagliosa PR 2015. Scaling mangrove aboveground biomass from site-level to continental-scale. Global Ecology and Biogeography 25:286-298



Global Estimates of Aboveground Biomass

Environmental Signature Hypothesis of Carbon Dynamics in Mangrove Ecosystems. In prep
Robert R. Twilley, Andre S. Rovai, Paulo R. Pagliosa, Alessandra Larissa Fonseca, Edward Castaneda



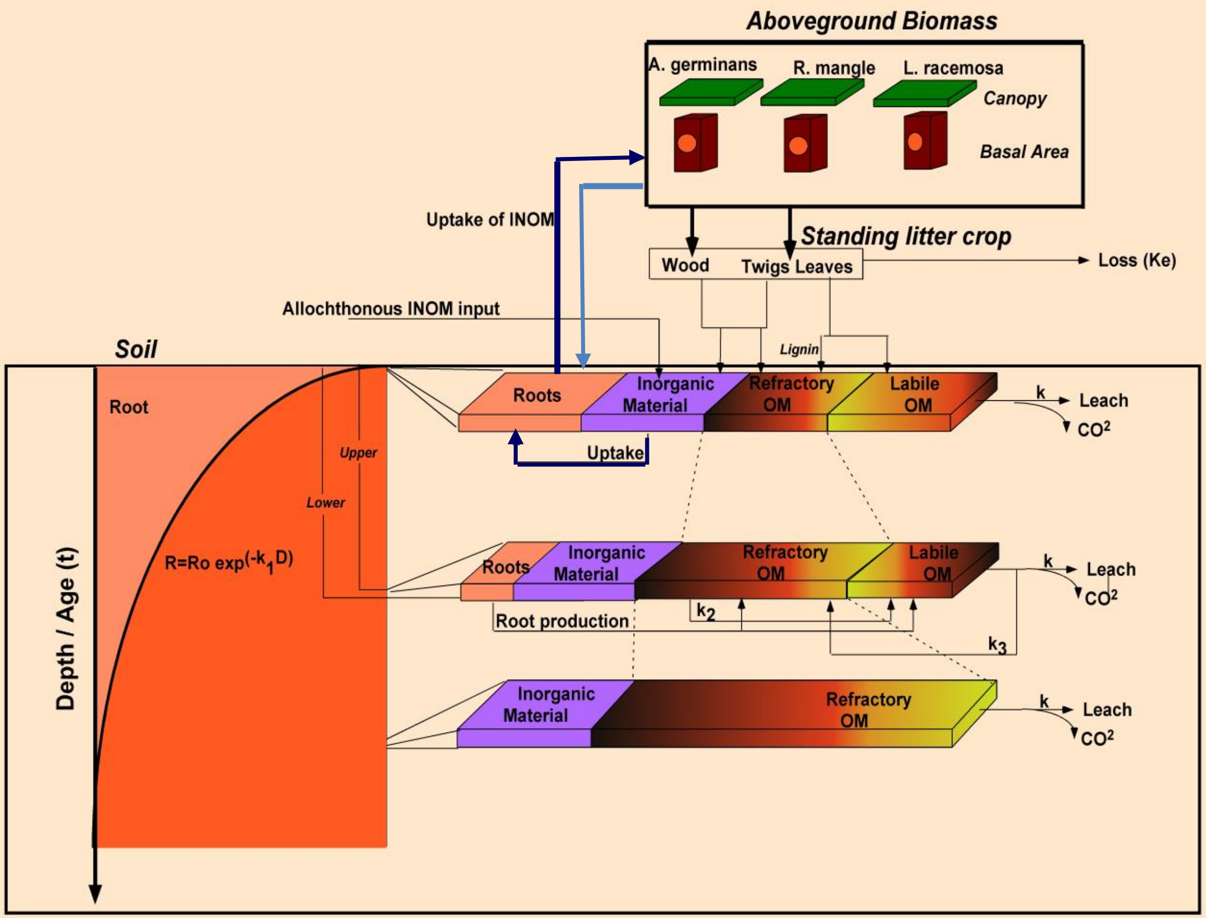
Synthesis of wood productivity estimates range from 1.1 to 14.6 t ha^{-1} yr^{-1}.

However, the number of global estimates for wood production (only about 60 sites) is much less than observed for litter fall; and much less than for estimates of AGB (135 sites).

The average wood production is about 5.8 t ha^{-1} yr^{-1}, which is very similar to global average of litter fall productivity.

4B. Global Estimates (Models) of Soil CarbonSequestration

NUMAN Conceptual Model
Y= Organic matter, N and P concentrations (distribution-depth)



Chen, R., and R.R. Twilley. 1999a. A simulation model of organic matter and nutrient accumulation in mangrove wetland soils. *Biogeochemistry* 44: 93-18

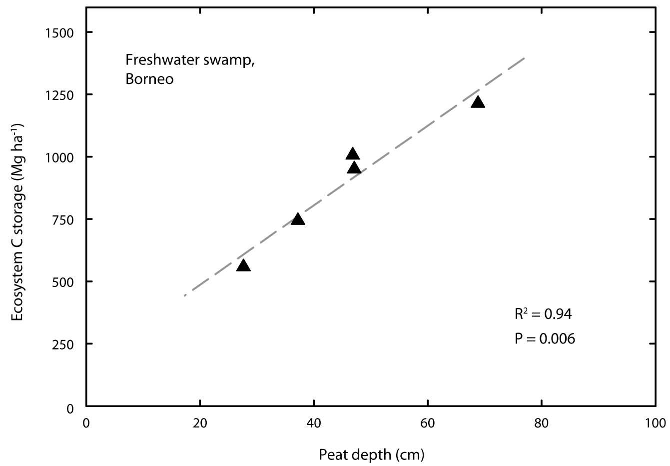


Figure 10. Variation in ecosystem carbon storage in riverine peat swamps of Tanjung Puting National Park, according to peat depth

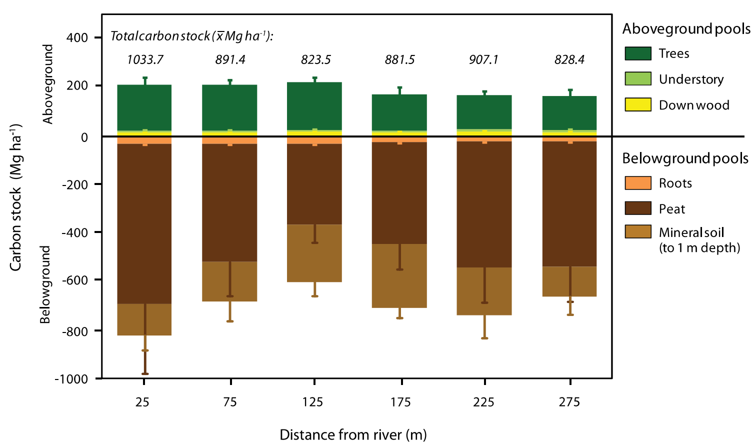


Figure 11. Ecosystem C-stocks (mean, SE) in riverine peat swamp forests of Tanjung Puting National Park, by distance from the river

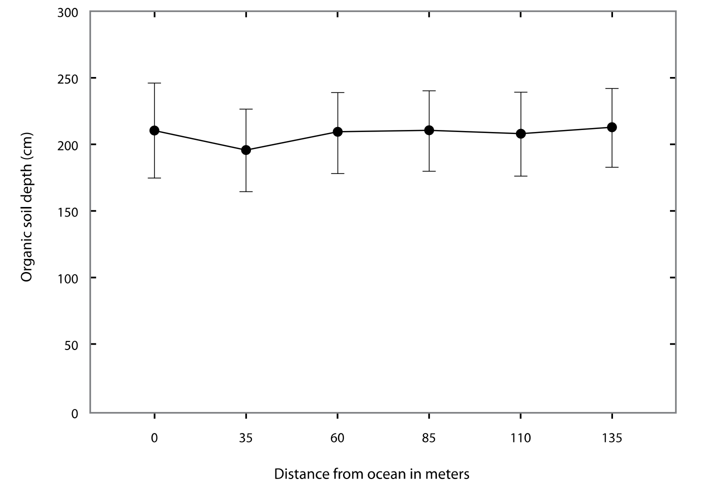


Figure 8. Depth (mean ± SE) of organic soil layers in mangroves by distance from the ocean

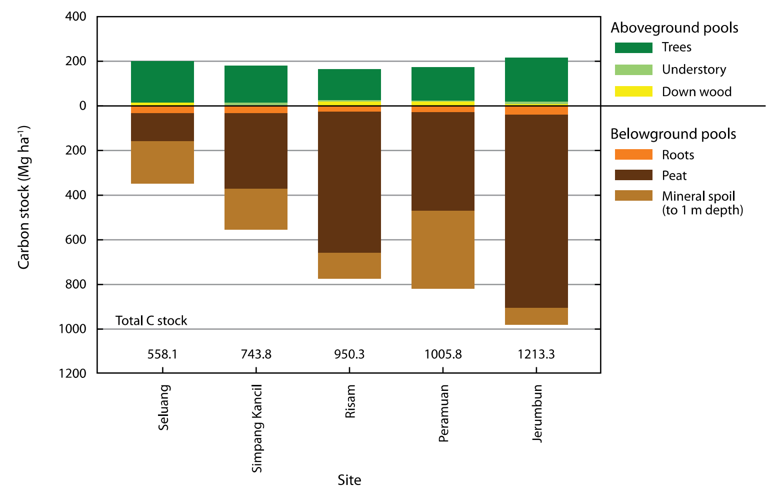
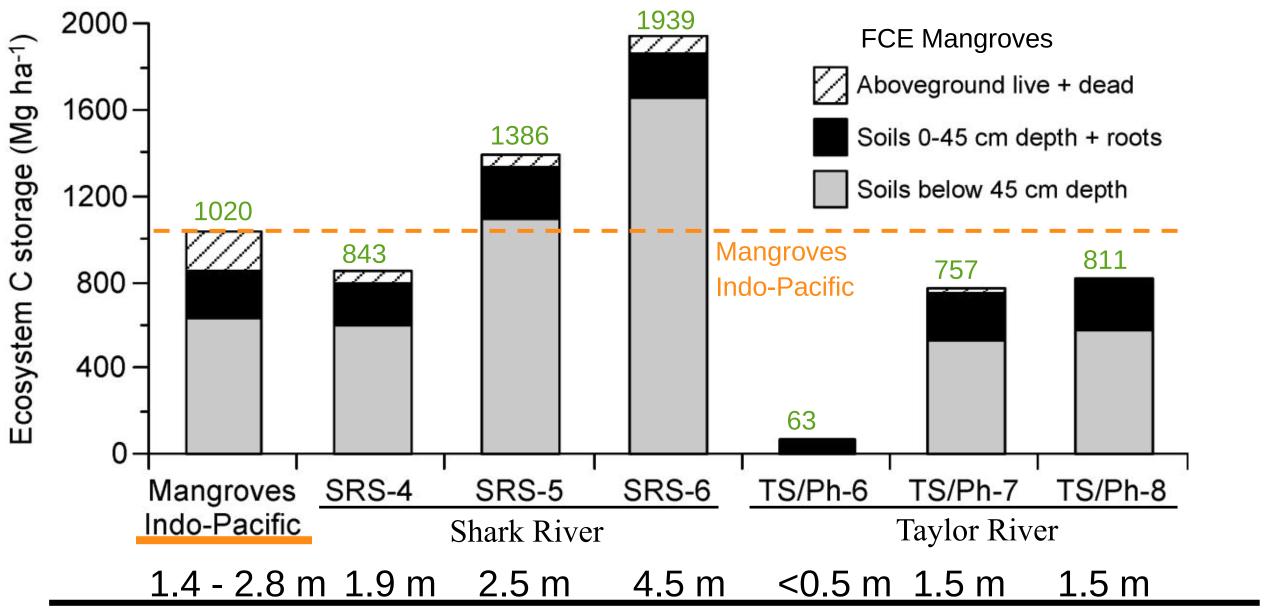


Figure 9. Above and belowground carbon pools in riverine peat swamps sampled in Tanjung Puting National Park

Murdiyarso, D., Donato, D., Kauffman, J.B., Kurnianto, S., Stidham, M. and Kanninen, M., 2009. Carbon storage in mangrove and peatland ecosystems: a preliminary account from plots in Indonesia.

➢ Shark River: 1120 ± 316 Mg C ha^{-1}



Total Soil Peat Depth (to underlying bedrock)

Importance of depth to integrate carbon stocks in mangroves.

Comparison of aboveground biomass and soil reservoirs to carbon inventories

Donato, D.C., J.B. Kauffman, D. Murdiyarso, S. Kurnianto, M. Stidham, and M. Kanninen. 2011. Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience* 4: 293-297.

Castaneda-Moya, E., R. R. Twilley, V.H. Rivera-Monroy, B.D. Marx, C.Coronado-Molina,and S.M. L. Ewe. 2011. Patterns of Root Dynamics in Mangrove Forests Along Environmental Gradients in the Florida Coastal Everglades, USA. *Ecosystems*, 14: 1178-1195. DOI: 10.1007/s10021-011-9473-3

Castañeda-Moya, E., Twilley, R.R. & Rivera-Monroy, V.H. (2013) Allocation of biomass and net primary productivity of mangrove forests along environmental gradients in the Florida Coastal Everglades, USA, *Forest Ecology and Management*, 307 226–241

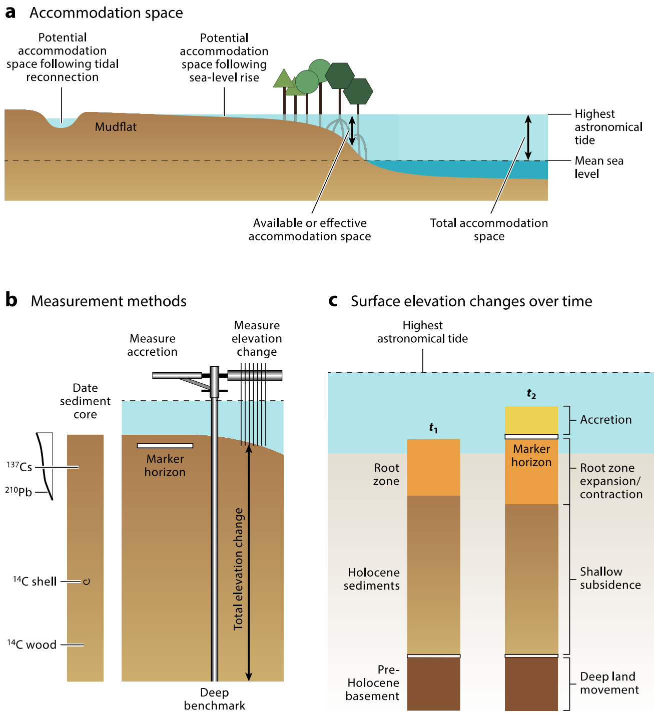


Figure 4

(*a*) Schematic cross section of substrate beneath mangroves, showing variations in accommodation space. (*b*) Measurement methods adopted to assess sedimentary processes beneath mangroves. (*c*) Surface elevation changes that occur over time.

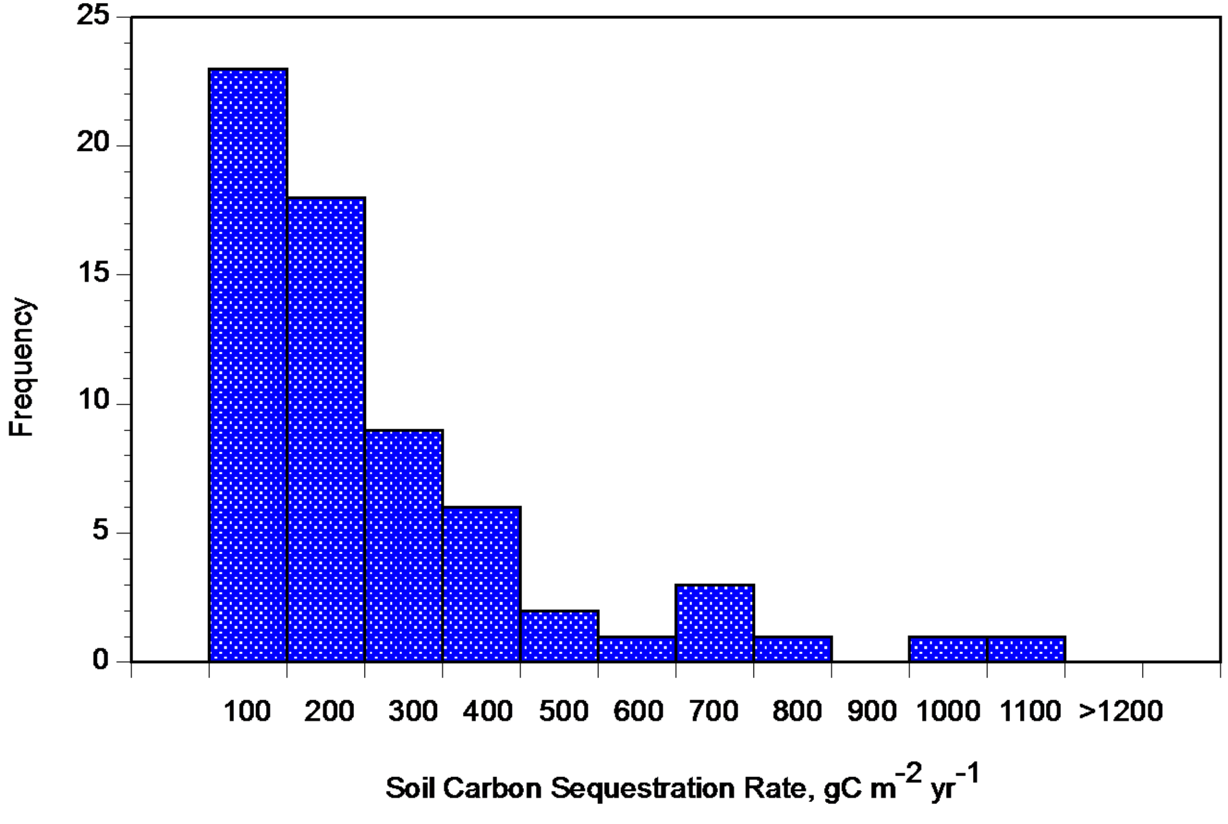
Mangroves NEP

$\Delta C_{org}/dt$

Table 1 Published ranges of surface elevation change, vertical accretion, and subsurface adjustment for different mangrove hydrogeomorphic settings determined using surface elevation table–marker horizon (SET-MH) methods (for a full list of references, see Krauss et al. 2014)

Hydrogeomorphic setting	Surface elevation change (mm year^{-1})	Vertical accretion (mm year^{-1})	Subsurface change (mm year^{-1})
Fringe	−1.3 to +5.9	+1.6 to +8.6	−9.7 to +2.4
Riverine	+0.9 to +6.2	+6.5 to +13.0	−11.2 to −0.2
Basin/interior	−3.7 to +3.9	+0.7 to +20.8	−19.9 to +2.8
Scrub	−1.1	−2.0	−3.1
Overwash	−0.6 to −2.5	+4.4 to +6.3	−3.8

Woodroffe, C, K. Rogers, K.L. McKee, C.E. Lovelock, I.A. Mendelssohn, and N. Saintilan, 2016. Mangrove Sedimentation and Response to Relative Sea-Level Rise. Annu. Rev. Mar. Sci. 8:243–66

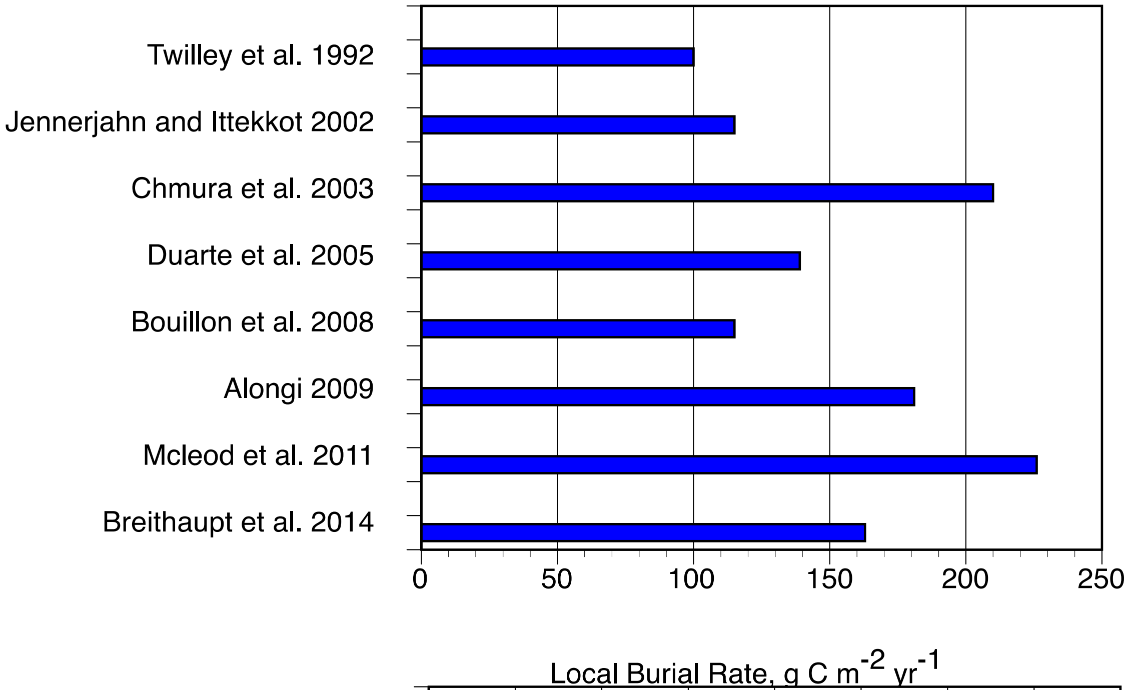


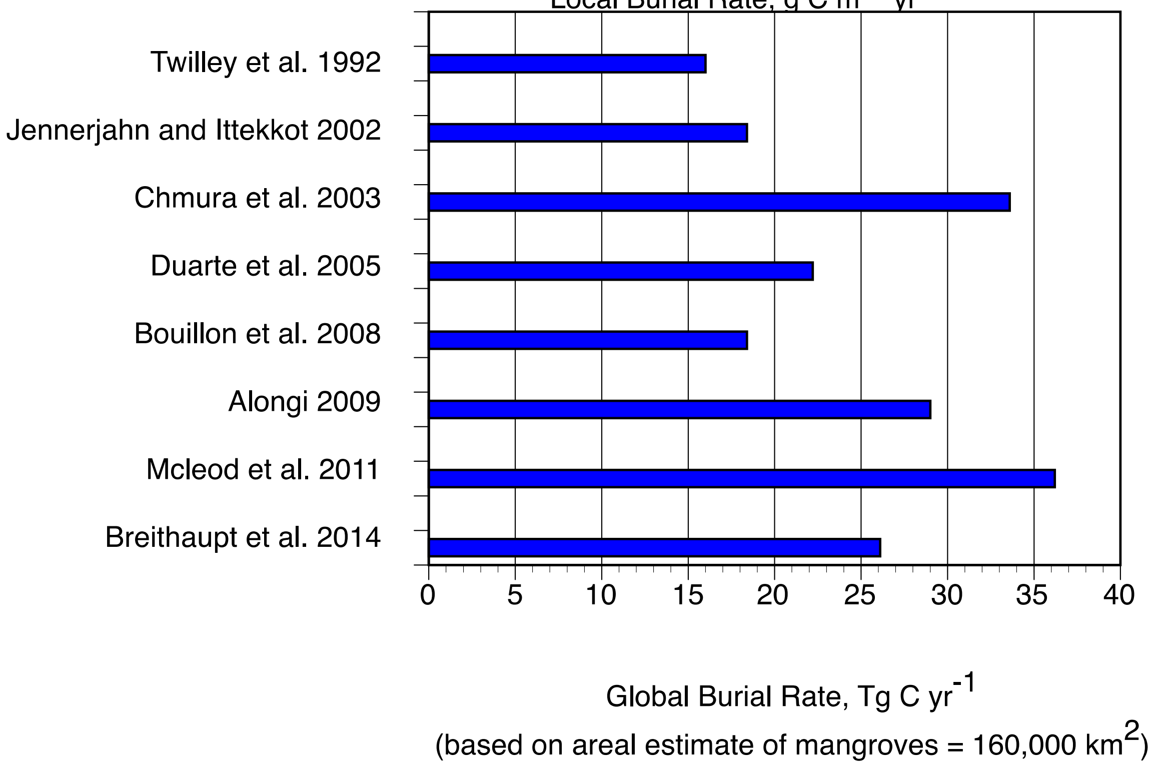
Rates can range from 4 to 1000 gC m^{-2} yr^{-1}

The largest proportion of observations, 41 of the 65 sites, occur from 4 to 200 gC m^{-2} yr^{-1},

Average = 224 gC m^{-2} yr^{-1} for all sites.

Breithaupt, J. L., J. M. Smoak, T. J. Smith, C. J. Sanders, and A. Hoare (2012), Organic carbon burial rates in mangrove sediments: Strengthening the global budget, Global Biogeochem. Cycles, 26, GB3011, doi:10.1029/2012GB004375



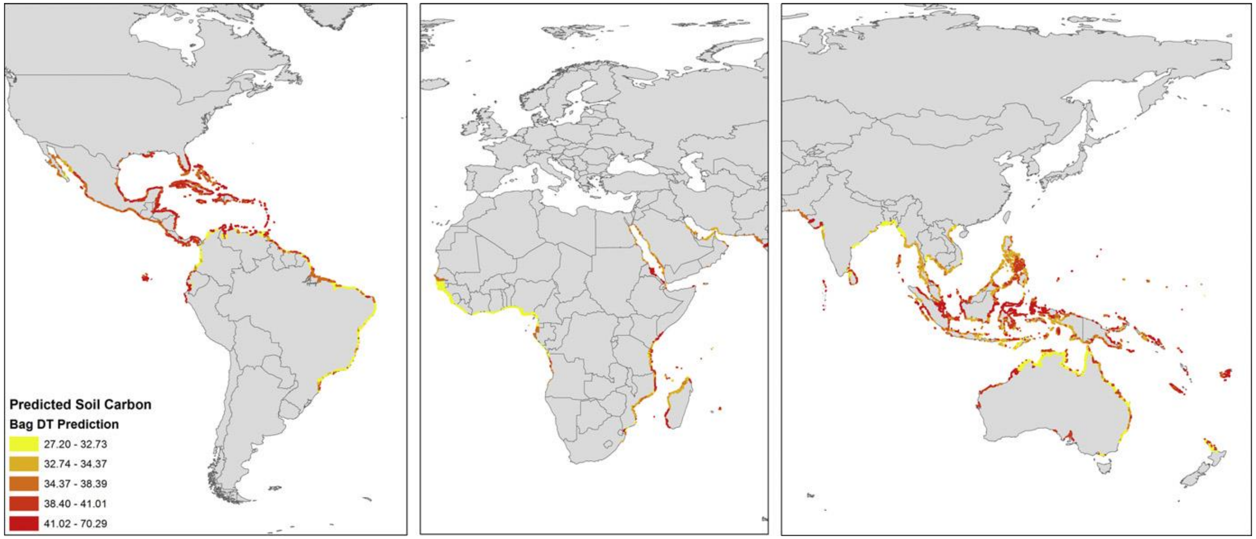


Soil Burial Rates

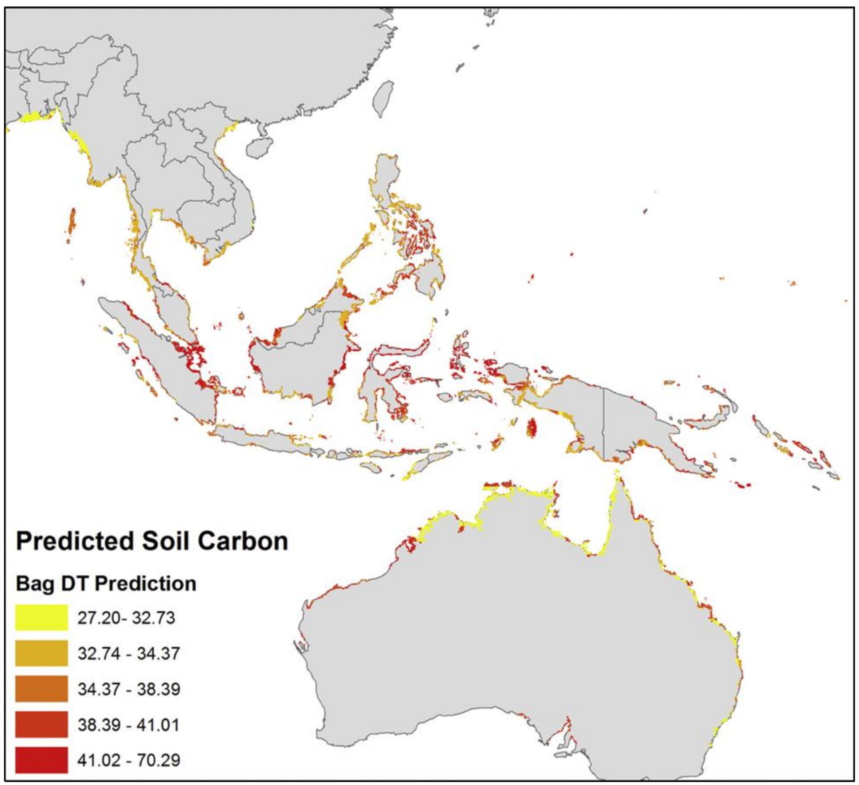
Rates can range from 17 to 36 Tg C yr^{-1}

Average = 25 Tg C yr^{-1}

Breithaupt, J. L., J. M. Smoak, T. J. Smith, C. J. Sanders, and A. Hoare (2012), Organic carbon burial rates in mangrove sediments: Strengthening the global budget, Global Biogeochem. Cycles, 26, GB3011, doi:10.1029/2012GB004375

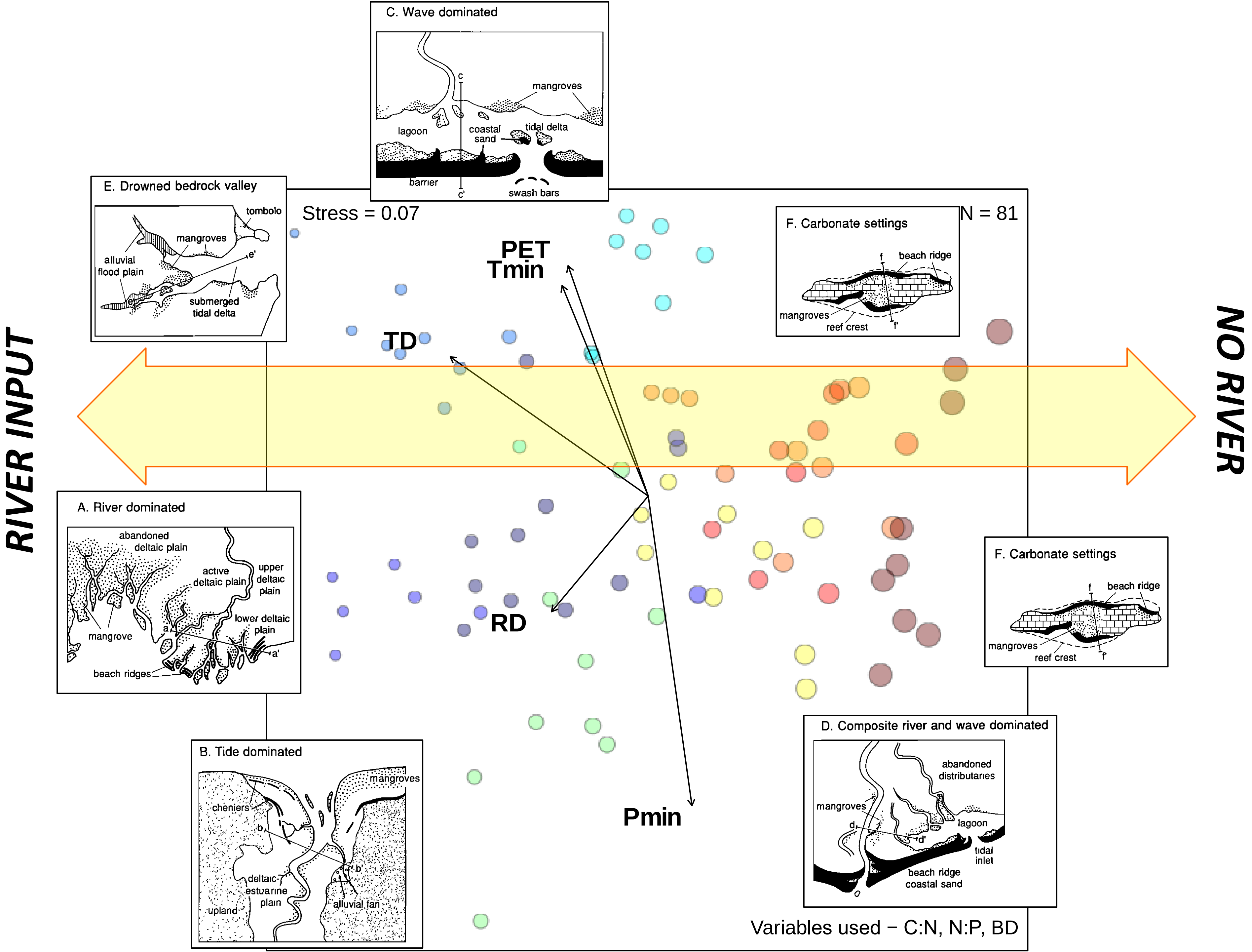


Jardine, S. L. & Siikamäki, J. V. 2014. A global predictive model of carbon in mangrove soils. Environ. Res. Lett. 9, 104013



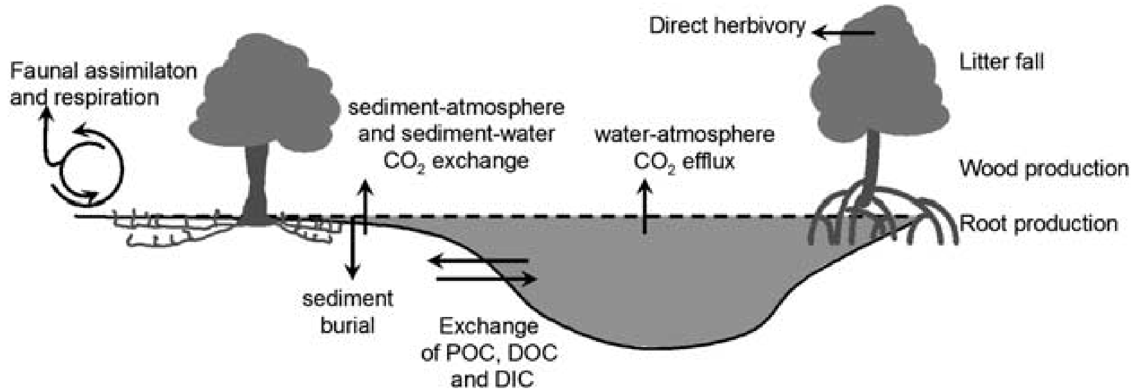
Developing global models of carbon sequestration in mangrove soils is one of the great challenges – both stocks and the annual burial rates – along with impacts from land use change.

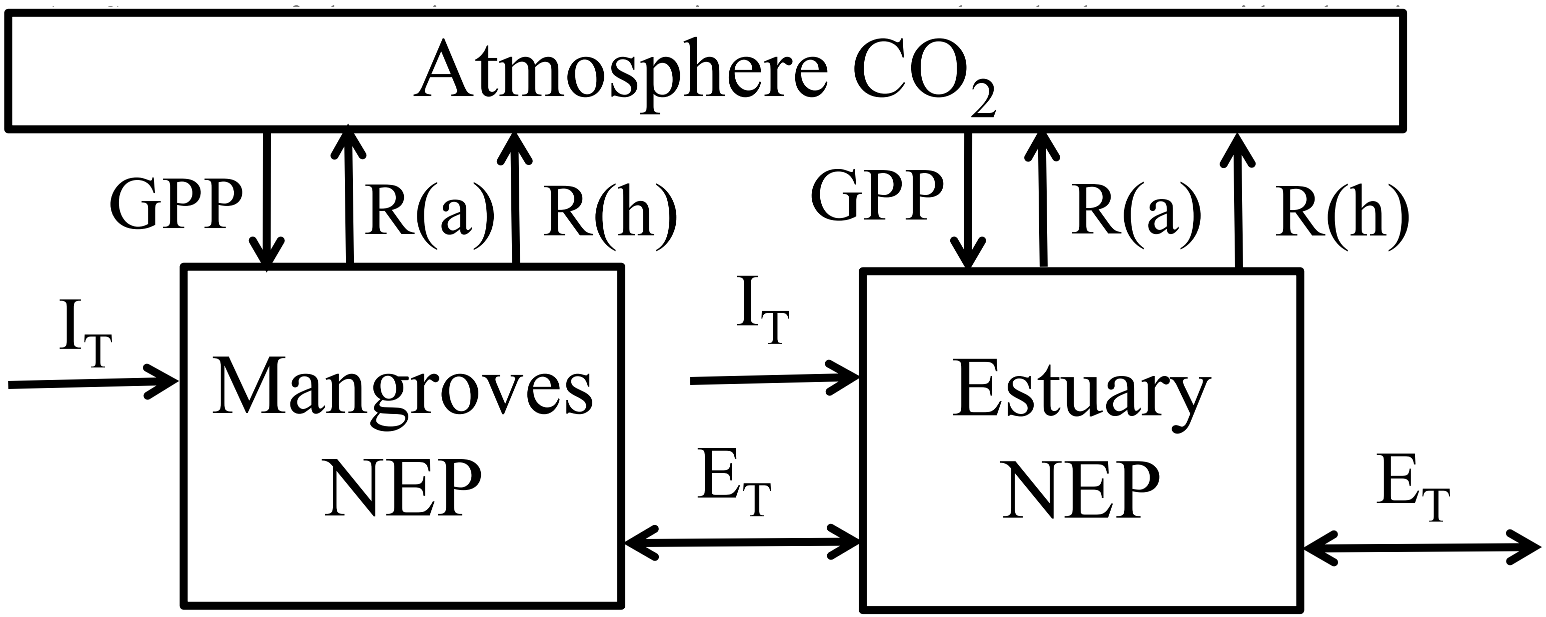
Armentano analysis for temperate marshes….



RIVER INPUT
NO RIVER
Stress = 0.07
N = 81
PET
Tmin
TD
RD
Pmin
Variables used − C:N, N:P, BD
C. Wave dominated
mangroves
lagoon
coastal sand
tidal delta
barrier
swash bars
E. Drowned bedrock valley
tombolo
mangroves
alluvial flood plain
submerged tidal delta
F. Carbonate settings
beach ridge
mangroves
reef crest
A. River dominated
abandoned deltaic plain
active deltaic plain
upper deltaic plain
lower deltaic plain
mangrove
beach ridges
B. Tide dominated
mangroves
cheniers
deltaic-estuarine plain
upland
alluvial fan
D. Composite river and wave dominated
abandoned distributaries
mangroves
lagoon
tidal inlet
beach ridge coastal sand

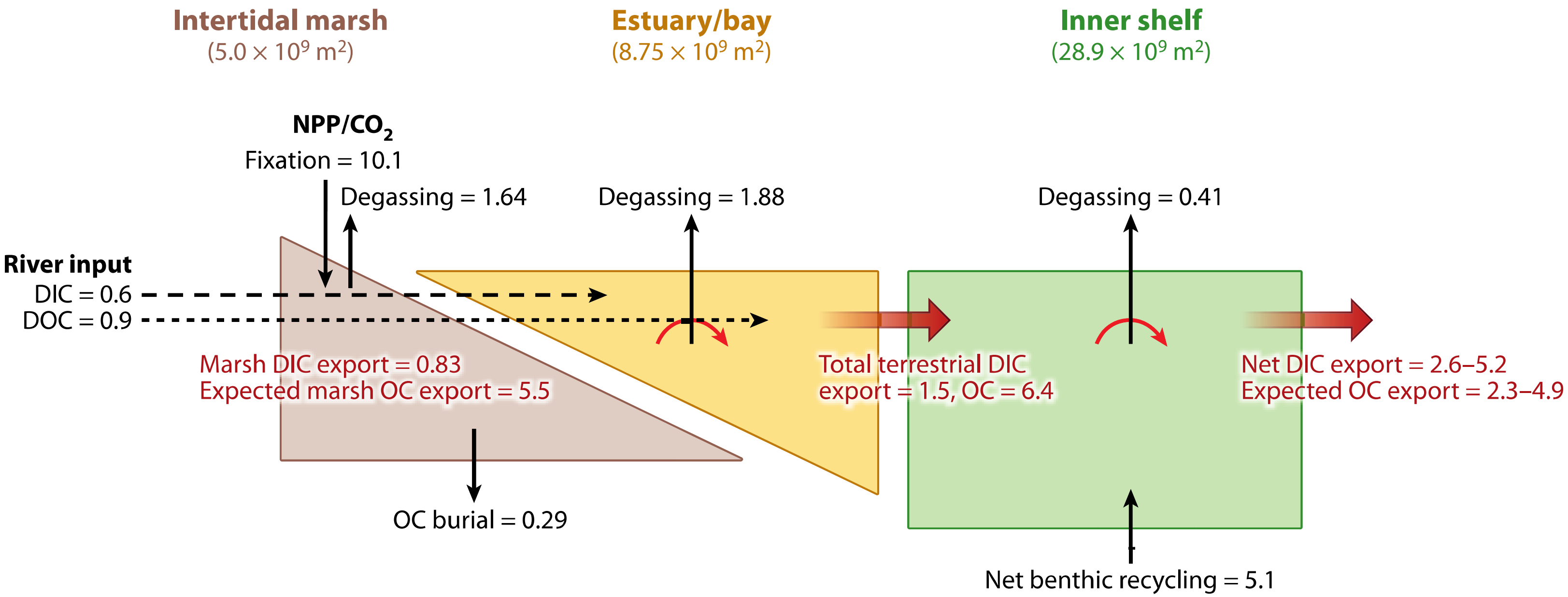
7. But What about the Fate of Carbon Outwelling?
C Sequestration?



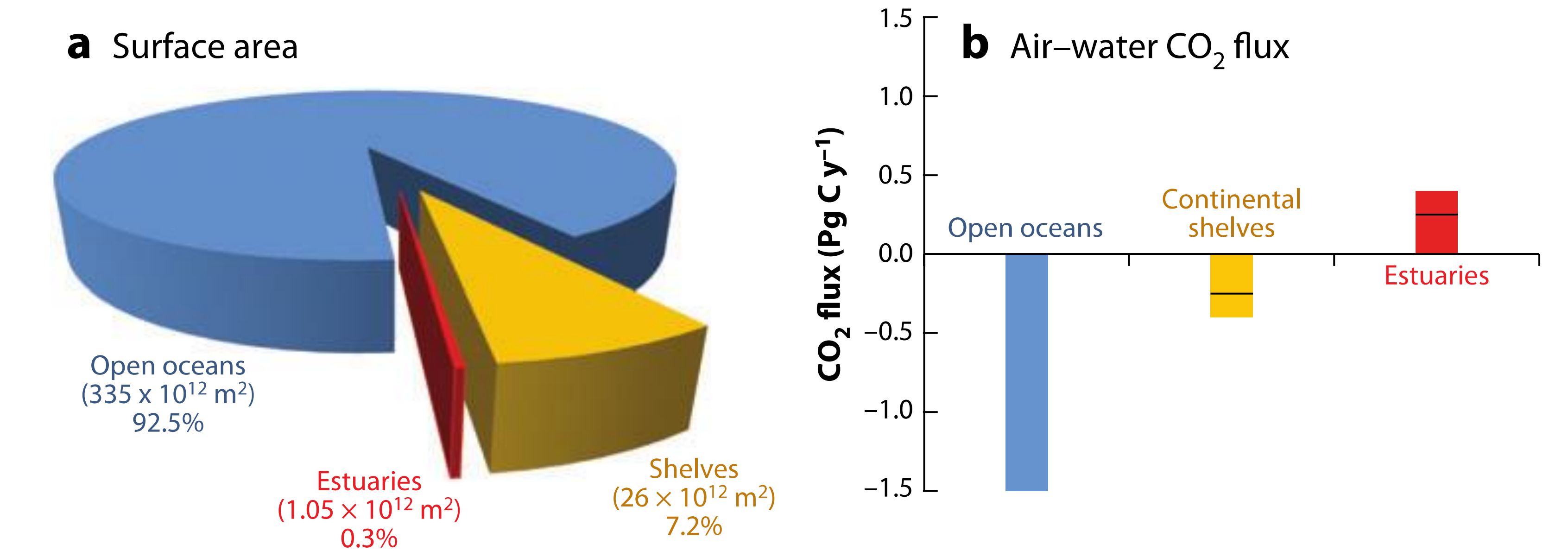


Have to get the export right?

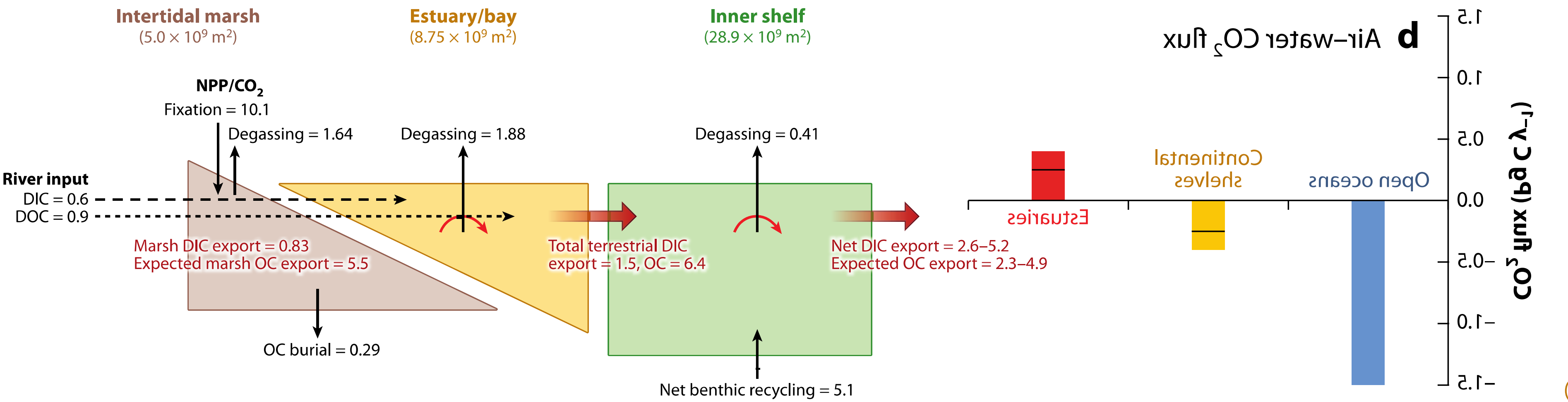
Net E_T = 550 gC m^{-2} yr^{-1}



Cai, W.J., 2011. Estuarine and coastal ocean carbon paradox: CO_2 sinks or sites of terrestrial carbon incineration?. Annual Review of Marine Science, 3, pp.123-145



Cai, W.J., 2011. Estuarine and coastal ocean carbon paradox: CO_2 sinks or sites of terrestrial carbon incineration?. Annual Review of Marine Science, 3, pp.123-145



Estuaries are heterotrophic ecosystems with negative NEP.

Is respiration the fate of mangrove organic carbon to coastal ocean? What fraction is stored in coastal sediments?

Cai, W.J., 2011. Estuarine and coastal ocean carbon paradox: CO_2 sinks or sites of terrestrial carbon incineration?. Annual Review of Marine Science, 3, pp.123-145

C. Giri *et al.*

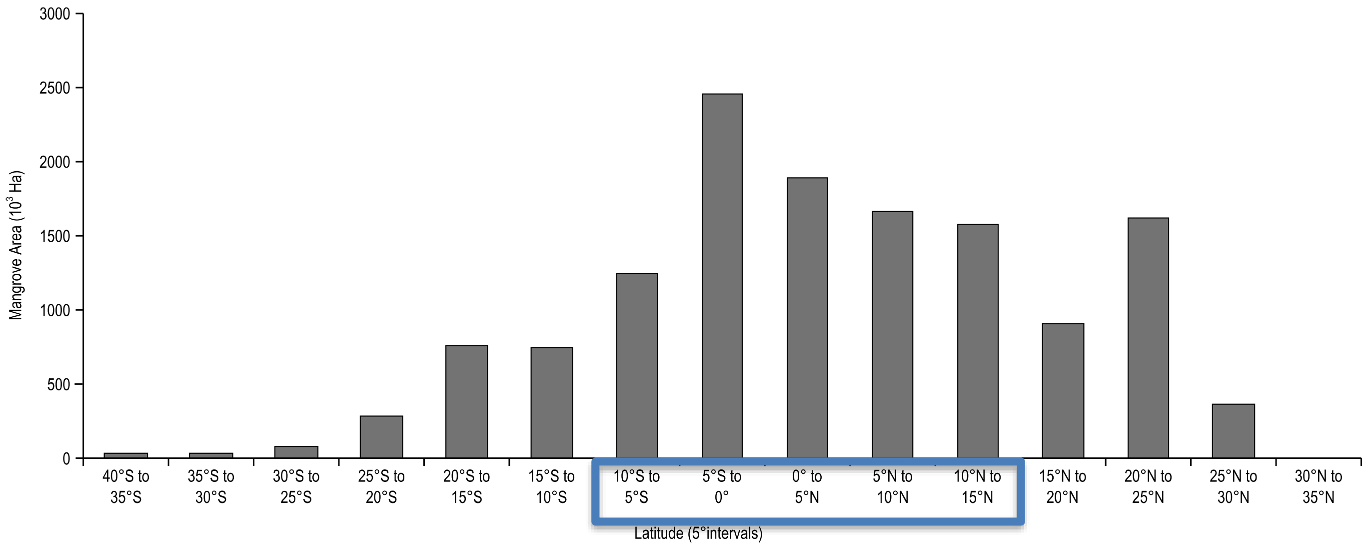


Figure 3 Latitudinal distribution of mangrove forest of the world.

Giri, C., E. Ochieng, L.L. Tieszen, Z. Zhu, A. Singh, T. Loveland, J. Masek, and N. Duke. 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography* 20: 154-159

DECEMBER 2002 DAI AND TRENBERTH

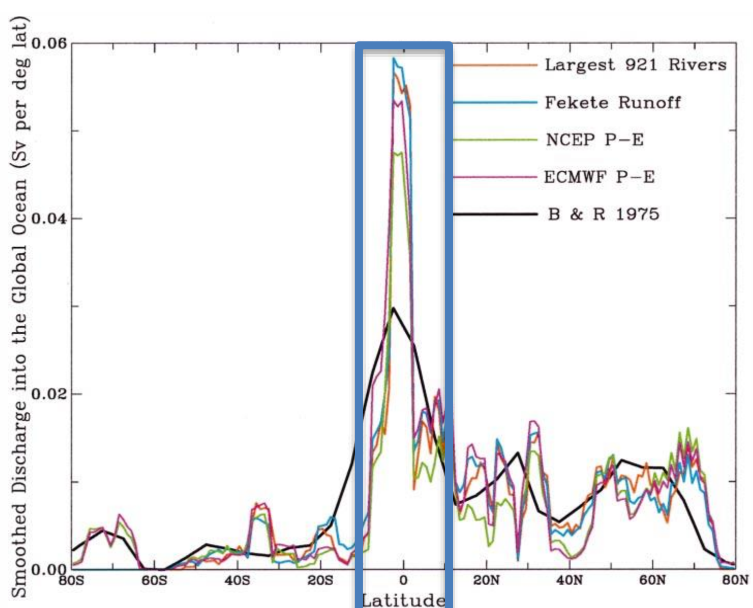
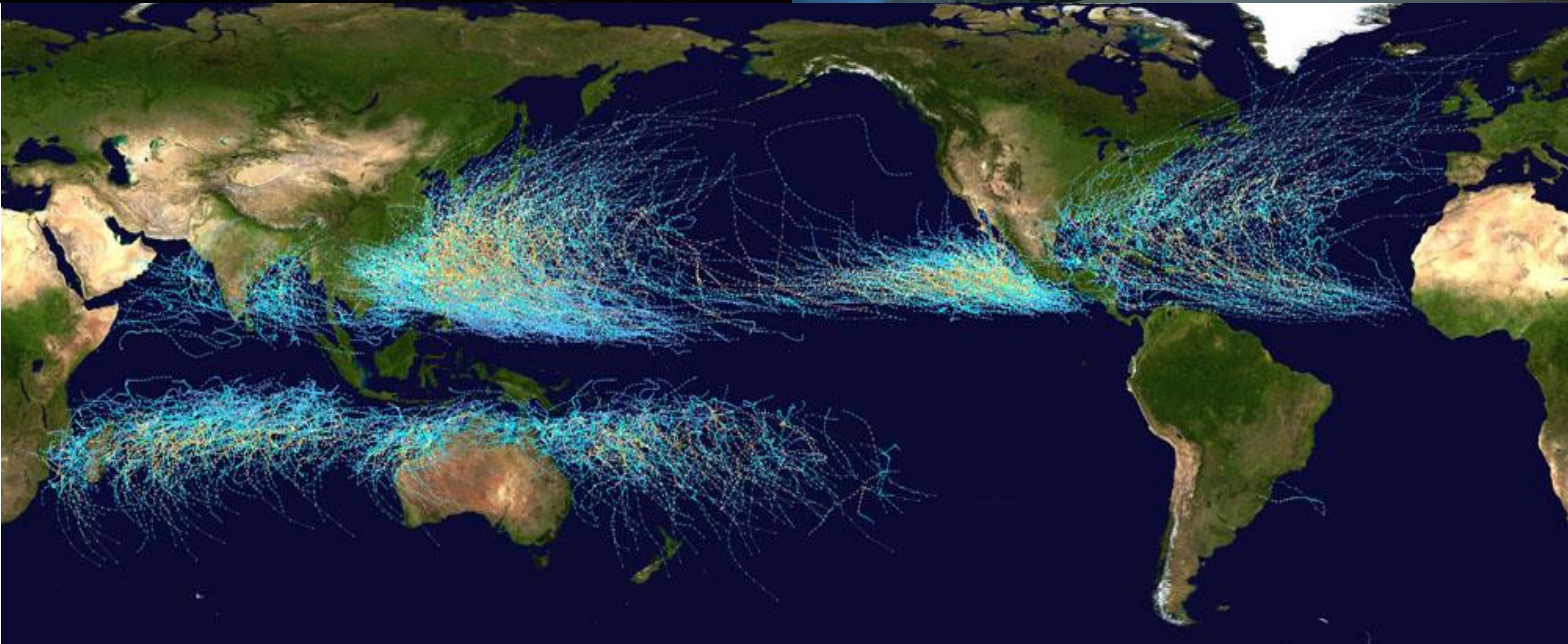


FIG. 8. Annual discharge into the global ocean smoothed using a 5° lat running mean from four different cases, compared with that of Baumgartner and Reichel (1975).

The significance of this fate of organic carbon is combination of where are mangroves located relative to flux of runoff to the oceans – wet tropics.

8. Accounting for Mangrove Disturbance NEP Recovery – Carbon Sequestration





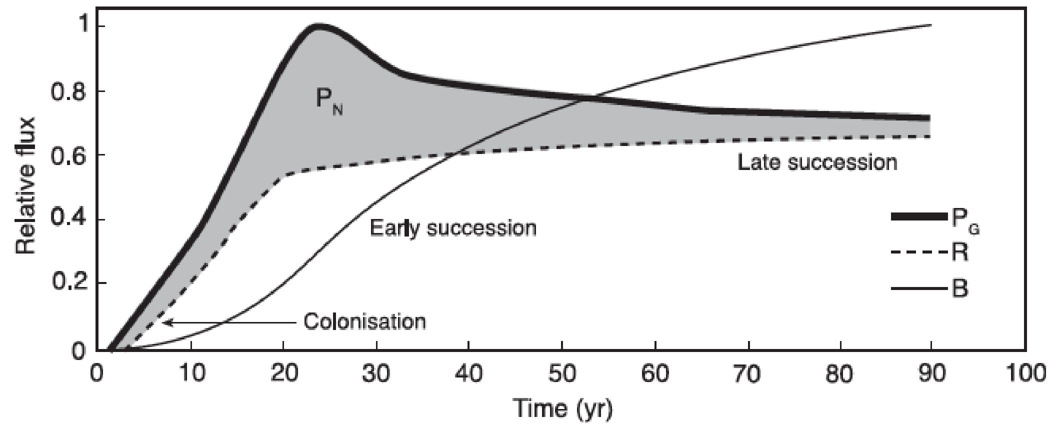
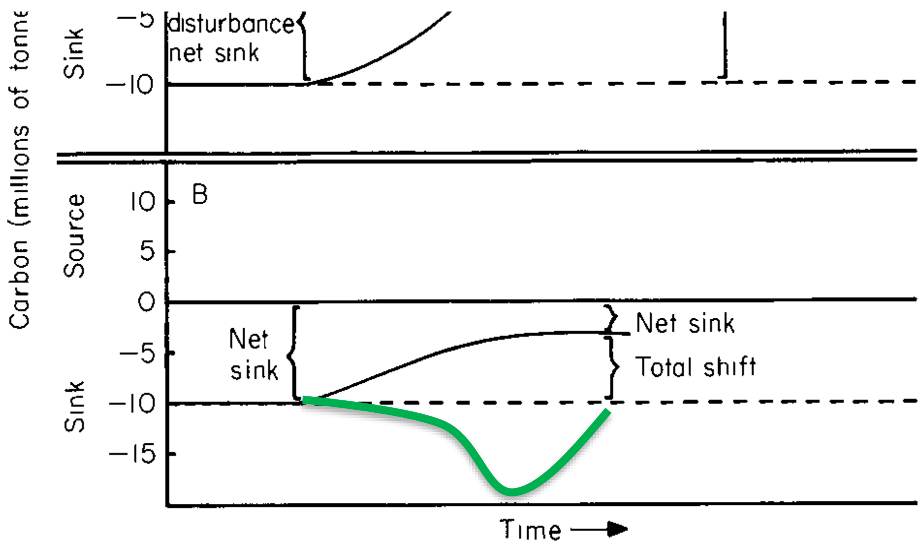


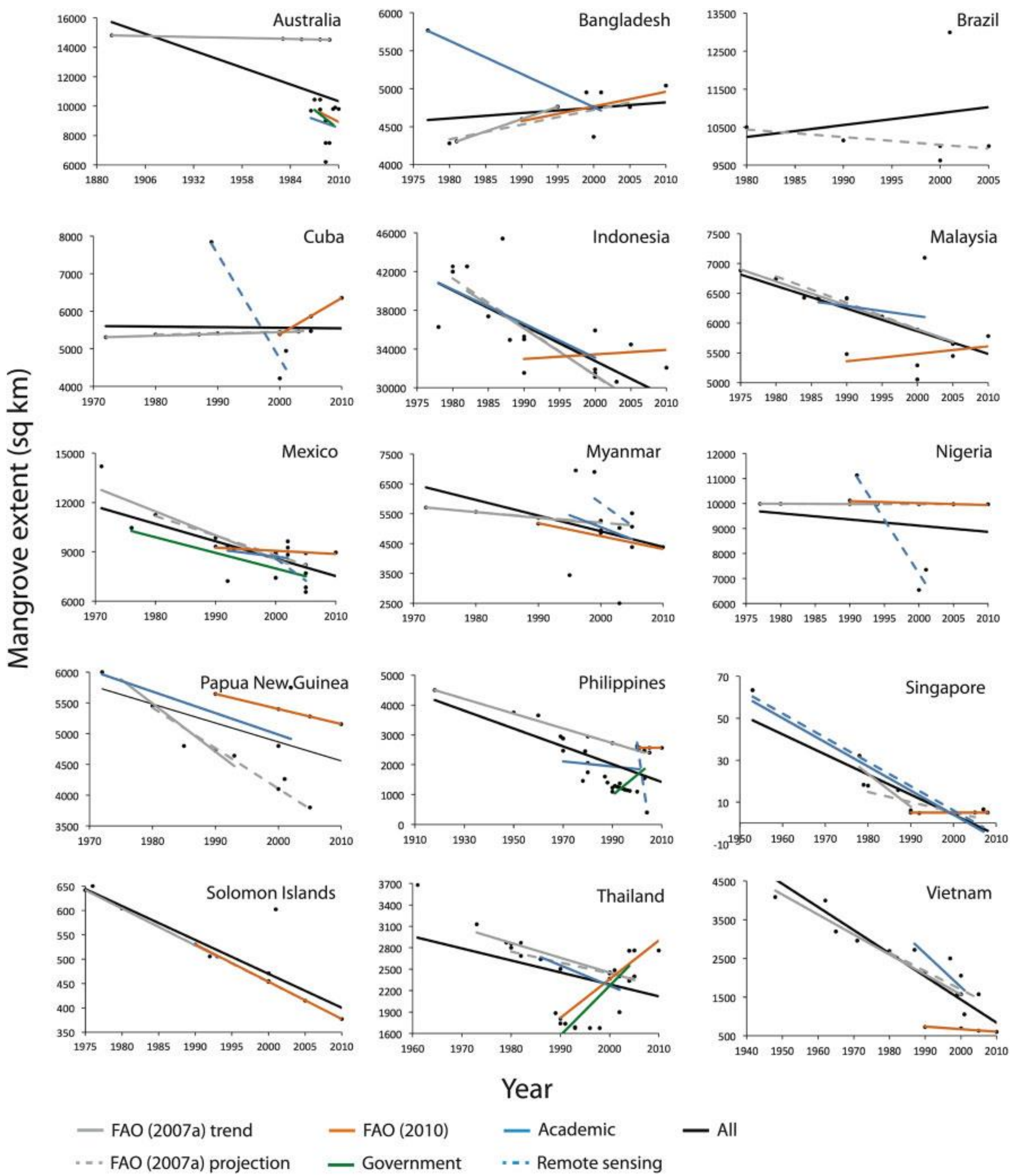
Fig. 1 – The original concept of ecosystem development over time.Modified from Odum (1969).



. Carbon exchange in two hypothetical wetland regions subject to artificial drainage. In
iginal net carbon sink is totally lost, and a net carbon source has been created. In B, t
currently functions as a diminished carbon sink because CO_2 release in drained wetlan
is lower than net CO_2 fixation in undrained wetlands.

Net sink
Increase shift

D. A. Friess and E. L. Webb



Summary of the different trend lines that can be extrapolated for mangrove extent in Australia, Bangladesh, Brazil, Cuba, Indonesia, Malaysia, Mexico, Myanmar, Nigeria, Papua New Guinea, the Phillippines, Singapore, the Soloman Islands, Thailand and Vietnam.

Daniel A. Friess and Edward L. Webb. 2014. Variability in mangrove change estimates and implications for the assessment of ecosystem service provision Global Ecology and Biogeography, 23, 715–725

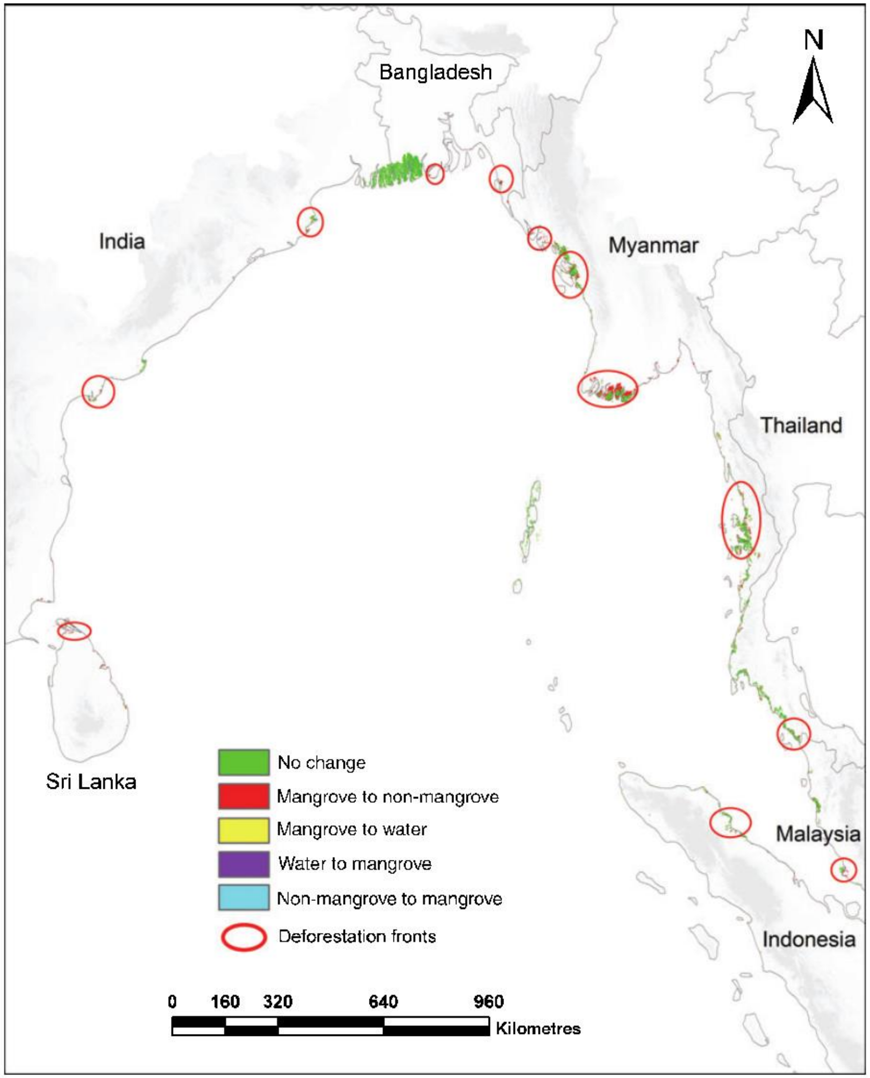
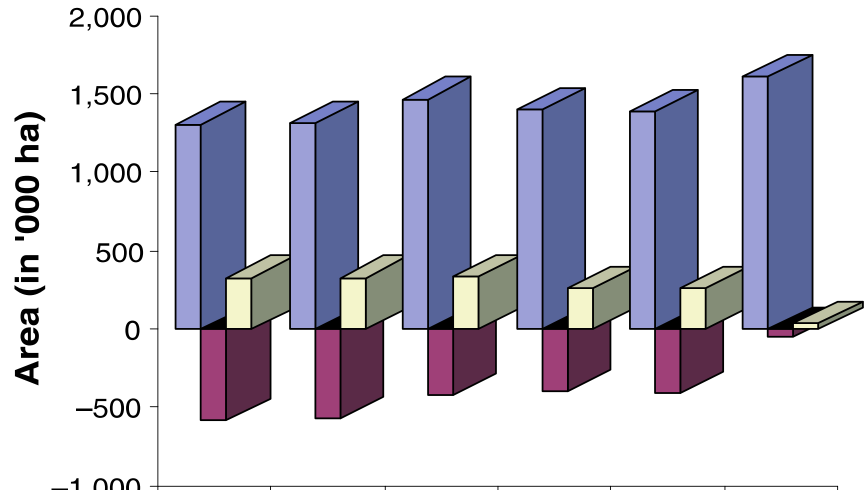


Figure 1 Change in mangrove forest cover change from 1975 to 2005.

Giri, C, Zhu, Z, Tieszen, LL, Singh, A, Gillette, S, & Kelmelis, JA. (2008). Mangrove forest distributions and dynamics (1975–2005) of the tsunami-affected region of Asia. Journal of Biogeography, *35*(3), 519-528



	1975–2005	1975–2000	1975–1990	1990–2000	1990–2005	2000–2005
No change (ha)	1,305,542	1,312,760	1,469,005	1,397,608	1,387,924	1,607,716
Deforestation (ha)	–584,363	–577,884	–426,432	–398,695	–407,601	–50,212
Afforestation (ha)	327,600	326,488	328,844	261,339	256,279	36,348

Figure 2. Areal estimate of deforestation and afforestation from 1975 to 2005.

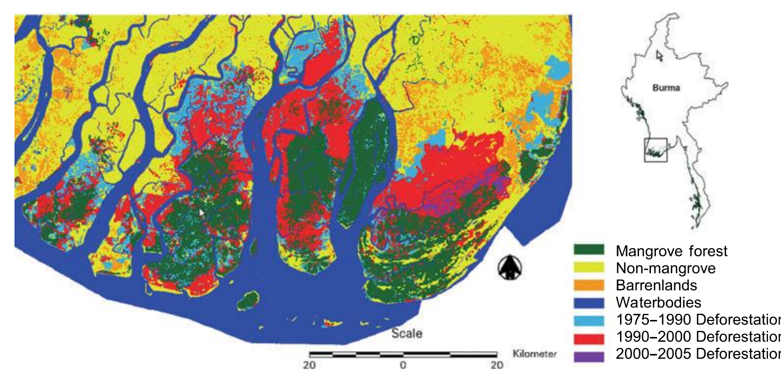


Figure 3 Spatial distribution of mangrove deforestation in Ayeyarwady Delta, Burma, during 1975–90, 1990–2000 and 2000–05.

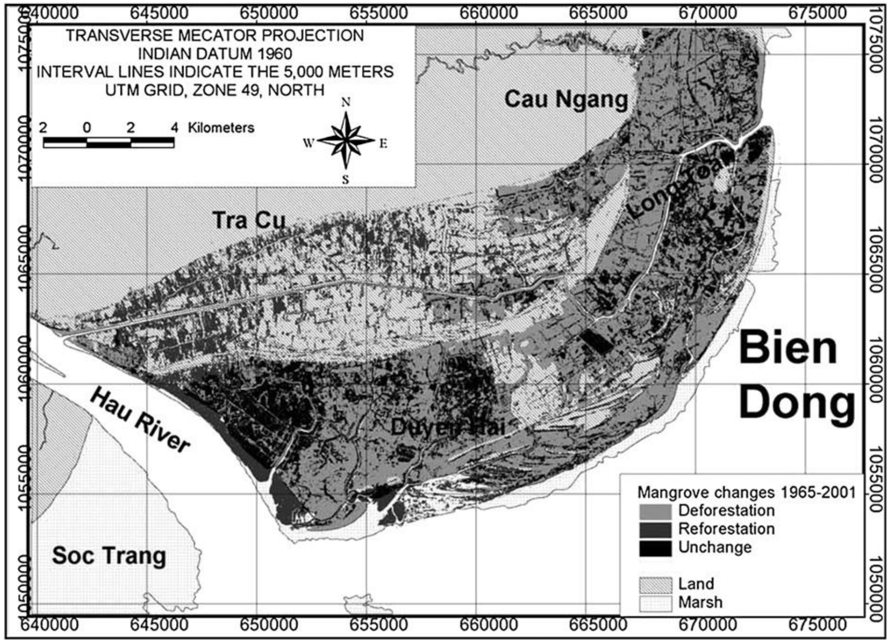


Fig. 4 (*continued*).

Thu, Phan Minh, & Populus, Jacques. (2007). Status and changes of mangrove forest in Mekong Delta: Case study in Tra Vinh, Vietnam. *Estuarine, Coastal and Shelf Science, 71*(1–2), 98-109.

Summary: Evidence of reforestation is about 10% of the change; deforestation is about 20 to 60%.

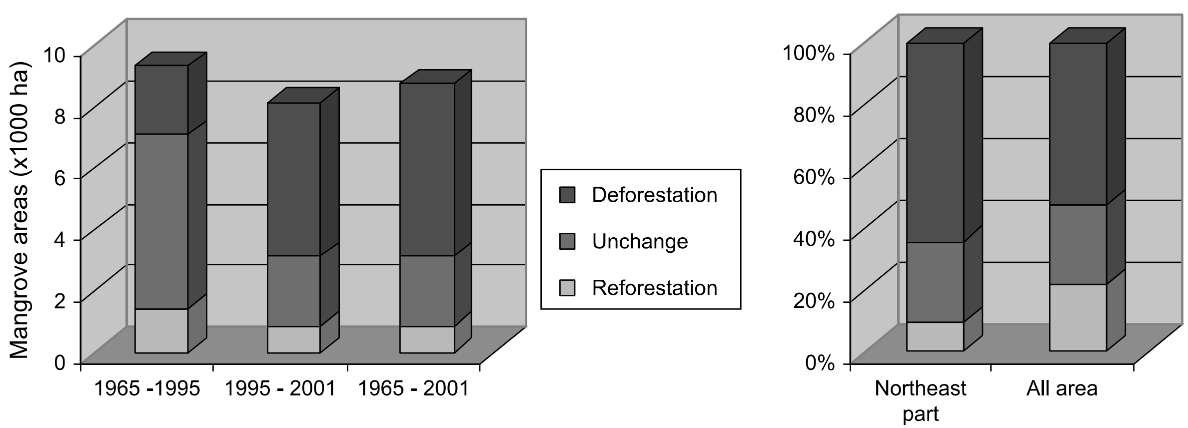
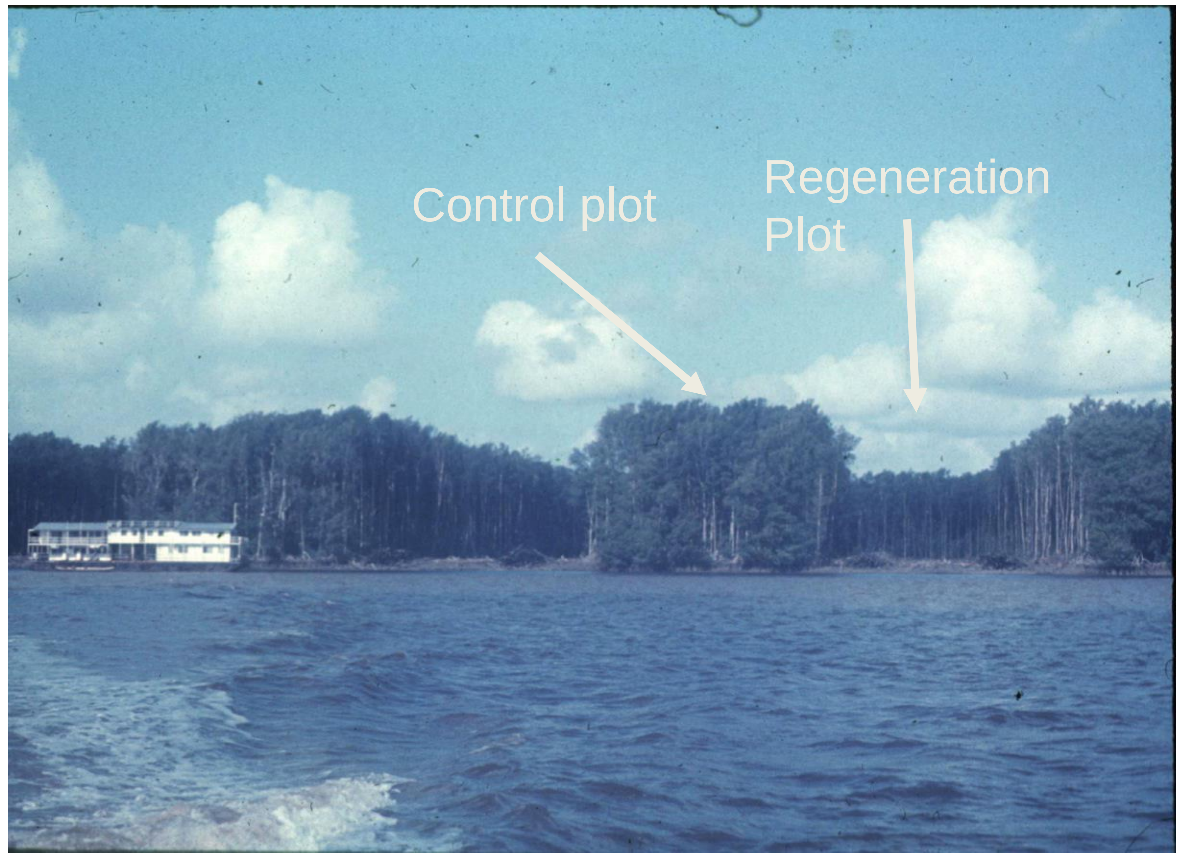
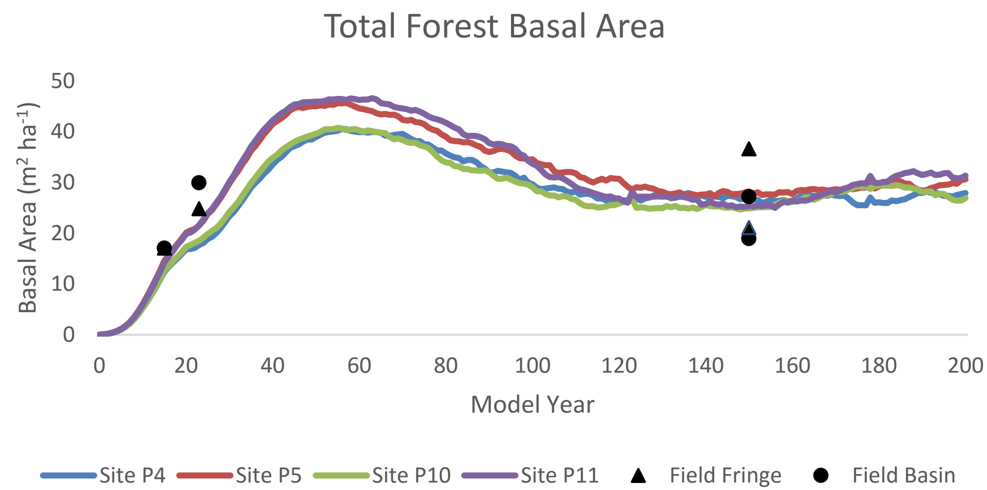


Fig. 5. Changes in mangrove forest in Tra Vinh from 1965–1995–2001 (Left: mangrove changes in northeast part in 1965–1996, 1995–2001 and 1965–2001, Right: Comparision of mangrove changes in two parts over period 1965–2001).

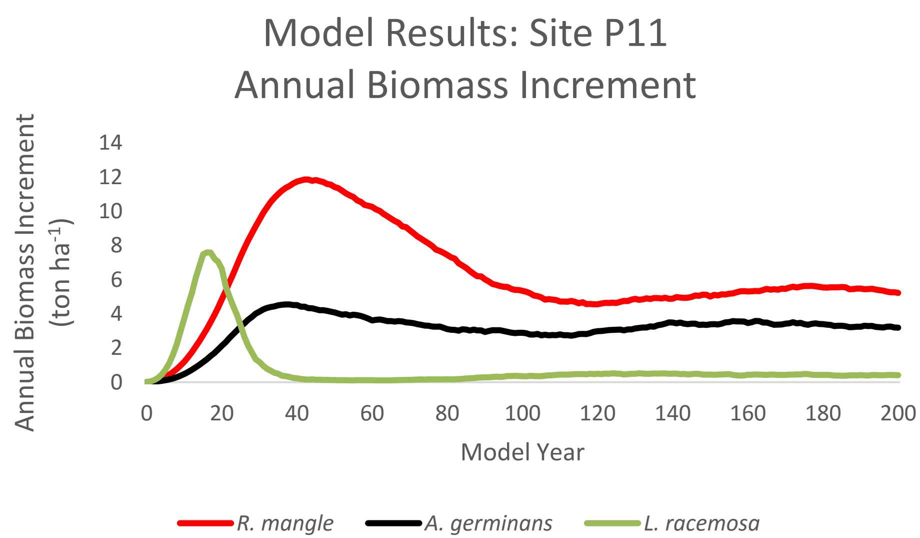
9A. Mangrove Disturbance and NEP Recovery - Evidence from Mangrove Plantations

In the mid-1970's the Department of Forestry in Venezuela conducted a series of clear cuts in mangroves along the San Juan River Estuary to develop a plantation system. Plots were 50 m wide by 300 m inland from shore. Recovery was measured in 1988 and 1998.





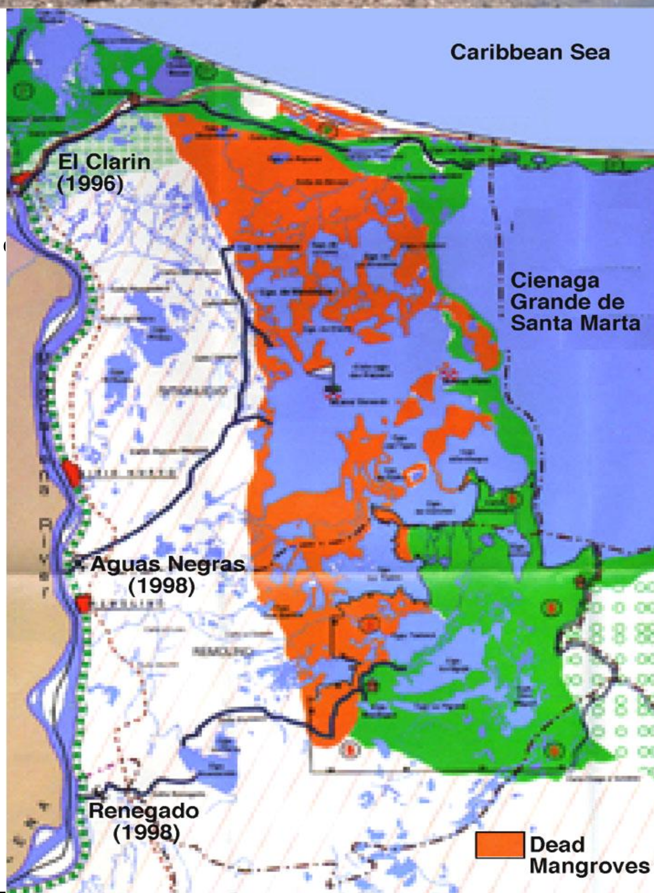
Total Forest Basal Area
Basal Area (m2 ha-1)
50
40
30
20
10
0
0
20
40
60
80
100
120
140
160
180
200
Model Year
Site P4
Site P5
Site P10
Site P11
Field Fringe
Field Basin



Model Results: Site P11
Annual Biomass Increment
Annual Biomass Increment
(ton ha-1)
14
12
10
8
6
4
2
0
0
20
40
60
80
100
120
140
160
180
200
Model Year
R. mangle
A. germinans
L. racemosa


9B. Mangrove Disturbance and NEP Recovery - Evidence from Mangrove Restoration


CENTRAL AMERICA AND THE CARIBBEAN
North Atlantic Ocean
Gulf of Mexico
UNITED STATES
THE BAHAMAS
CUBA
MEXICO
BELIZE
GUATEMALA
HONDURAS
EL SALVADOR
NICARAGUA
COSTA RICA
PANAMA
JAMAICA
HAITI
DOMINICAN REPUBLIC
Puerto Rico
Caribbean Sea
Cayman Trench
Puerto Rico Trench
Middle America Trench
North Pacific Ocean
COLOMBIA
VENEZUELA
GUYANA
BRAZIL
GUIANA HIGHLANDS
ANDES
Cienaga Grande
de Santa Marta,
Magdalena Colombia
Scale 1:12,500,000



Caribbean Sea
El Clarin
(1996)
Cienaga
Grande de
Santa Marta
Aguas Negras
(1998)
Renegado
(1998)
Dead
Mangroves

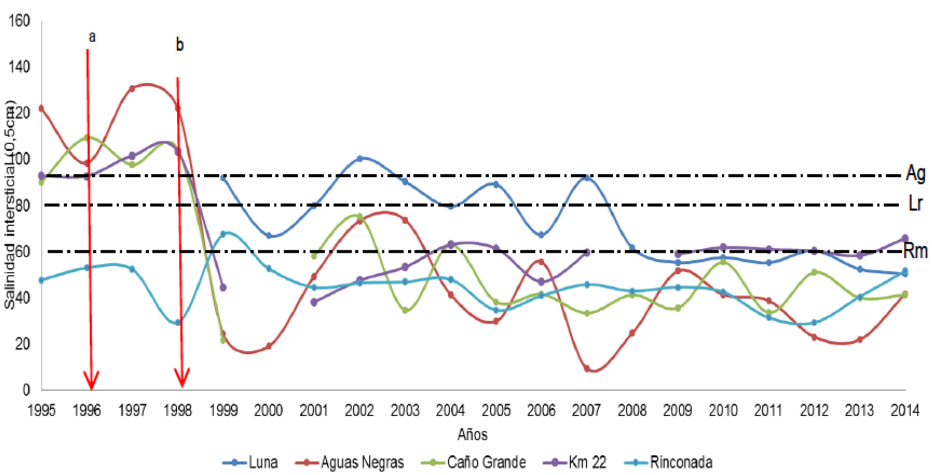


Figura 4.2-14. Salinidad intersticial máxima (0,5 m) registrada en los suelos de manglar de las cinco estaciones de monitoreo durante el periodo 1995-2013. Las flechas rojas indican la apertura de los caños Clarín (año 1996) (a), Agu legras y Renegado (año 1998) (b). Las líneas punteadas indican los límites fisiológicos máximo tolerables para las plai de mangle: Límite máximo de *R. mangle*=60; límite máximo de *L. racemosa=80; límite máximo de* A. *germinans*= 90

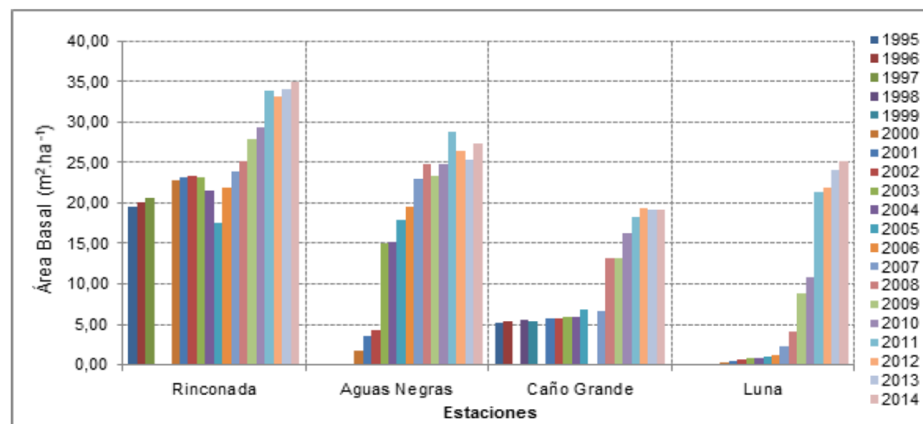
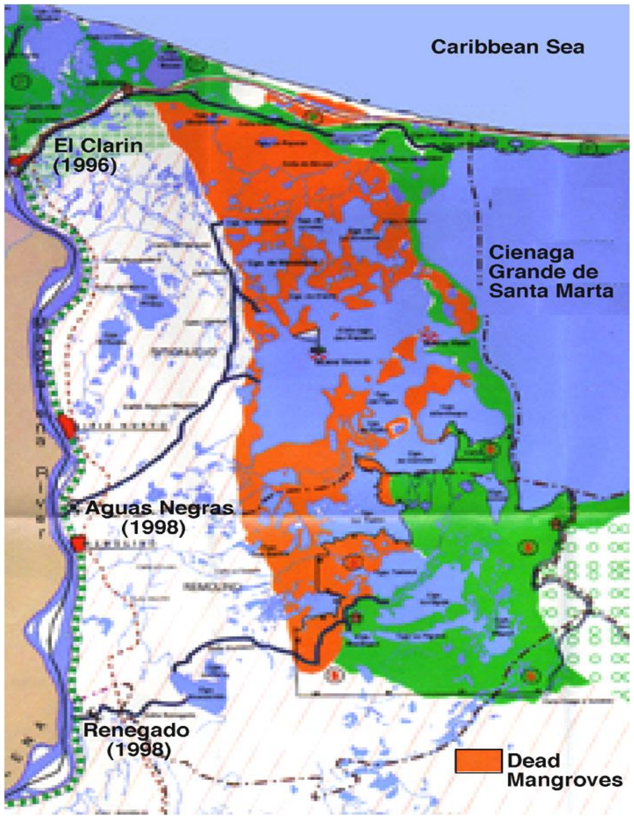


Figura 4.2-2. Área basal ($m^2.ha^{-1}$) de los bosques de manglar en las cinco estaciones de monitoreo en la CGSM durante el periodo 1995 – 2014.

Rate of Increase: 11.9 km^2 $year^{-1}$



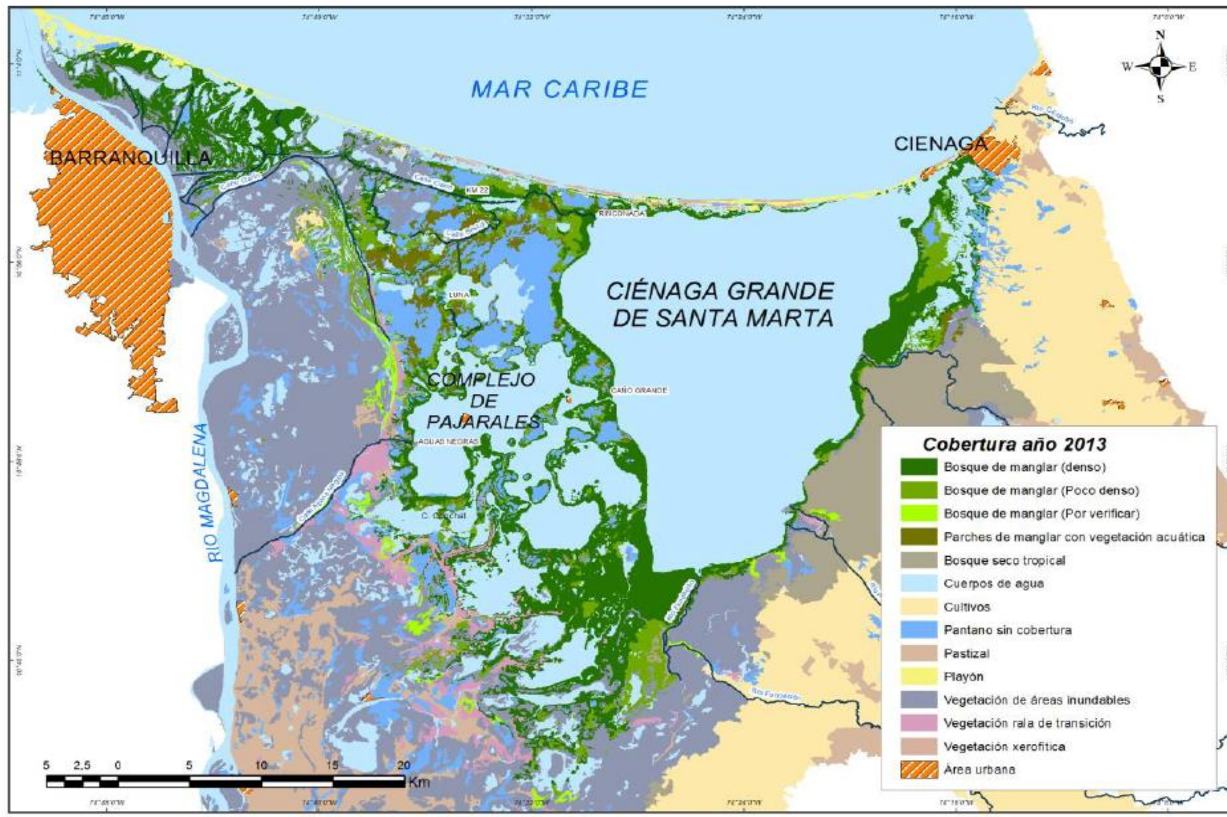
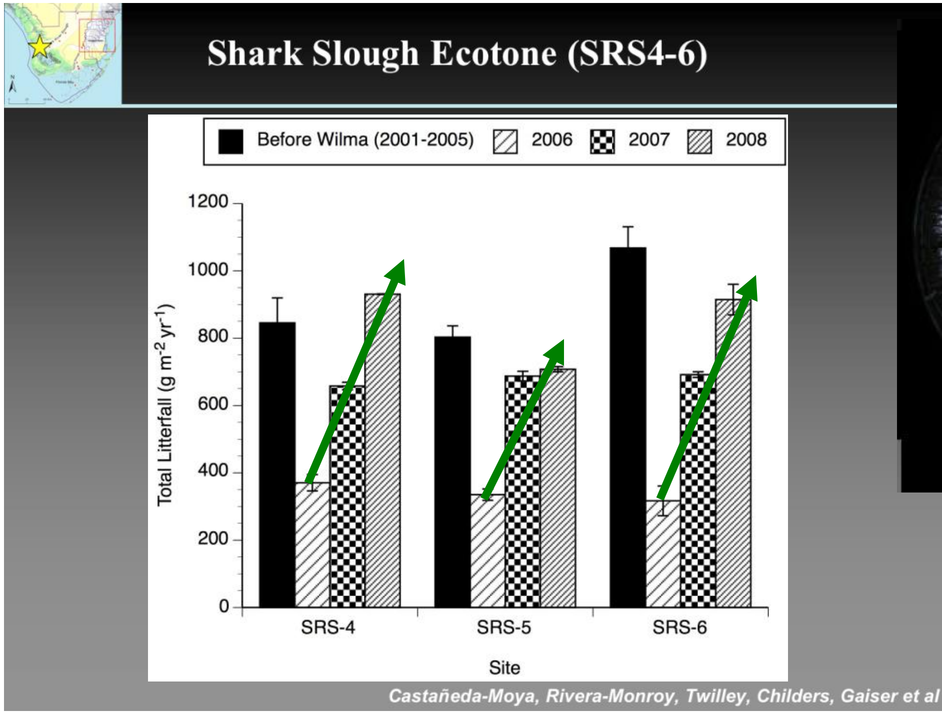
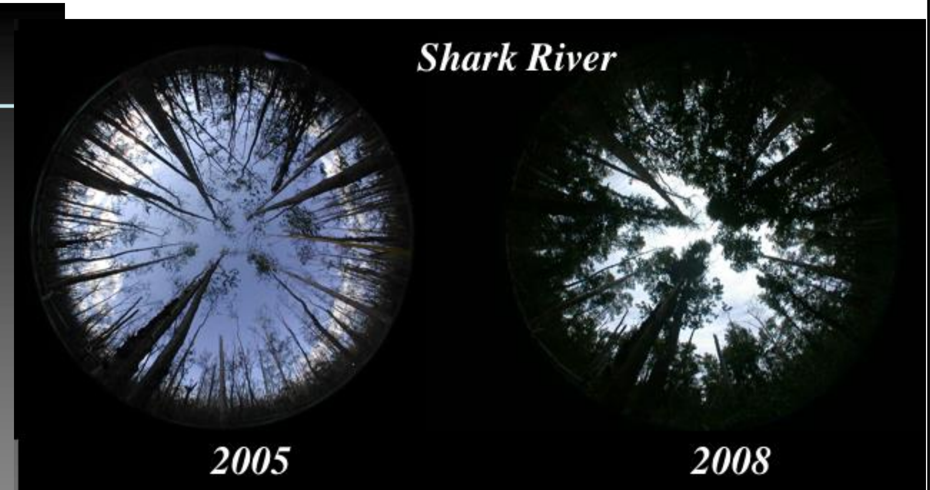
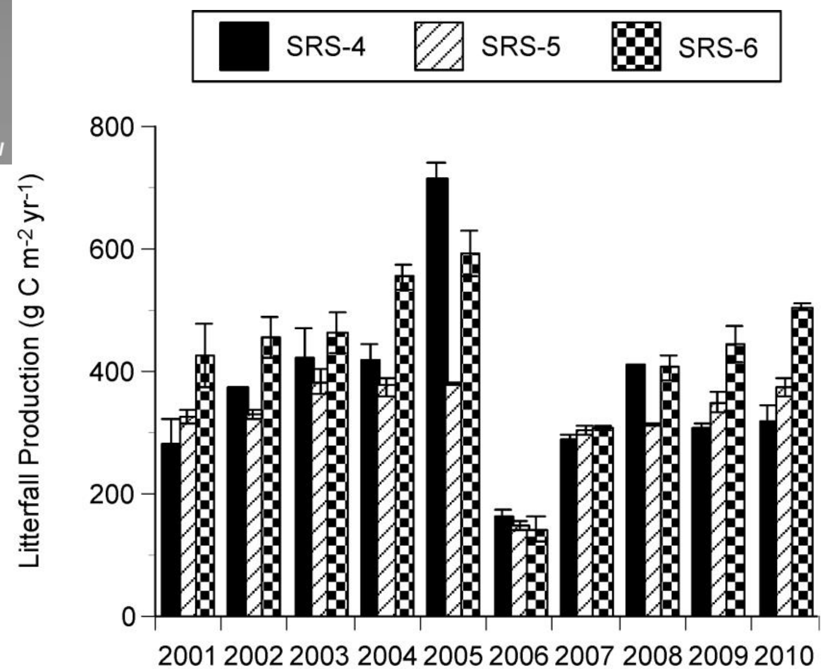


Figura 4.2-18. Mapa de cobertura de la tierra de la CGSM para el año 2013.

9C. Mangrove Disturbance and NEP Recovery – Hurricane Disturbance


Shark Slough Ecotone (SRS4-6)
Before Wilma (2001-2005)
2006
2007
2008
Total Litterfall (g m-2 yr-1)
0
200
400
600
800
1000
1200
SRS-4
SRS-5
SRS-6
Site
Castañeda-Moya, Rivera-Monroy, Twilley, Childers, Gaiser et al


Shark River
2005
2008


SRS-4
SRS-5
SRS-6
Litterfall Production (g C m-2 yr-1)
0
200
400
600
800
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010

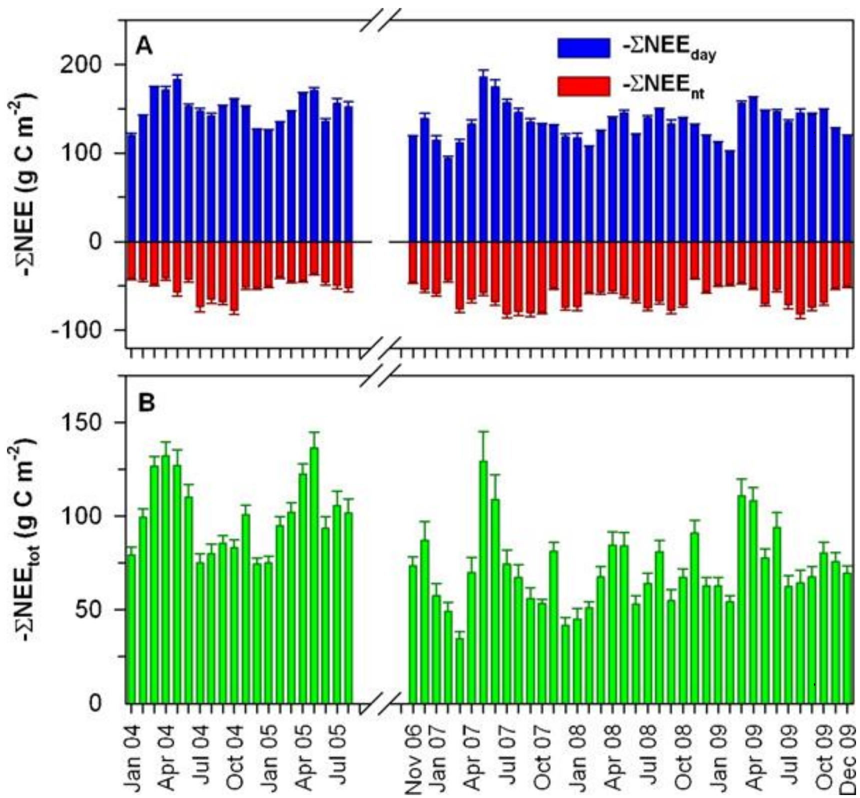


Fig. 7. Monthly integrated (A) daytime ($-\Sigma NEE_{day}$) and nighttime (ΣNEE_{nt}), and (B) 24-h total ($-\Sigma NEE_{tot}$) net ecosystem CO_2 exchange.

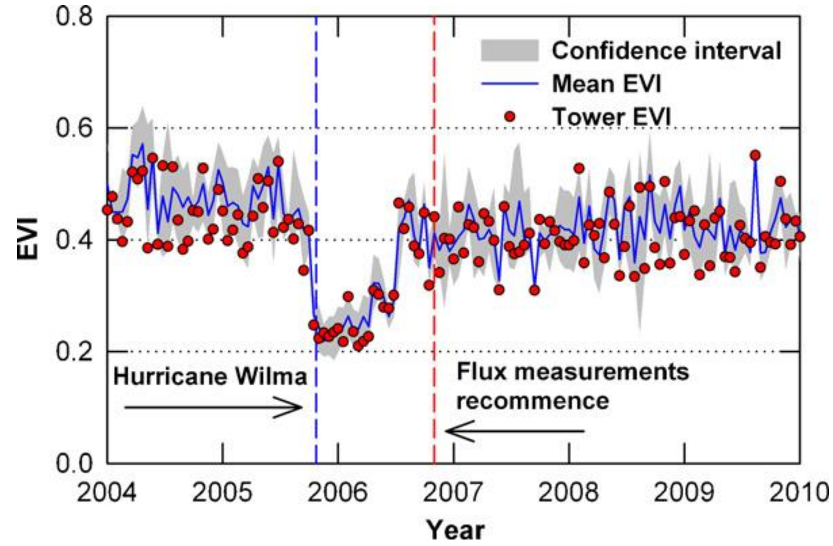
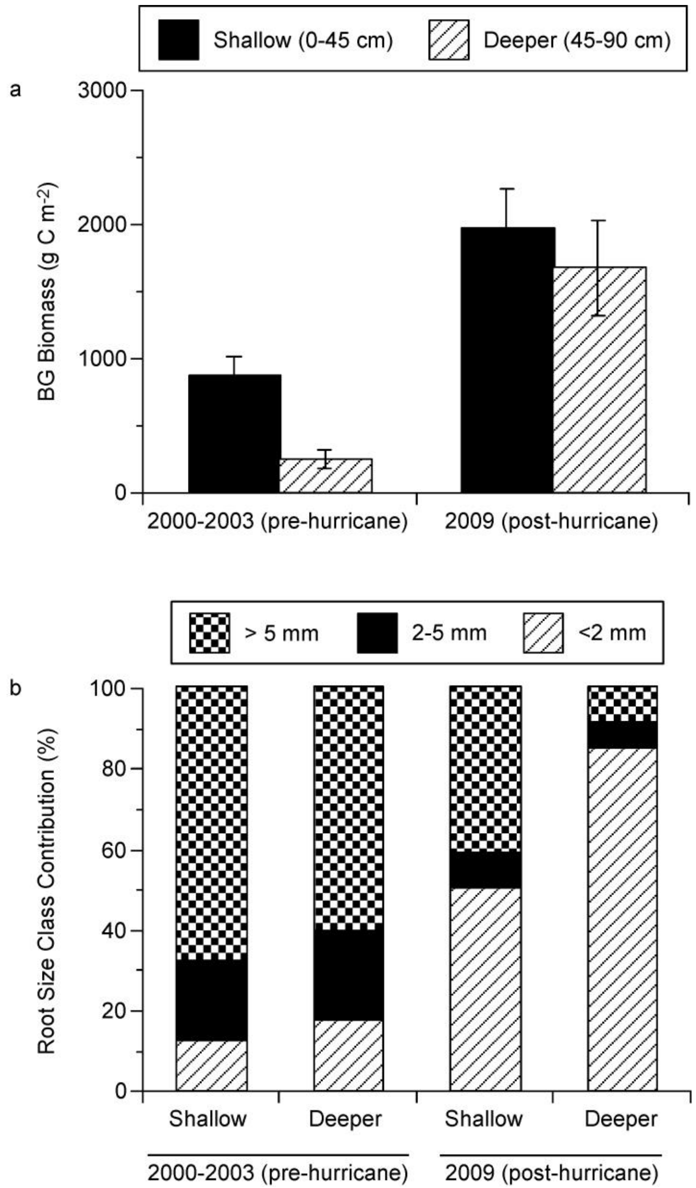


Fig. 4. Enhanced Vegetation Index (EVI) values at the tower location for pre- and post-Hurricane Wilma periods during which eddy-covariance data were also available. Confidence bands represent the minimum and maximum EVI values of the site pixel and 8 adjacent pixels during each 16-day averaging period.

Barr, J.G., V. Engel, J.D. Fuentes, J.C. Zieman, T.L. O'Halloran, T.J. Smith, and G.H. Anderson. 2010. Controls on mangrove forest-atmosphere carbon dioxide exchanges in western Everglades National Park. *Journal of Geophysical Research* 115: G0202

Post-hurricane Effect on Belowground Biomass (SRS-6)

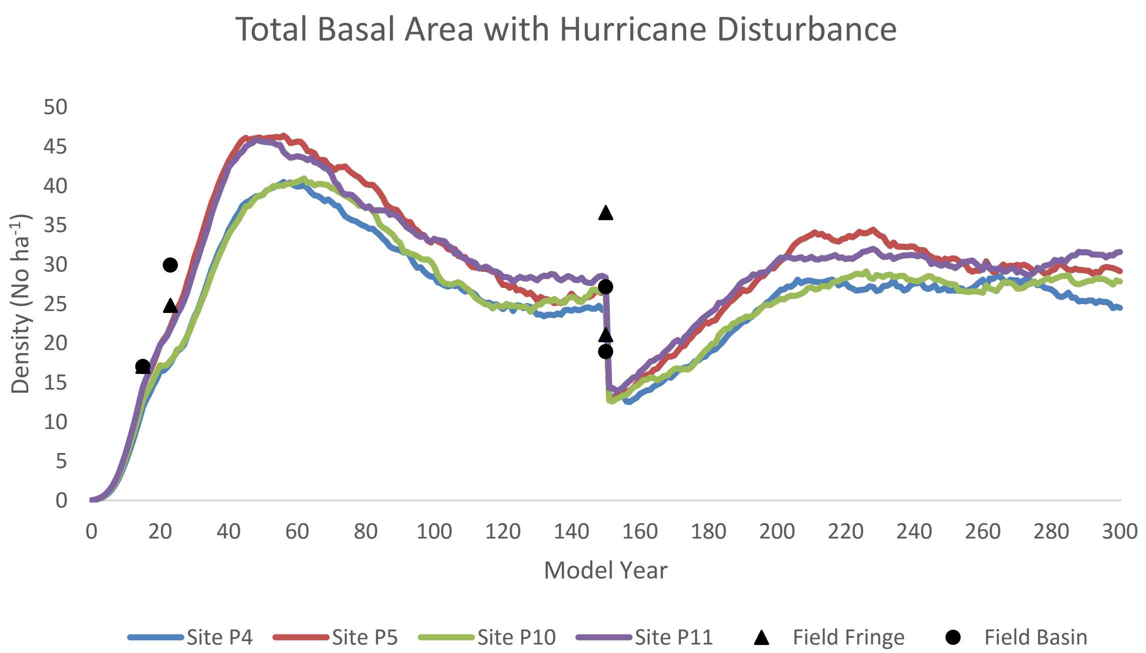


Strong response of BG biomass to post-hurricane Wilma in terms of resilience.

Similar responses were observed with litterfall rates.

Higher allocation to fine root production.

Castaneda et al. in prep



Total Basal Area with Hurricane Disturbance
Density (No ha-1)
50
45
40
35
30
25
20
15
10
5
0
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
Model Year
Site P4
Site P5
Site P10
Site P11
Field Fringe
Field Basin

10. Mangroves and the Global Carbon Budget

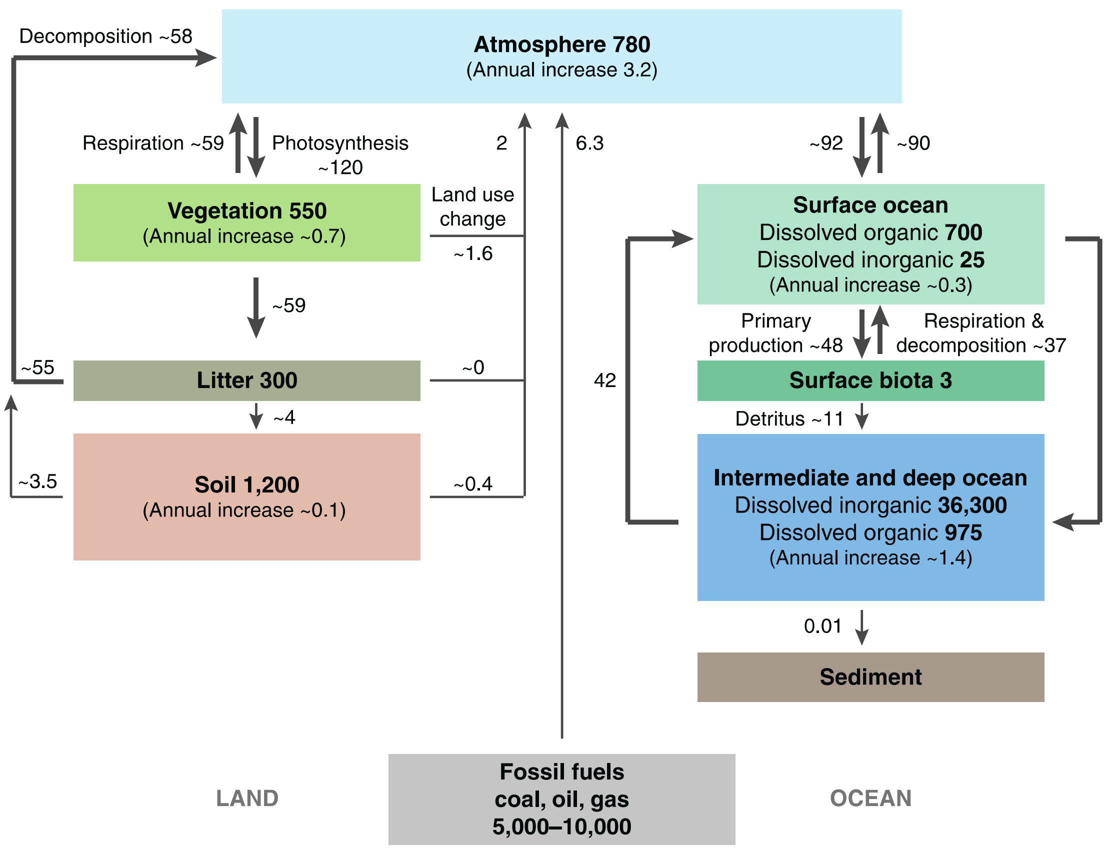
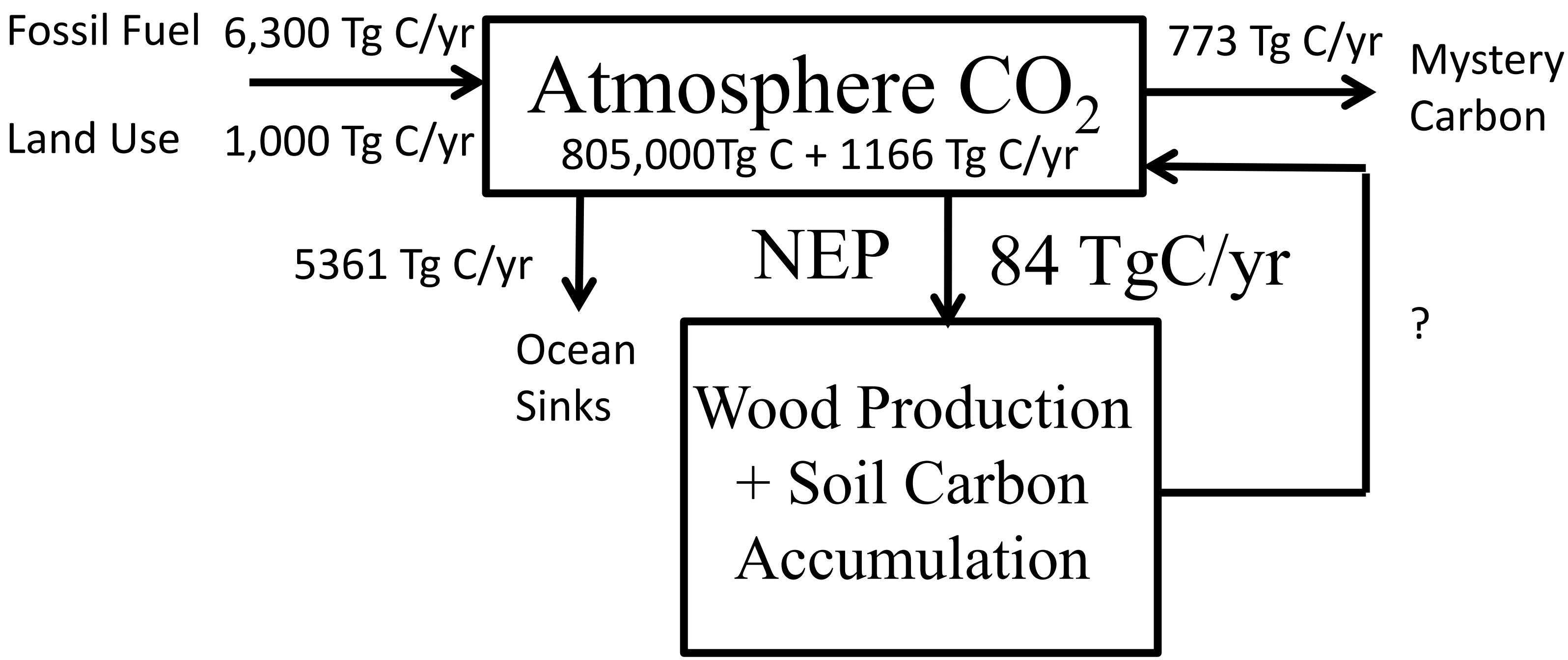


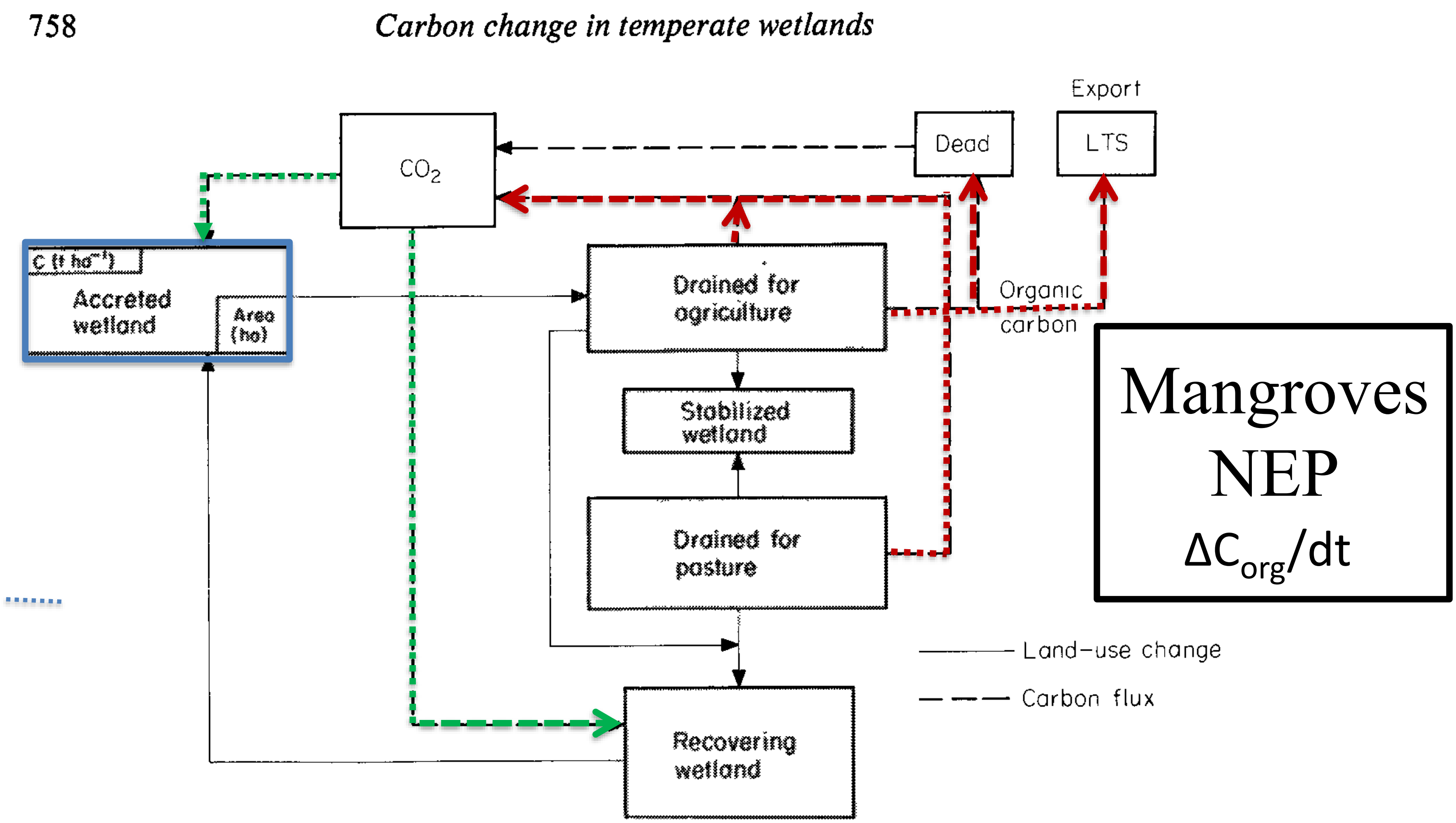
Figure 1

The global carbon cycle in the 1990s. Units are PgC or PgC year^{-1}.



Based on global reviews of observations, wood production is about 600 gdm m^{-2} yr^{-1} or about 300 g C m^{-2} yr^{-1}. The average carbon sequestration in mangroves soils, again based on observations described above, is about 225 g C m^{-2} yr^{-1}. The sum of these two measures, ($NPP_W + \Delta S_{org}$), is an estimate of NEP at about 525 g C m^{-2} yr^{-1}.

Land-use changes and carbon fluxes in simulation of wetland carbon exchange. Dead plant material is indicated as ‘Dead’ and long-term storage as reduced carbon (mostly exported in drainage waters) as LTS. Stabilized wetlands have depleted organic soils and no longer release carbon. (Armentano and Menges 1986)



Armentano, T.V. and Menges, E.S., 1986. Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. The Journal of Ecology, pp.755-774

Focus on the carbon derivative – annual carbon storage - NEP

Operational methodologies for NEP of mangroves – wood production and soil organic carbon accumulation (mangrove origin vs hinterland) – fate of net carbon export

Variation in NEP among ecogeomorphic settings to scale global estimates

Variation in NEP with disturbance – change in land use and change in NEP – Armentano method of carbon accounting

F

Photos of inter ... , taken at a time
of high tide du ... Kenya. Courtesy
of Alberto Bor

Victor Rivera-Monroy

Edward Castaneda and Andre Rovai

Ken Krauss

All my mangrove students
Ronghua Chen, Nicole Cormier, Andre Rovai, Victor Rivera-Monroy, Ernesto Mancer, Pablo Cardona, Ken Krauss, Nicole Poret, Kelly Henry, Laura Lawton, Greg Steyer, Jim Lynch, Claudia Lamperelli, Washington Cardenas, Heather Warner

Questions/Comments

rtwilley@lsu.edu

Papers on researchgate