Christina River Basin CZO

Spatial and temporal integration of carbon and mineral fluxes:

a whole watershed approach to quantifying anthropogenic modification of critical zone carbon sequestration

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Christina River Basin CZO

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Holly A. Michael, UD

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George M. Hornberger, Vanderbuit Univ.
Ilya Zaslavsky, San Diego Super Computing Center, UCSD

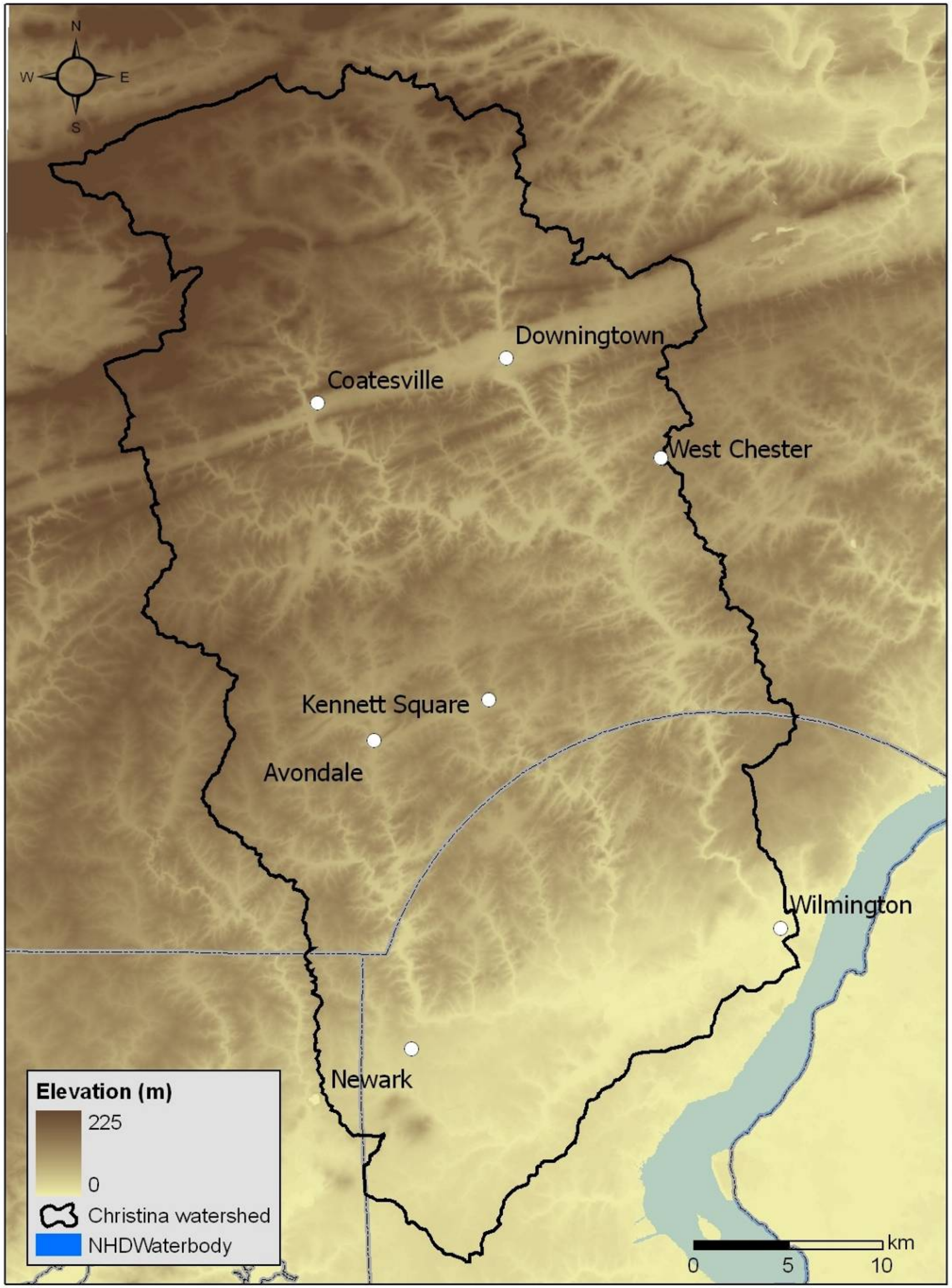
Alain Plante, Univ. of Penn
Daniel Leathers, Unvi. Of Delaware

Christina River Basin (CRB)

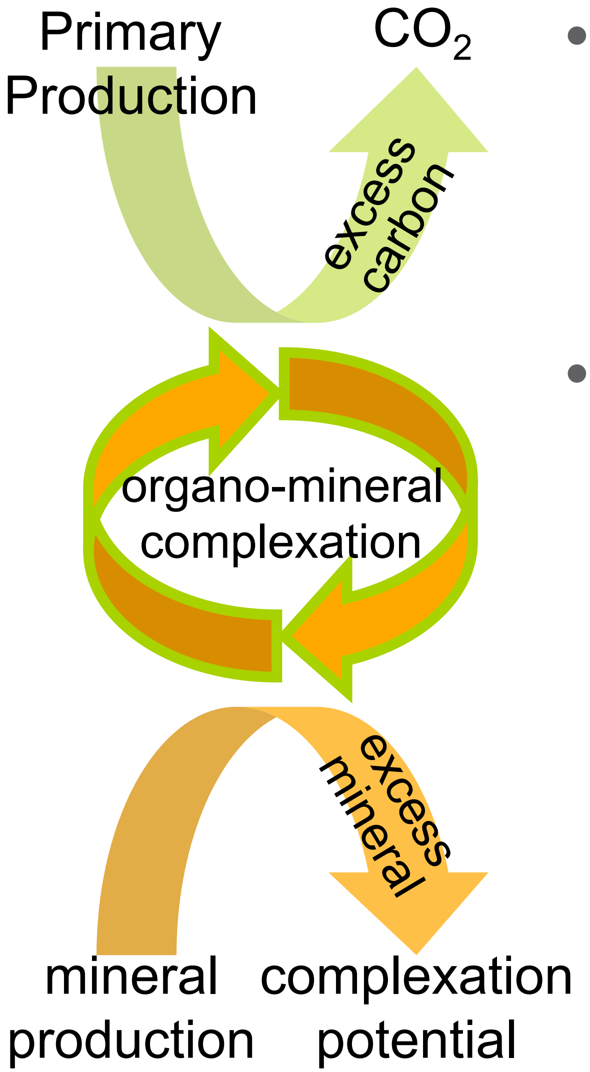
- Piedmont & Atlantic Coastal Plain
- Human Landuse for centuries
- Exceptionally well-studied

Table 1: Christina River Basin

Sub-Watershed	km^2
Brandywine Creek	842
Red Clay Creek	140
White Clay Creek	277
Upper Christina River	202
Christina River Basin	1,440

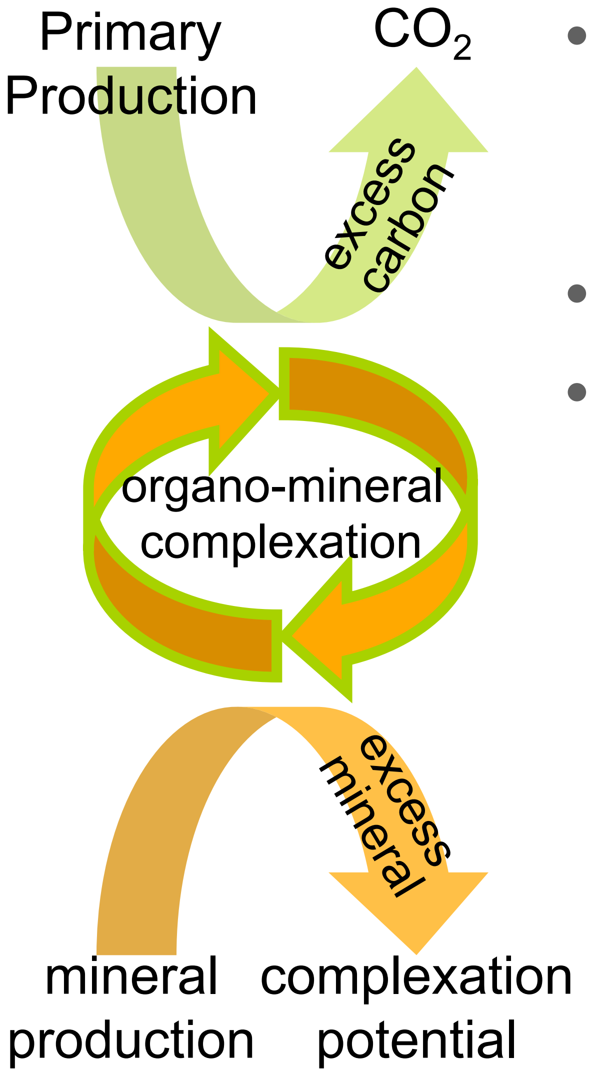


Overall Hypothesis



- Processes that mix minerals and carbon are rate limiting to watershed-scale carbon sequestration and chemical weathering
- Humans accelerate rates of carbon-mineral mixing, resulting in anthropogenic carbon sequestration fluxes that are significant to local, regional and global budgets

Overall Goal



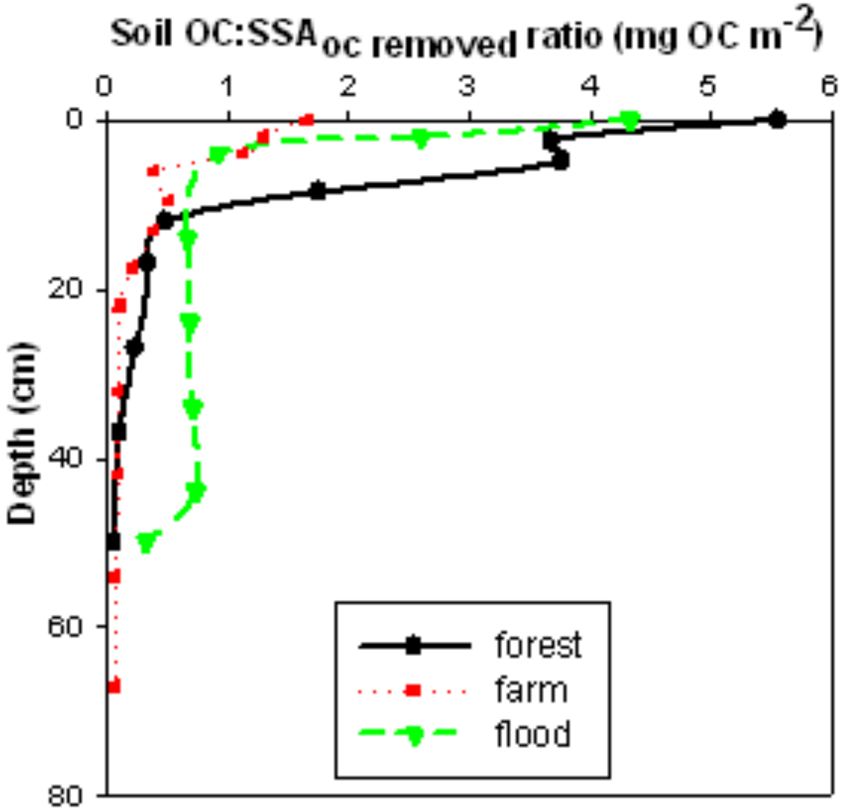
- To quantify the net carbon sink (or source) due to mineral production, weathering, erosion and deposition …
- in contrasting land uses…
- as materials are transported and transformed across geophysical boundaries that traditionally separate scientific disciplines, i.e.:

topsoils → subsoils → aquifers
→ riparian floodplains → river networks
→ estuaries


Sharpie
FINE POINT
Permanent Marker

Legacy Sediment in WCC

- Walter & Merritts, 2008, *Science*.



- Chunmei Chen's PhD

CRB-CZO Objectives

Spatial Scaling

1. Properties of Carbon-Mineral Complexes
2. Weathering and Erosion Controls on Carbon-Mineral Complex Formation
3. Fluvial Network Controls on Carbon-Mineral Complex Formation & Preservation
4. Watershed Integration of Erosion-Driven Carbon Sequestration

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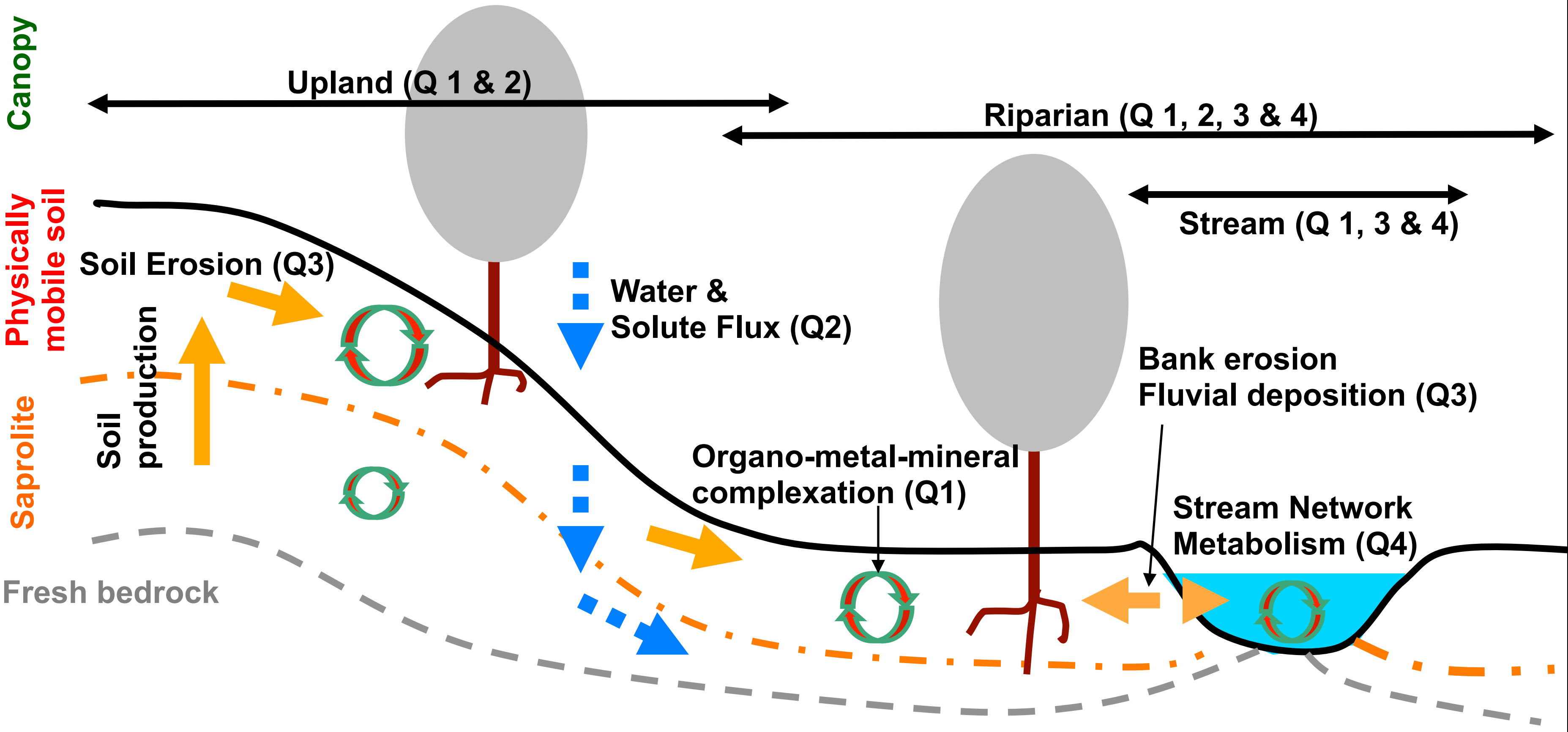
Research Approach For CRB-CZO



New Hires

- 3 Post-Docs
- 5 Graduate Students
- 1 Sensor Network Engineer
- 1 Research Watershed Manager (50% on CZO)
- 1 Accountant/Administrative Assistant (50% on CZO)

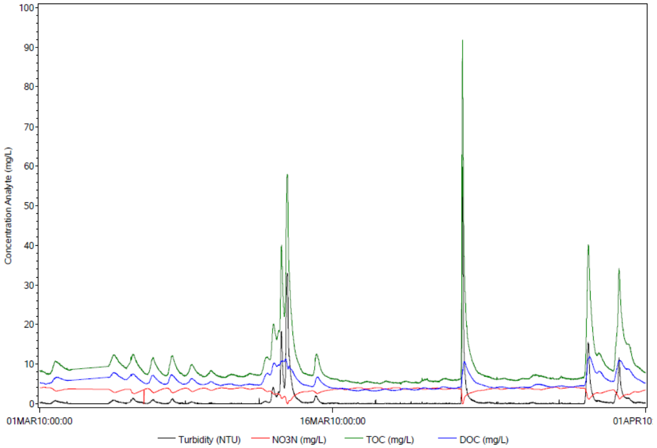
Study Site Selection

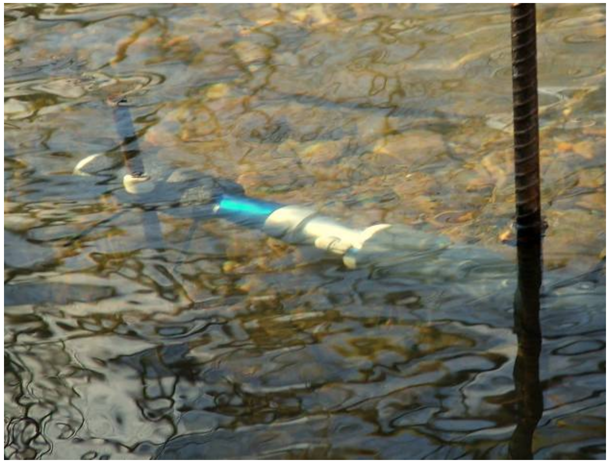
1. 1st order forest
2. 1st order row crops
3. 1st order construction
4. 3rd order WCC at SWRC
5. Lower WCC
6. Lower BC

- We will trace sediments and carbon down the CRB network to all depositional zones
  - floodplains, wetlands, salt marshes, Delaware Bay

Sensor Network Development

- Wireless real-time networks
- 100's of simple sensors constructed from high quanlity, inexpensive components
- Advanced geochemical sensors
- See poster!





CRB-CZO Cyber-Infrastructure

- Actively participating in the development of the national CZO cyber-infrastructure
- Transitioning local data into a hybrid of:
  - CUAHSI's Hydro-Server data system
  - EarthChem data model
- All sensor data will be available in real time, with QA'ed datasets provided later
- Partnering with Delaware Environmental Observing System (DEOS) to aggregate data from other regional sources for public visualization and access
  - See poster by Aufdenkampe and talk by Gill

Vegetation Survey

- In conjunction with NCALM LIDAR flights
  - See poster by Levia
- Very interested in characterizing tree heights in riparian areas, to understand potential for Large Woody Debris to modify sediment dynamics

Modeling

- Implementing the Penn State Integrated Hydrology Model (PIHM) at multiple scales in the CRB and by multiple investigators
  - 6 of us have received training
  - model running for 800 ha WCC at SWRC
- Refining results from TOPMODEL and a 2-D hillslope hydrological model
  - See poster by Mei and Hornberger
- Will use a number of other models
  - Groundwater geochemistry models
  - Sediment transport models

Education & Outreach

- NSF Education award related to CZO
  - Model My Watershed
  - Critical Zone education
- Pending and Planned Proposals
  - Monitor My Watershed
  - STEP Geosciences
  - REU Distributed Site for CZOs
- Christina River Basin public workshops
  - Partnership with UD Water Resources Agency

  - See talk by Gill

Planned Activities for 2010-11

- Intense effort to install infrastructure
  - Install water gauging and sampling infrastructure at 6 stream stations.
    - Flumes, wells, lysimeters, rain collectors, automated water collectors, etc.
  - Install wireless sensor communication system, with
    - 1 hub at each of 6 stream stations
    - 4-6 sensor nodes communicating to each hub
  - Implement data infrastructure to harvest real-time data
  - Establish hillslope and floodplain transects

Planned Activities for 2010-11

- Intense field surveying and sampling effort
  - Dig and sample soil pits along transects, installing soil sensors
  - Identify and sample important erosional source sites and depositional sink sites

- Develop experimental and analytical approaches to test specific hypotheses

Thank You

Funded by:
US National Science Foundation

UNIVERSITY OF DELAWARE
1743

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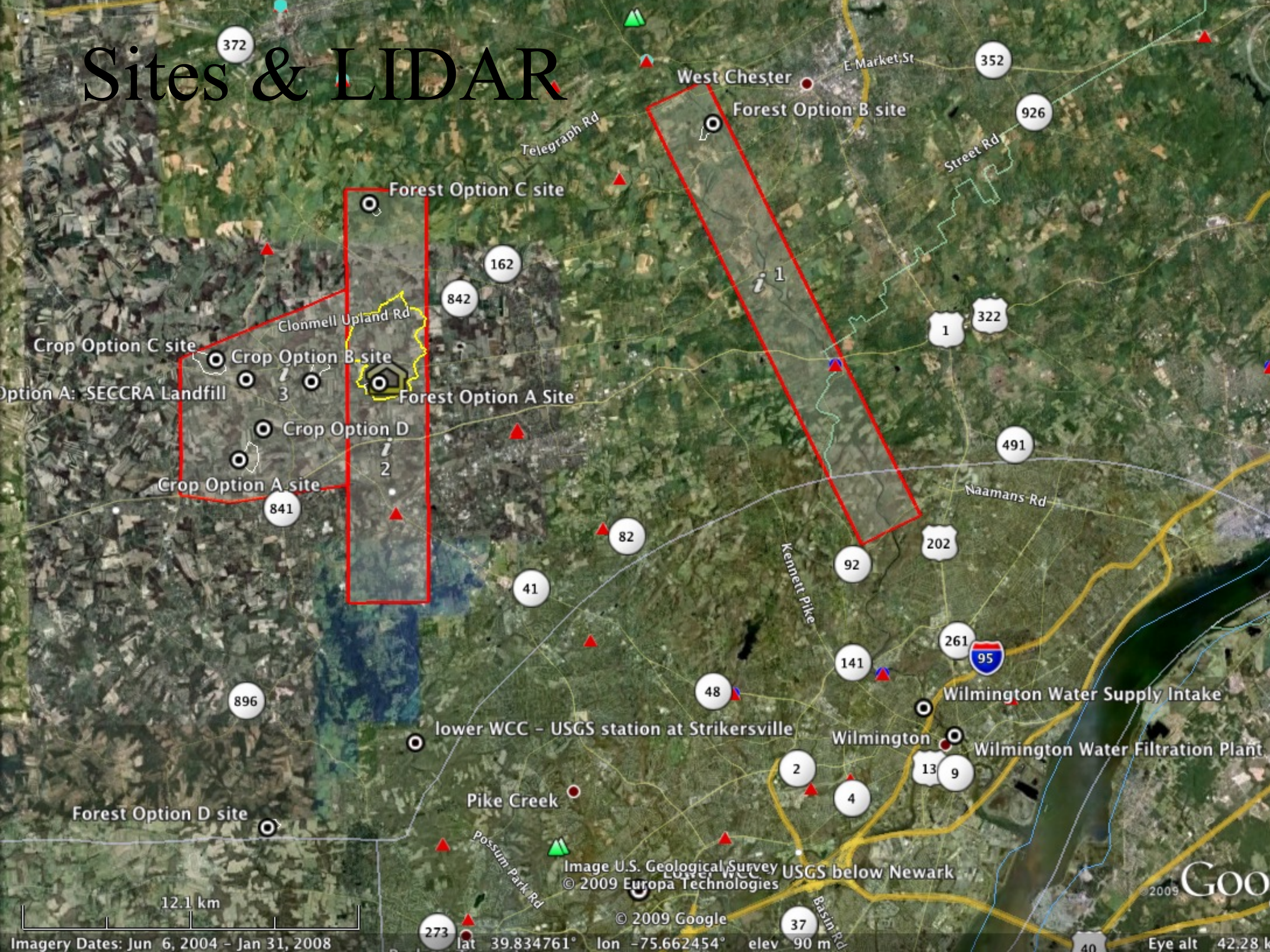
WATER RESEARCH CENTER

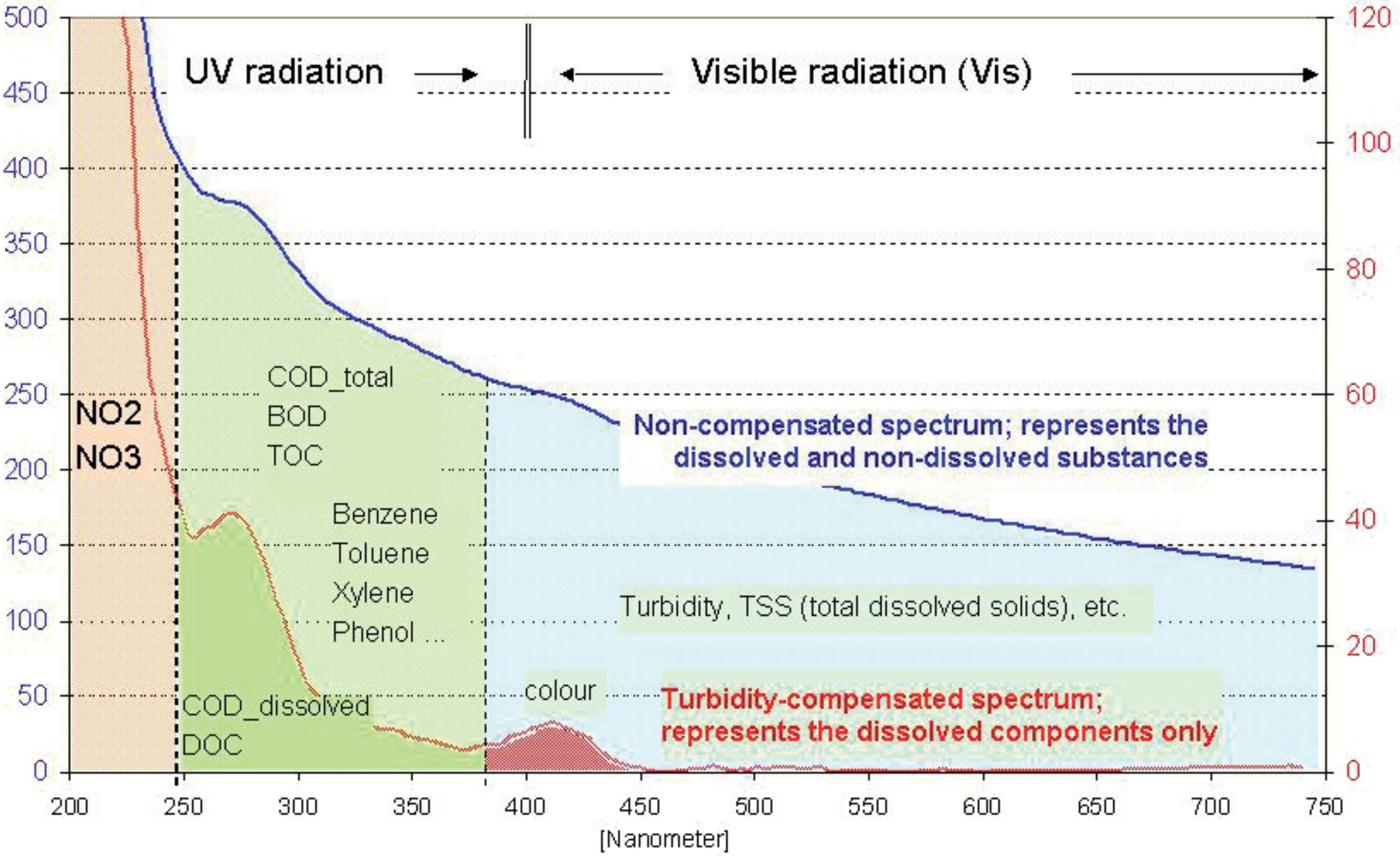
Sites & LIDAR


372
West Chester
E Market St
352
Forest Option B site
926
Telegraph Rd
Street Rd
Forest Option C site
162
842
i 1
Clonmell Upland Rd
1
322
Crop Option C site
Crop Option B site
i 3
Option A: SECCRA Landfill
Forest Option A Site
Crop Option D
i 2
491
Crop Option A site
841
Naamans Rd
82
202
92
Kennett Pike
41
261
95
141
48
Wilmington Water Supply Intake
896
lower WCC - USGS station at Strikersville
Wilmington
Wilmington Water Filtration Plant
2
13
9
4
Pike Creek
Forest Option D site
Possum Park Rd
Lower WCC - USGS below Newark
Image U.S. Geological Survey
© 2009 Europa Technologies
© 2009 Google
Basin Rd
37
12.1 km
273
Imagery Dates: Jun 6, 2004 - Jan 31, 2008
lat 39.834761° lon -75.662454° elev 90 m
40
Eye alt 42.28 k
©2009 Goo

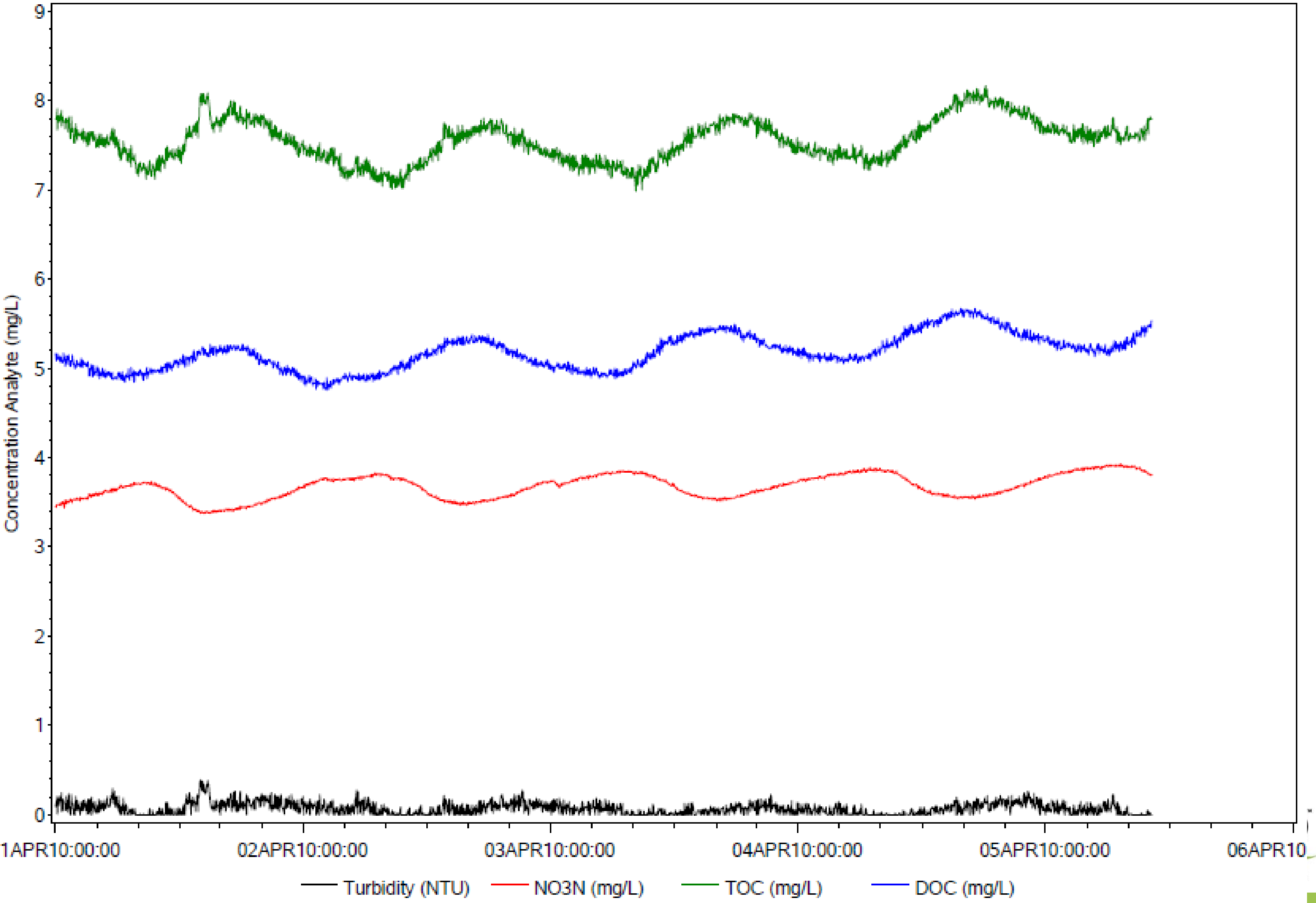
Required Data

- Stream Stations:
  - Continuous: Q, TSS, TOC, cond., DO, T, pH, NO_3
  - Samplers: %OC of TSS, $\delta^{13}C$ of POC & DOC, mineral elements and isotopes (^{210}Pb, ^{137}Cs), etc.
- Hydrology & Climate
  - Precip., ET, runoff
  - Groundwater, soil moisture
  - Flow paths and fluxes (measured and modeled)
- Sediment source and deposit samples
  - %OC of TSS, $\delta^{13}C$ of POC & DOC, mineral elements and isotopes (^{210}Pb, ^{137}Cs), etc.

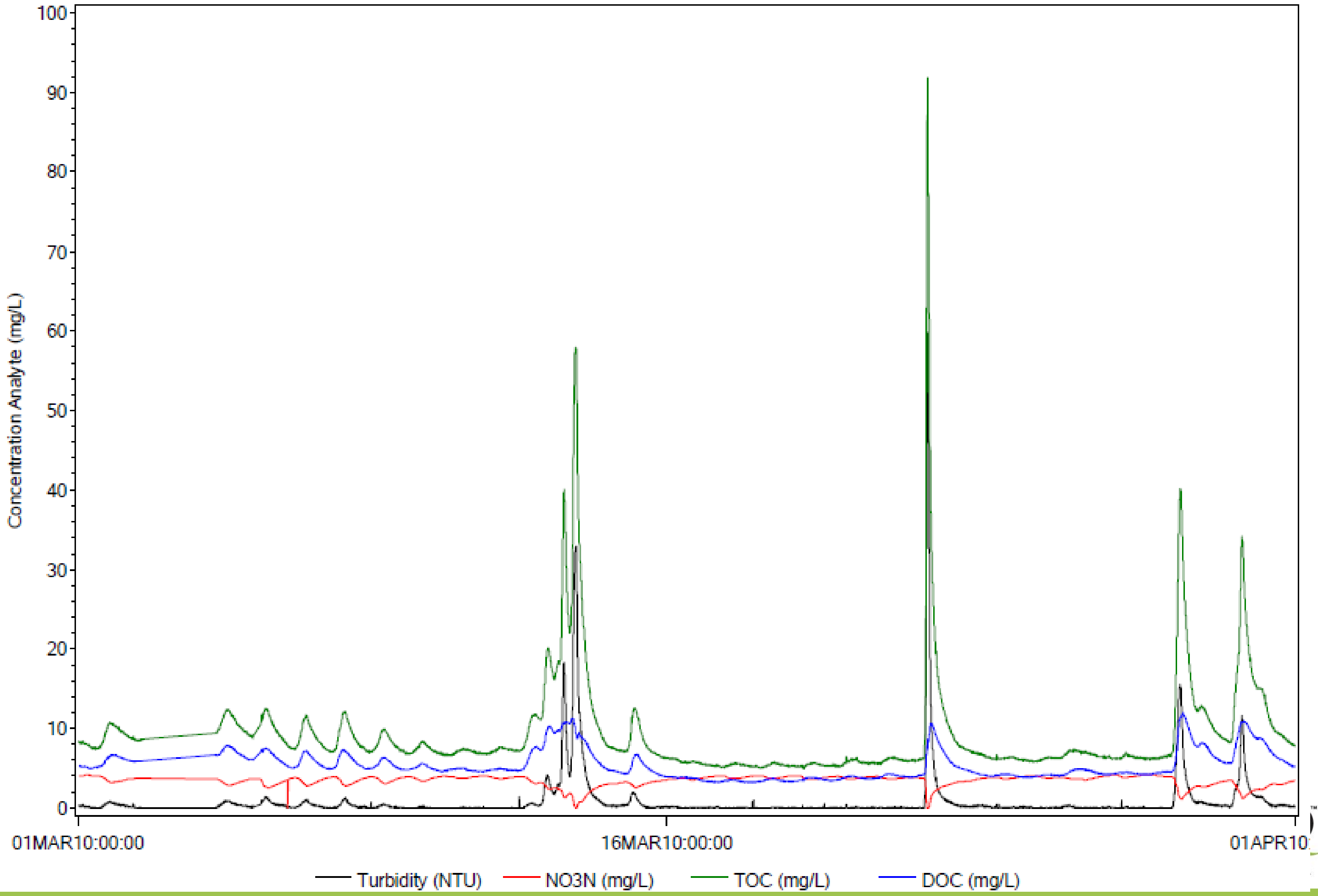
In Situ UV-Vis-Derived Parameters



In Situ UV-Vis-Derived Parameters



In Situ UV-Vis-Derived Parameters

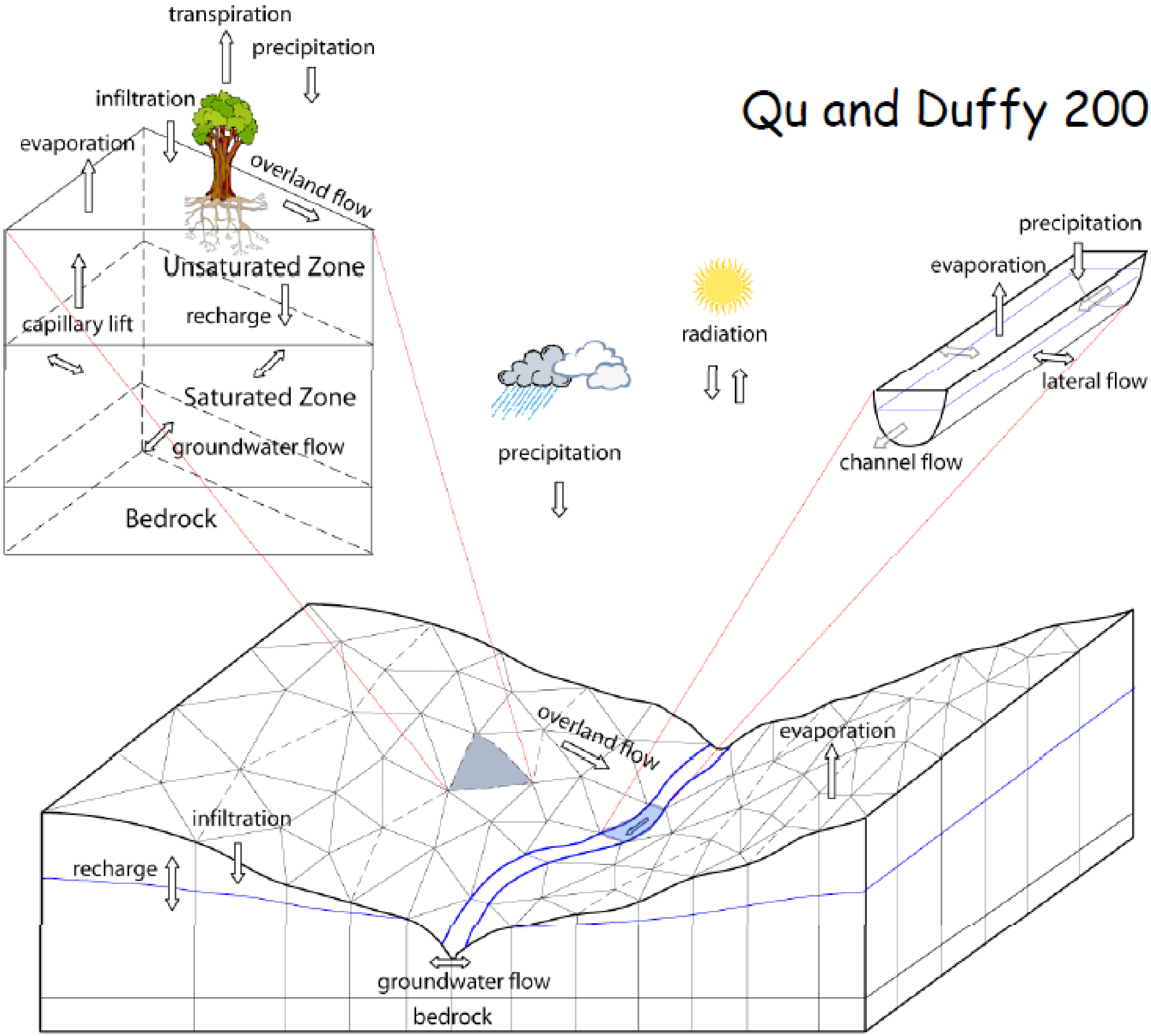


CZO Cyber-Infrastructure Goals

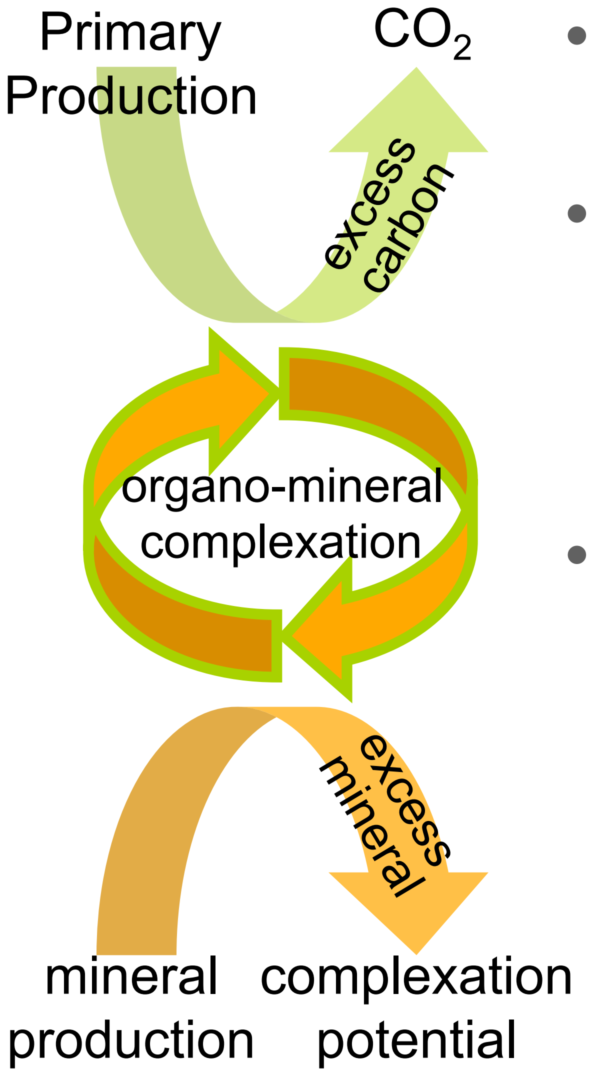
- Create a system of "one-stop-shopping" for water and sediment data for CRB
  - Share data within project
  - Share data online with public
    - As much in real-time as possible
  - Curate future and historical data
- Integrate with CUAHSI's Hydrological Information Systems (HIS)
  - Observations Data Model (ODM) relational database for our project data
  - Web services to search and retrieve data from partners

Penn State Integrated Hydrologic Model: PIHM

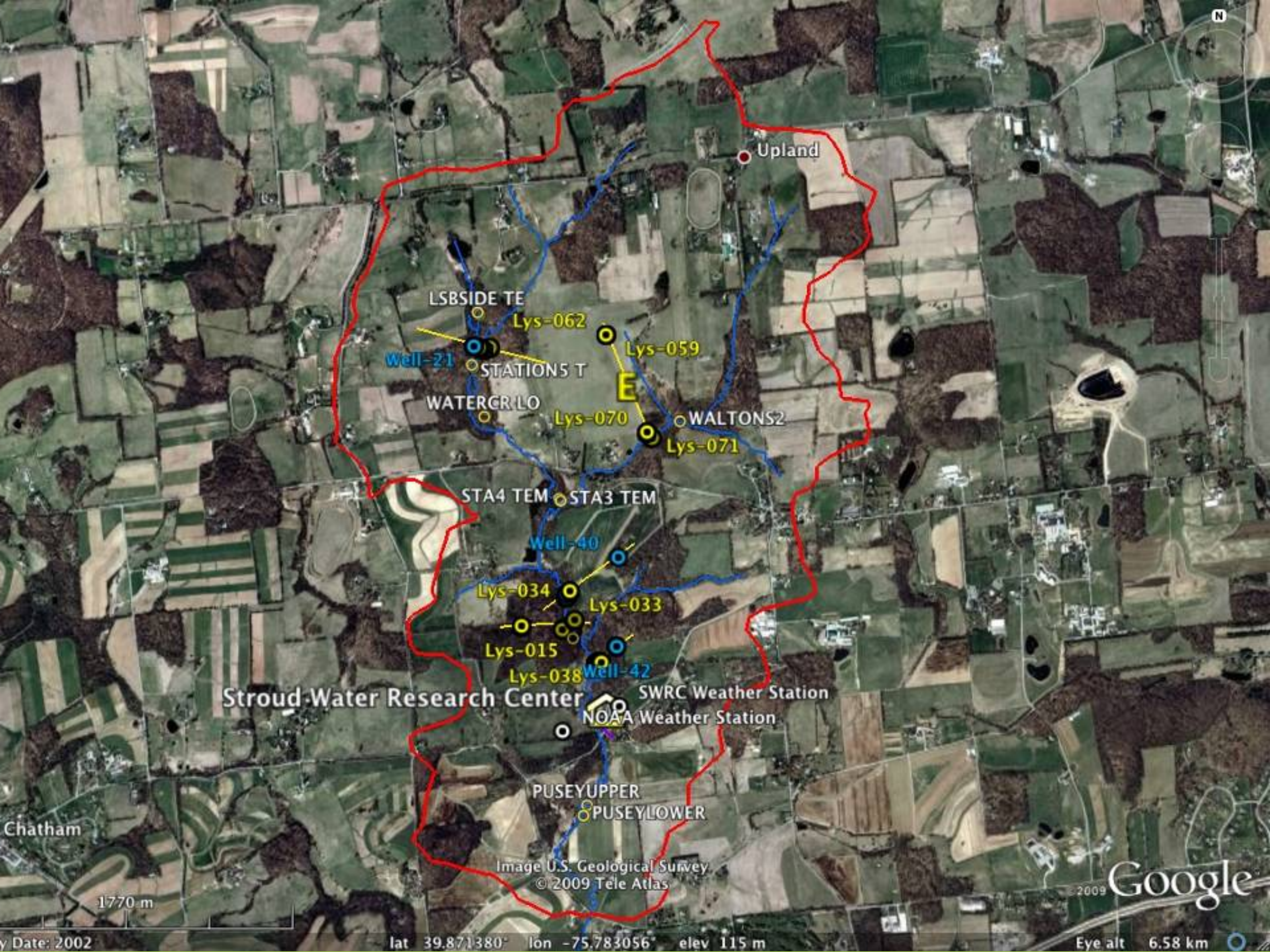
Qu and Duffy 2007



Overall Hypothesis



- If minerals exert a primary control on organic matter preservation, and …
- If water and carbon (carbonic acid, organic acids and microbial substrates) exert a primary control on mineral weathering, then …
- Processes that mix minerals and carbon may be rate limiting to watershed-scale carbon sequestration and chemical weathering


Upland
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Well-21
STATION5 T
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Lys-071
STA4 TEM
STA3 TEM
Well-40
Lys-034
Lys-033
Lys-015
Lys-038
Well-42
Stroud Water Research Center
SWRC Weather Station
NOAA Weather Station
PUSEYUPPER
PUSEYLOWER
Chatham
Image U.S. Geological Survey
© 2009 Tele Atlas
1770 m
©2009 Google
y Date: 2002
lat 39.871380°
lon -75.783056°
elev 115 m
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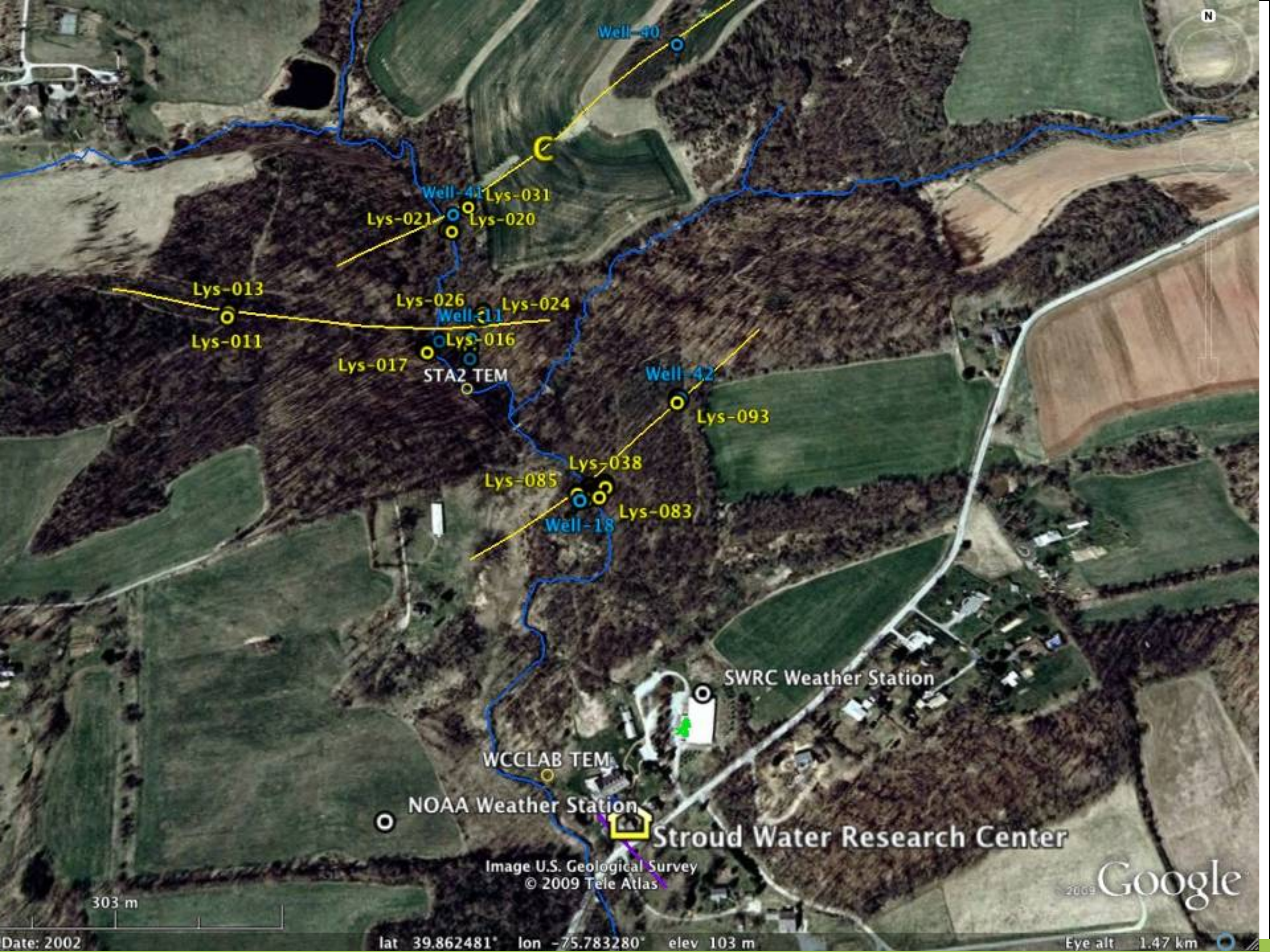

N
Well-40
Well-41
Lys-031
Lys-021
Lys-020
Lys-013
Lys-026
Lys-024
Well-11
Lys-011
Lys-016
Lys-017
STA2 TEM
Well-42
Lys-093
Lys-038
Lys-085
Lys-083
Well-18
SWRC Weather Station
WCCLAB TEM
NOAA Weather Station
Stroud Water Research Center
Image U.S. Geological Survey
© 2009 Tele Atlas
© 2009 Google
303 m
Date: 2002
lat 39.862481° lon -75.783280° elev 103 m
Eye alt 1.47 km

Obj. 1: Properties of Carbon-Mineral Complexes

1.1: The capacity of the inorganic matrix to complex and stabilize OC is a multivariate function of mineral surface area, mineralogy, polyvalent cations and OM composition

%OC = f(surface area, mineral, cations, OM composition, etc.)

1.2: The intrinsic biological and chemical stability of organic carbon complexed by an inorganic matrix can be predicted from the OM composition and its concentration relative to complexation potential

Obj. 2: Weathering and Erosion Controls on Carbon-Mineral Complex Formation

2.1: Organo-mineral complexation in natural uplands is limited by physical mineral supply from the underlying B horizon or saprolite, which are governed by vertical soil mixing (<10 yr time scale) and landscape lowering (>10 Kyr time scale).

2.2: Coupled chemical and microbial weathering processes determine the spatial distribution of the sources of OC-complexation potential

2.3: Human accelerated erosion and chemical weathering significantly increase the production of OC-complexation potential

Obj. 3: Fluvial Network Controls on Complex Formation & Preservation

3.1: Accelerated erosion by modern agricultural and construction activities (1) creates fluvial carbon sinks within the watersheds and (2) decreases overall bioavailability of the stream water carbon leaving the watershed

- Tracer Characterization of Sediment Sources
- Determine Modern Sedimentation Rates and Concentrations
- Determine Historical Rates and Concentrations

Obj. 4: Watershed Integration of Erosion-Driven Carbon Sequestration

4.1: Instream heterotrophic metabolism is supported primarily by non-complexed carbon, a large fractions of which has been stored in floodplains for long periods (>50 y).

Note: Major task for Obj. 4 should be Integrated Watershed Model of following equations 1 & 2.

Frontiers in Exploration of the Critical Zone

An NSF-Sponsored Workshop

University of Delaware
Newark, Delaware
Monday October 24 - Wednesday October 26, 2005

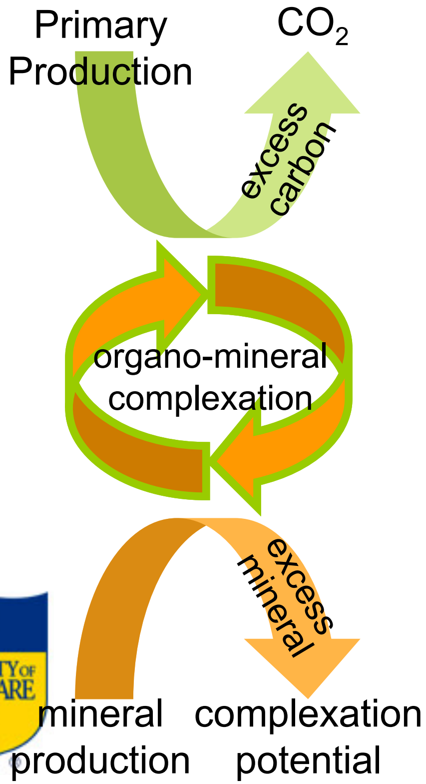
Workshop Organizing Committee

Don Sparks, Co-Chair, University of Delaware
Sue Brantley, Co-Chair, The Pennsylvania State University
Jon Chorover, The University of Arizona
Mary Firestone, University of California, Berkeley
Dan Richter, Duke University
Art White, USGS, Menlo Park

Christina River Basin CZO

Spatial and temporal integration of carbon and mineral fluxes: a whole watershed approach to quantifying anthropogenic modification of critical zone carbon sequestration

Sparks, Aufdenkampe, Yoo, Kaplan, Pizzuto, Aalto and many others



Primary Production

CO_2

excess carbon

organo-mineral complexation

excess mineral

mineral production

complexation potential

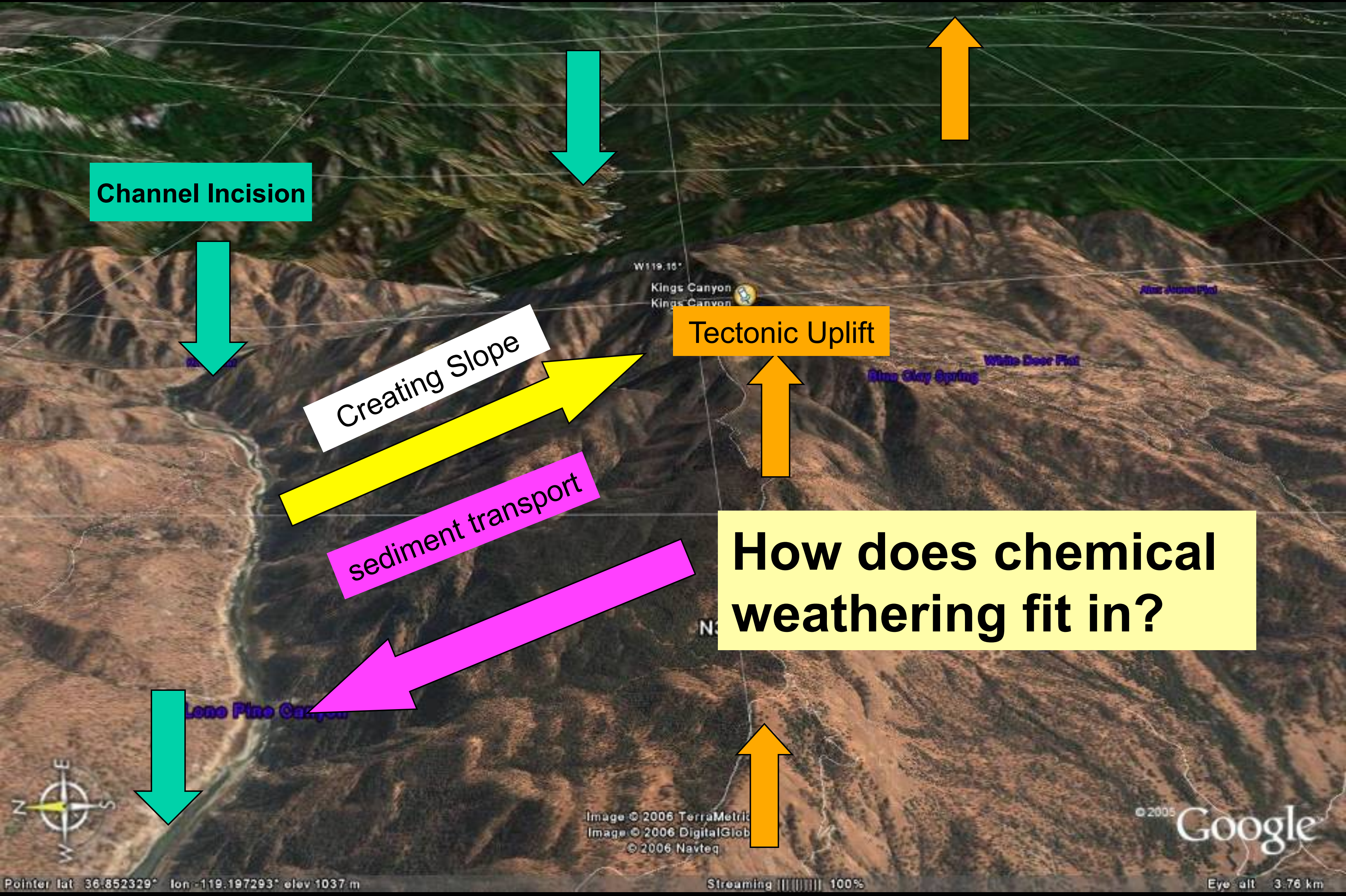
Overall goal:

To quantify the net carbon sink (or source) due to mineral production, weathering, erosion and deposition …

as materials are transported and transformed across geophysical boundaries that traditionally separate scientific disciplines, i.e.:

topsoils → subsoils → aquifers → riparian floodplains → river networks → estuaries

Simultaneous Mass balance of Transport and Weathering: Yoo



Channel Incision

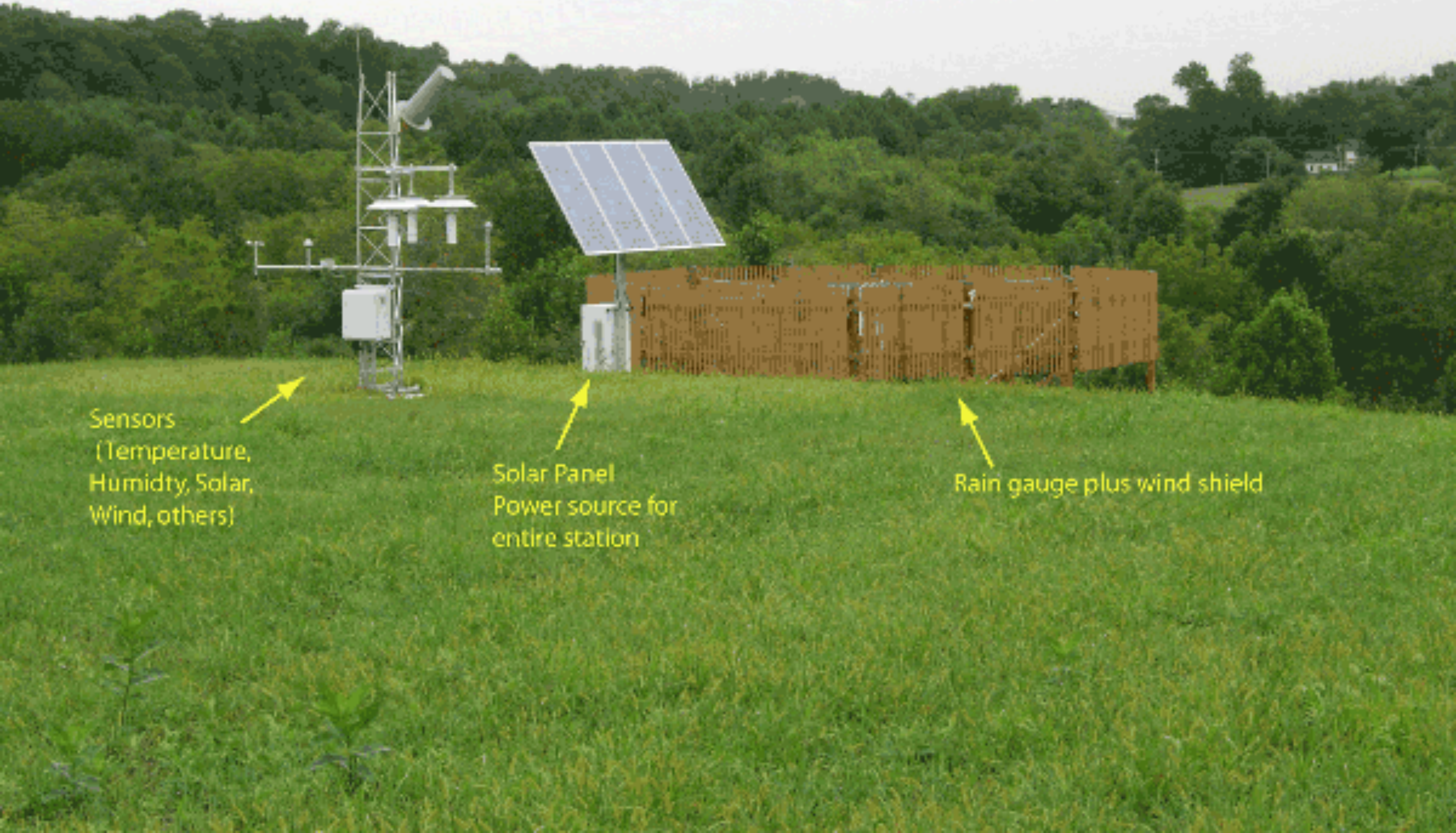
Creating Slope

Tectonic Uplift

sediment transport

How does chemical weathering fit in?

NOAA Climate Reference Network Station at SWRC



Sensors (Temperature, Humidty, Solar, Wind, others)

Solar Panel
Power source for entire station

Rain gauge plus wind shield

Carbon Sequestration by Human Erosion

Table 1: A simplified depiction of calculation of potential carbon sequestration from human erosion of fresh, carbon-poor mineral surfaces into the biosphere (M4). % values are % of the preceeding column found in the following column.

Objective 2 constrain these values

Objective 1 constrain these values

Objective 2 constrain these values

Objective 1 constrain these values

	Sediment	**Organic Carbon**		**Passive OC**			**Sediment**	**Organic Carbon**		**Passive OC**	
	Gt y^{-1}	*%*	*Gt y^{-1}*	*%*	*Gt y^{-1}*		*Gt y^{-1}*	*%*	*Gt y^{-1}*	*%*	*Gt y^{-1}*
Sediment Sources						**Sediment Sinks**					
Natural											
Topsoils	15	1.0%	0.15	75%	0.11	Upland Deposition	30	1.5%	0.45	75%	0.34
Deep	15	0.1%	0.02	95%	0.01	Floodplain	30	2.0%	0.60	95%	0.57
						Fluvial Bed & Bar	22	1.0%	0.22	75%	0.17
Human						Lake & Reservoir	17	2.5%	0.43	95%	0.40
Agriculture-Topsoil	50	1.0%	0.50	75%	0.38						
Forestry-Mixed	15	0.4%	0.06	85%	0.05	Estuary & Delta	15	2.0%	0.30	95%	0.29
Construction-Mixed	10	0.2%	0.02	90%	0.02	Coasta Shelf	8	1.5%	0.12	95%	0.11
Mining-Deep	20	0.1%	0.02	95%	0.02	Coastal Slope	3	1.0%	0.03	80%	0.02
Source Total	**125**		**0.77**		**0.59**	**Sink Total**	**125**		**2.15**		**1.90**

Sequestered carbon = the net change in passive OC = 1.90 – 0.59 = 1.31 Gt C y^{-1}

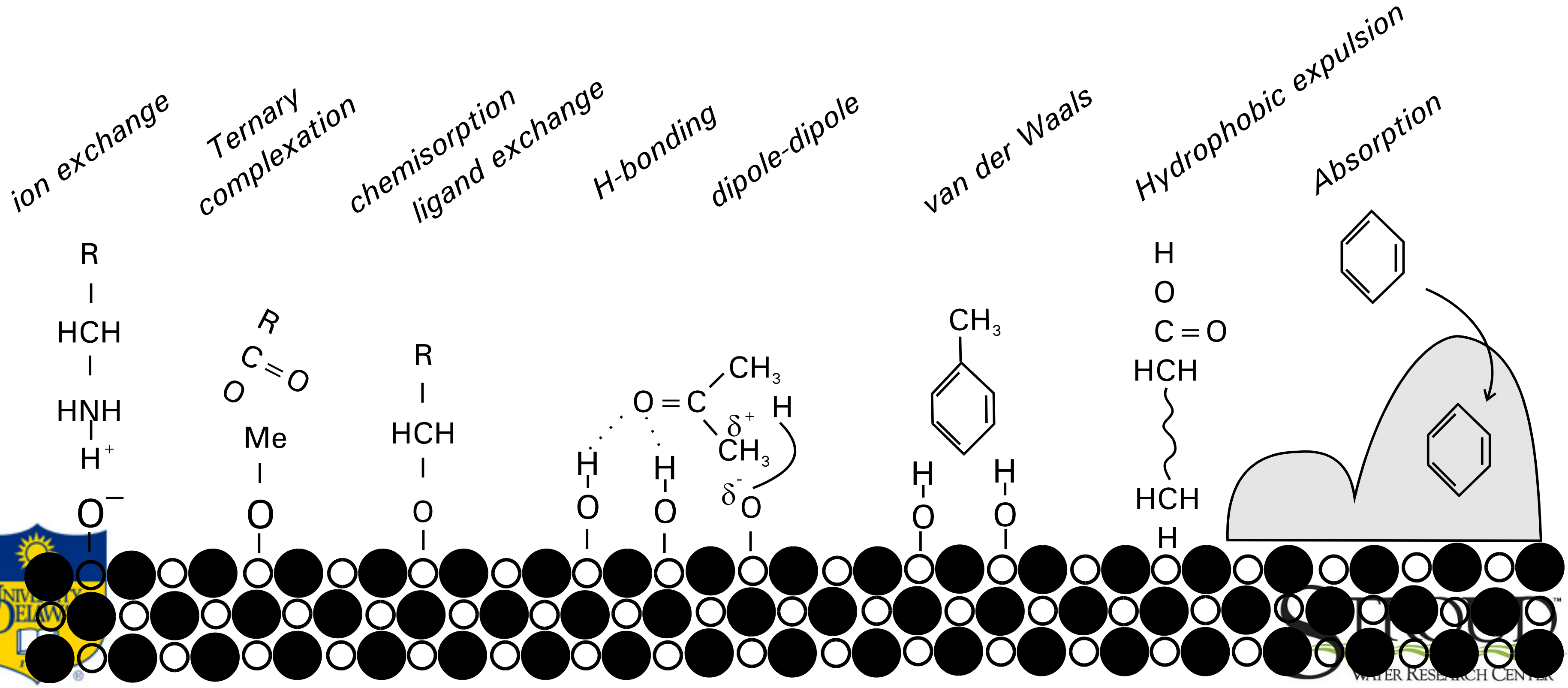
If human erosion were 75% of total, it would = **1.0 Gt C y^{-1} human sequestration sink due to M4.**

Objective 3 Global Synthesis

Obj. 1: Properties of Carbon-Mineral Complexes

1.1: Predict potential for minerals to complex carbon

1.2: Predict biological and chemical stability of mineral-complexed organic carbon



1. Organic matter complexation to fine minerals is a critical factor to stabilizing carbon

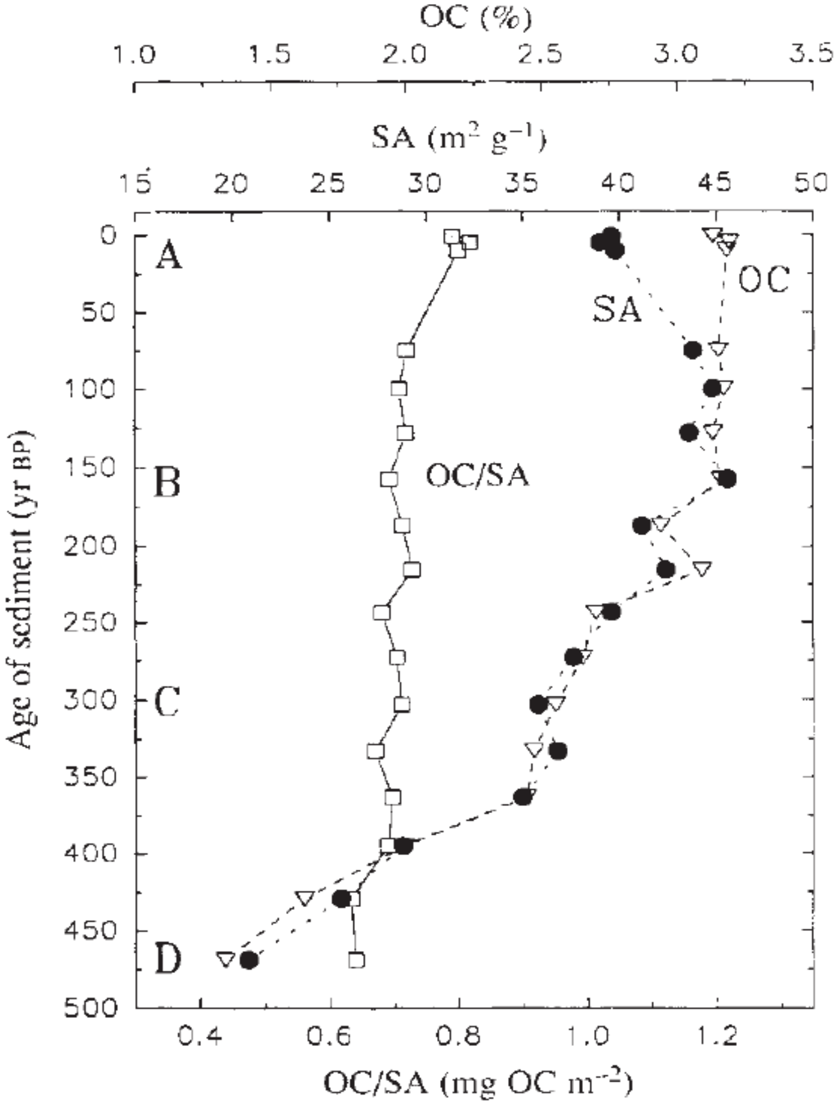
In Soils:

- CENTURY soil model (Schimel et al. 1994 GBC)
  - detrital carbon: $\boldsymbol{\tau}_d = -0.1 + 0.6\,(\text{clay content}) + 7.3e^{-0.04\text{Temp}}$
  - slow fraction: $\boldsymbol{\tau}_s = -67 + 9.1(\text{clay content}) + 159e^{-0.02\text{Temp}}$
  - passive fraction: $\boldsymbol{\tau}_p = -3300 + 370(\text{clay content}) + 7400e^{-0.02\text{Temp}}$
- Radiocarbon ages in density fractions (Trumbore et al. 1995, GBC)
  - Low density ➔ years to decades
  - High density ➔ decades to millenia

1. Organic matter complexation to fine minerals is a critical factor to stabilizing carbon

In Marine Sediments:

- % Organic Carbon (OC) covaries with
  mineral surface area (SA)
- 70% of 470 year old OC degrades in 7 d after desorbed.

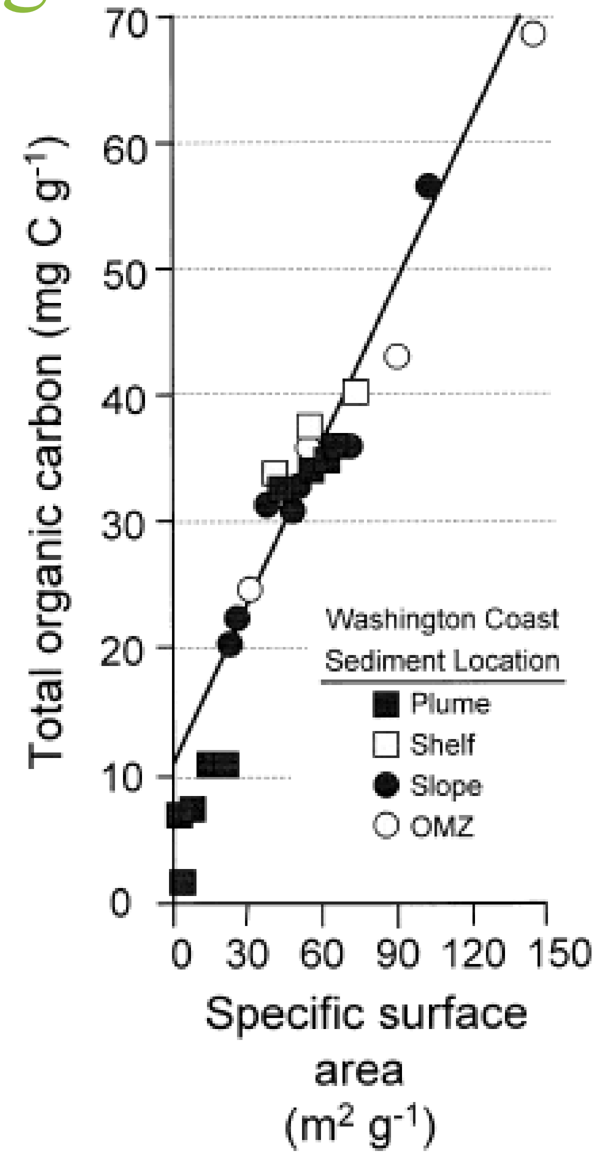


Keil *et al.*, 1994 *Nature*

1. Organic matter complexation to fine minerals is a critical factor to stabilizing carbon

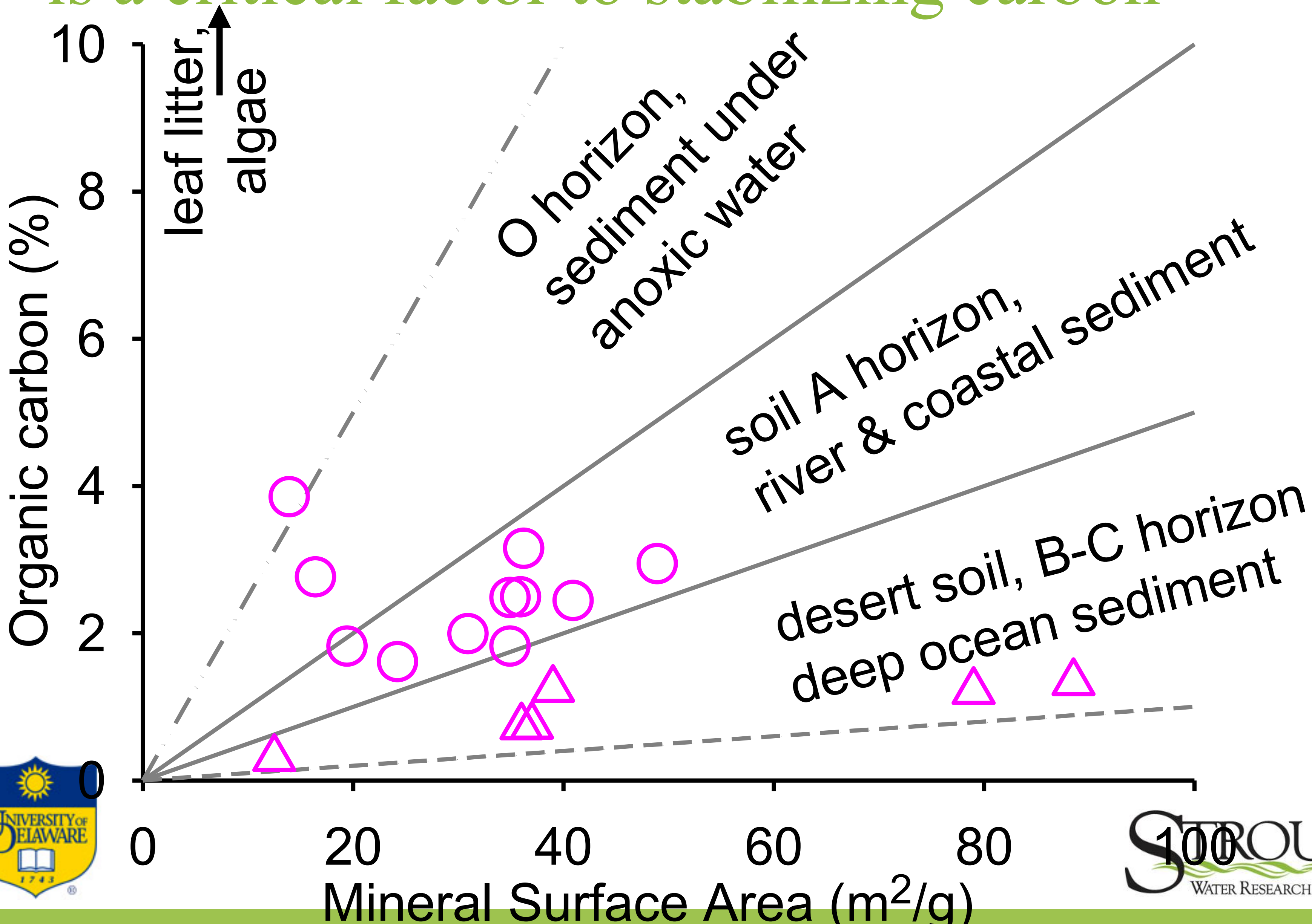
OC/SA Relationships

- A ratio of 0.5 to 1.0 mg/m² was observed in typical sediments and soils and dubbed the “monolayer equivalent”
- Later shown that distribution on surface was not uniform, but rather in large blobs (Mayer 1999 GCA)



Keil *et al.*, 1994 *GCA*

1. Organic matter complexation to fine minerals is a critical factor to stabilizing carbon



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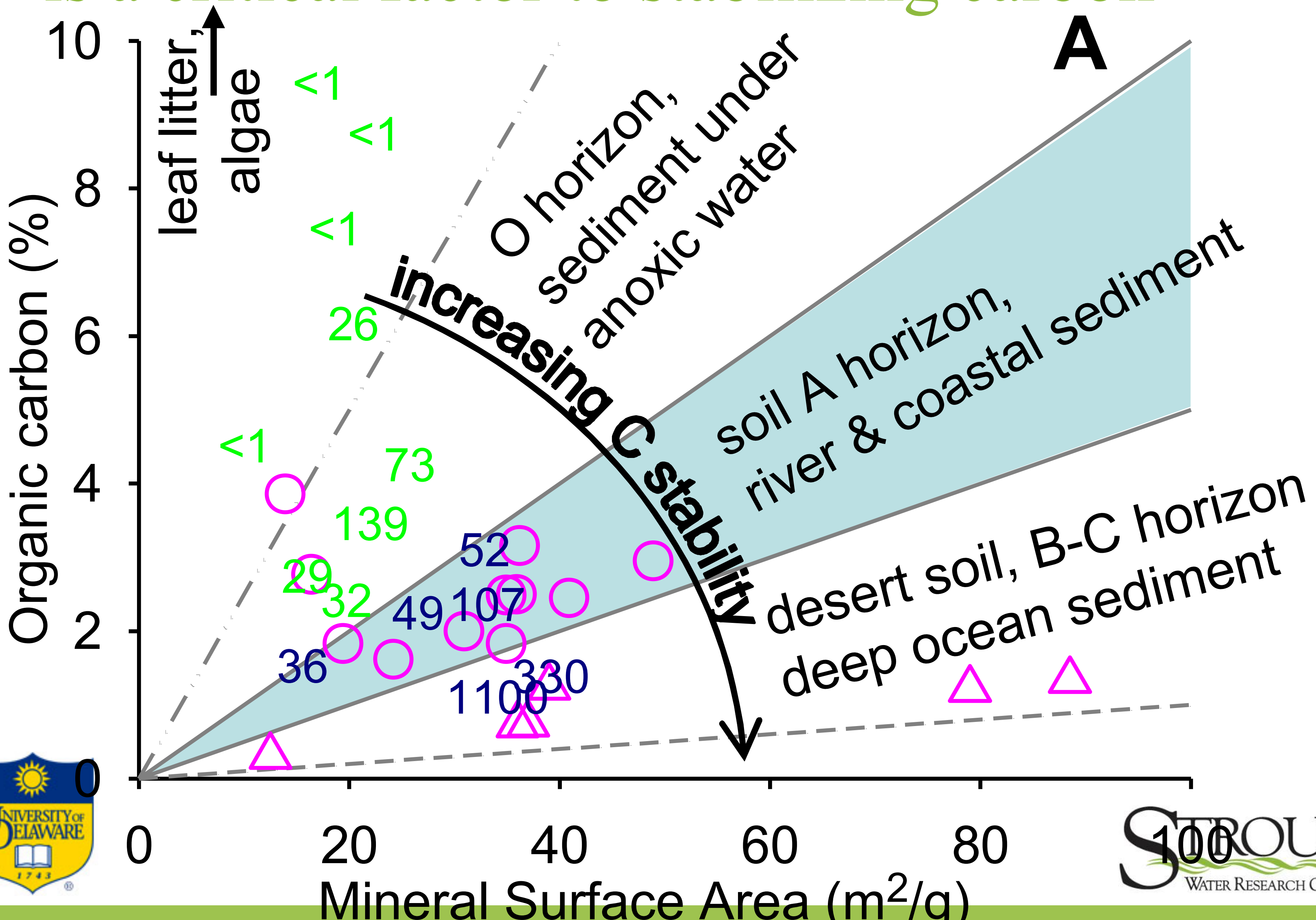
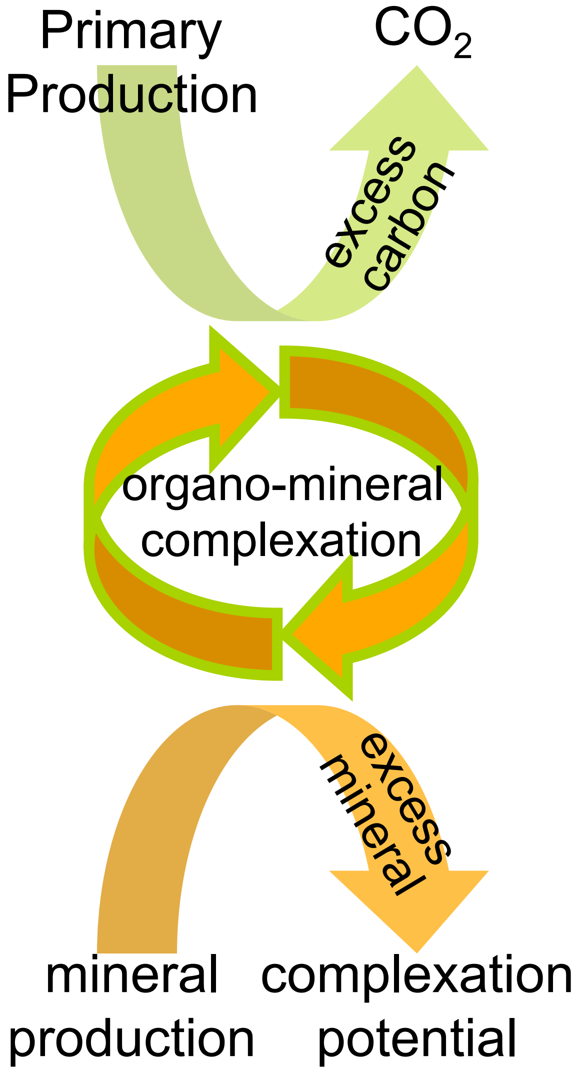


Obj. 2: Weathering and Erosion Controls on Carbon-Mineral Complex Formation



Primary Production

CO_2

excess carbon

organo-mineral complexation

excess mineral

mineral production

complexation potential

Vegetation, Litter & Detritus

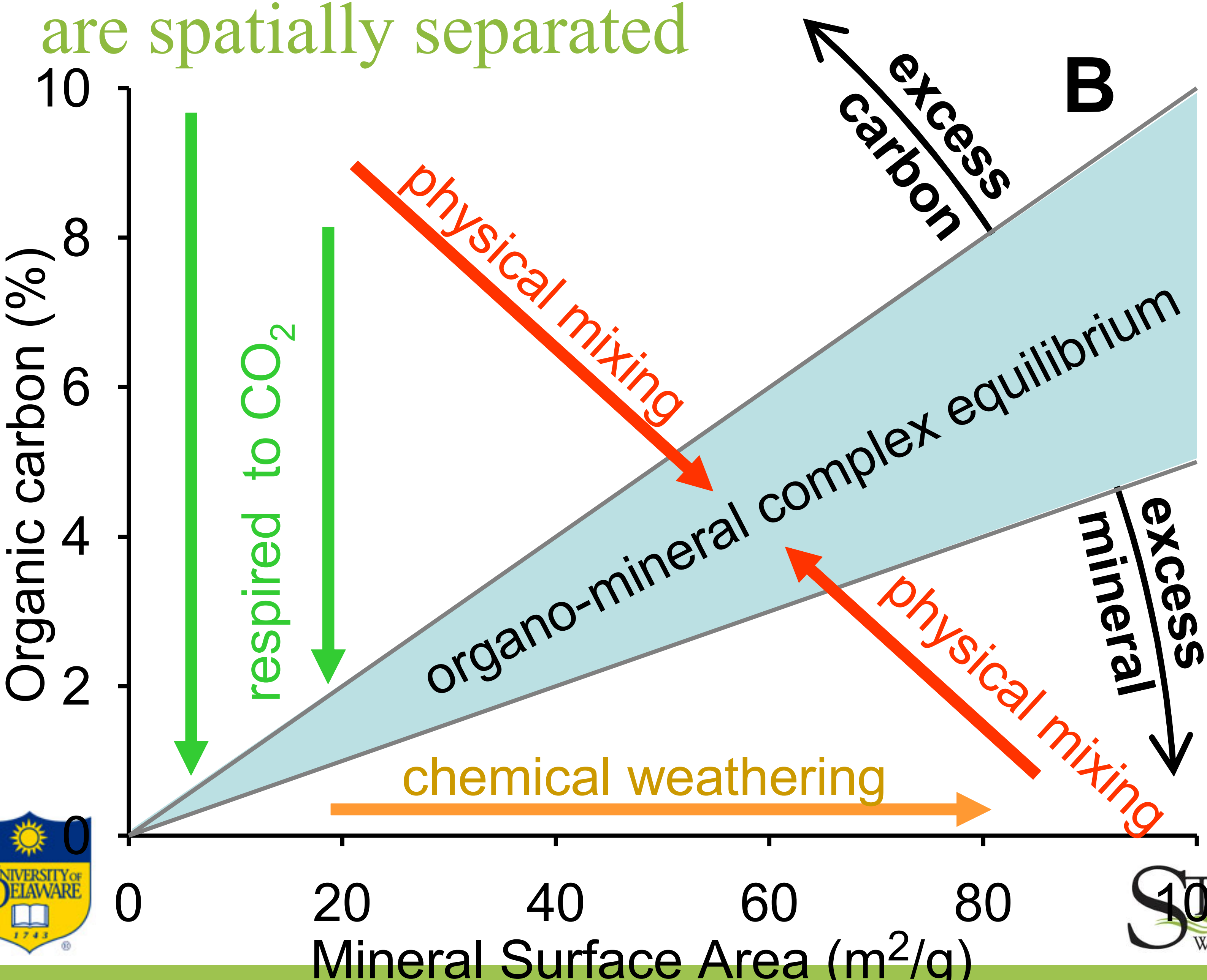
↓

A Horizon, Stream Suspension, Sediment Deposit

↑

Bedrock, Saprolite & B Horizon

2. OM production and fine mineral production are spatially separated

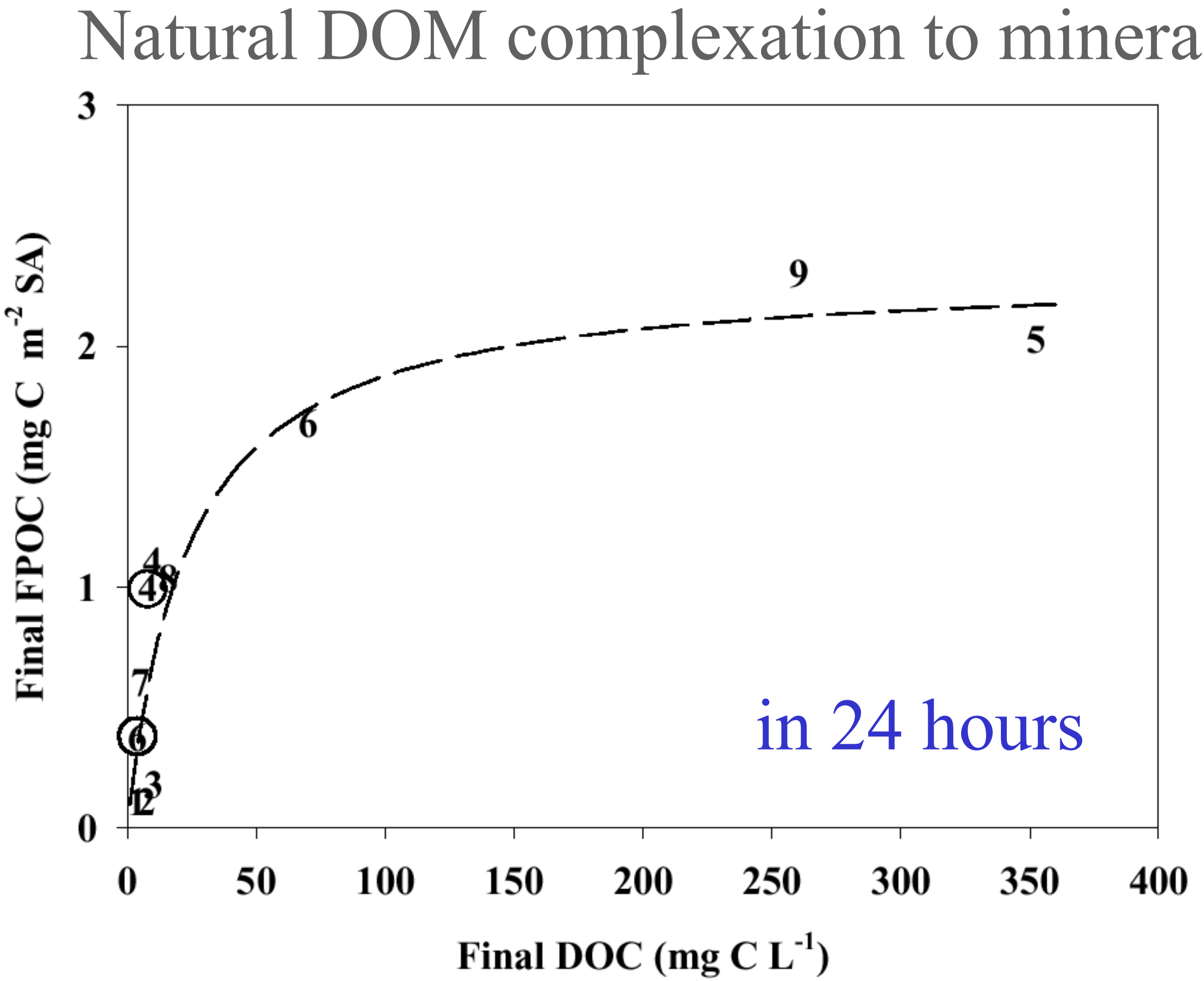


Obj. 3: Fluvial Network Controls on Complex Formation & Preservation

3.1: Accelerated erosion by modern agricultural and construction activities (1) creates fluvial carbon sinks within the watersheds and (2) decreases overall bioavailability of the stream water carbon leaving the watershed

- Tracer Characterization of Sediment Sources
- Determine Modern Sedimentation Rates and Concentrations
- Determine Historical Rates and Concentrations

3. Minerals will rapidly acquire normal carbon loadings when well-mixed with fresh OM


Natural DOM complexation to minerals

in 24 hours

Aufdenkampe *et al.*, 2001

C-Sequestration in Andean Amazon: Aufdenkampe & Aalto

Carbon Sequestration by Human Erosion

$$\frac{\Delta\left(OC_{sequestered}\right)}{\Delta t} = \underbrace{\left\{\begin{matrix}\text{replacement of}\\ \text{soil OC at}\\ \text{erosion site}\end{matrix}\right\}}_{\text{M1}} + \underbrace{\left\{\begin{matrix}\text{burial of}\\ \text{non-}\\ \text{complexed OC}\end{matrix}\right\}}_{\text{M2}} - \underbrace{\left\{\begin{matrix}\text{respiration of}\\ \text{non-}\\ \text{complexed OC}\end{matrix}\right\}}_{\text{M3}}$$

Mechanism:

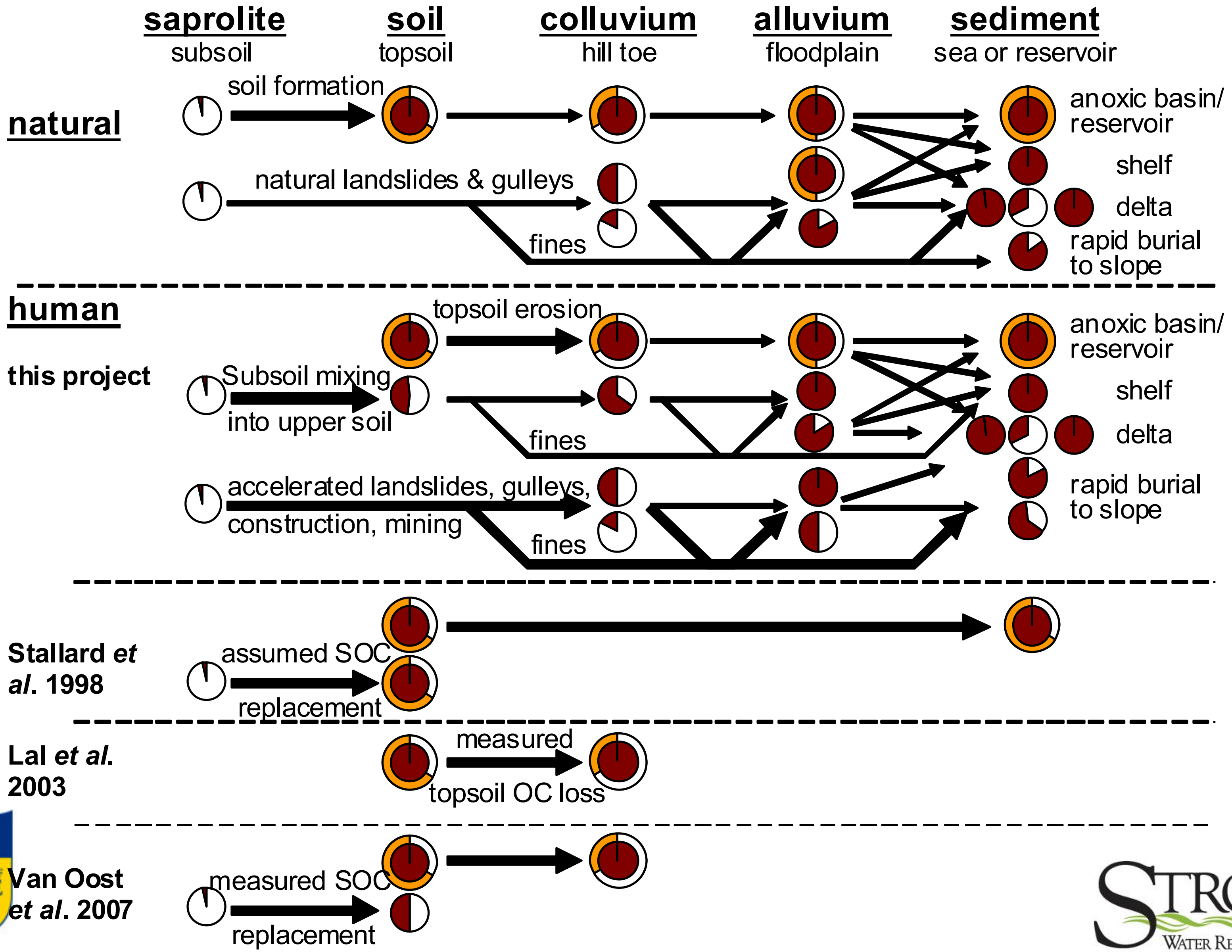
M1. Complete to partial replacement of soil OC at agricultural eroding sites via crop production (Stallard 1998; Harden et al. 1999)

M2. Burial and inhibited decomposition of OC eroded from topsoils (Stallard 1998; Smith et al. 2001; Smith et al. 2005) & enhanced burial of in situ plant growth in coluvium (Yoo et al. 2005)

M3. Enhanced decomposition of soil OC due to breakdown of protective soil structures during erosion and transport (Cole and Caraco 2001; Lal 2003; Ewing et al. 2006).

M4. Production and transport of OC-poor minerals from depth into biologically active settings with excess organic carbon forms stable carbon-mineral complexes (Aufdenkampe, Aalto & Yoo)

Whole Watershed Approach



saprolite
subsoil

soil
topsoil

colluvium
hill toe

alluvium
floodplain

sediment
sea or reservoir

natural

soil formation

natural landslides & gulleys

fines

anoxic basin/
reservoir

shelf

delta

rapid burial
to slope

human

this project

topsoil erosion

Subsoil mixing
into upper soil

fines

accelerated landslides, gulleys,
construction, mining

fines

anoxic basin/
reservoir

shelf

delta

rapid burial
to slope

Stallard *et al*. 1998

assumed SOC
replacement

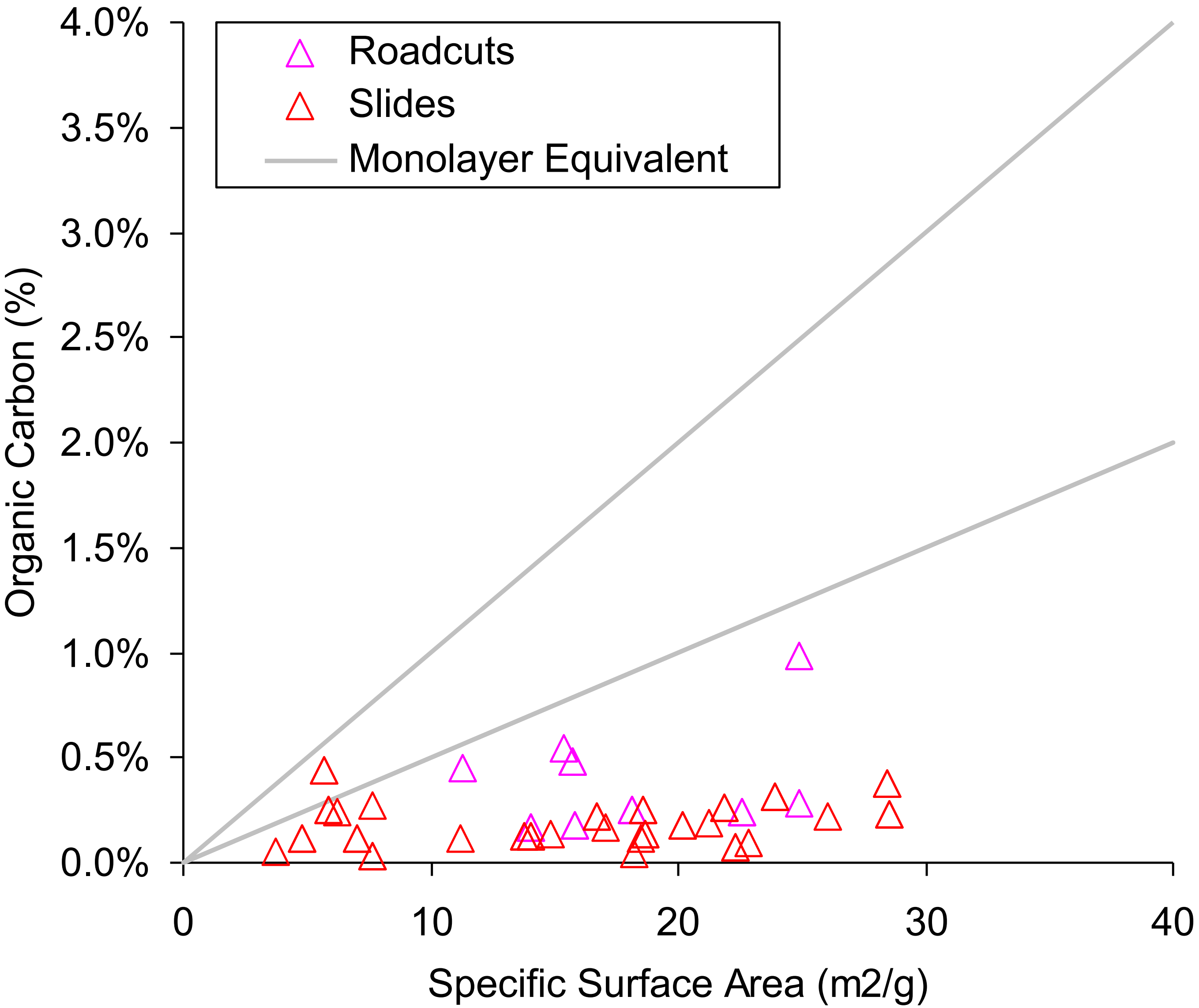
Lal *et al.* 2003

measured
topsoil OC loss

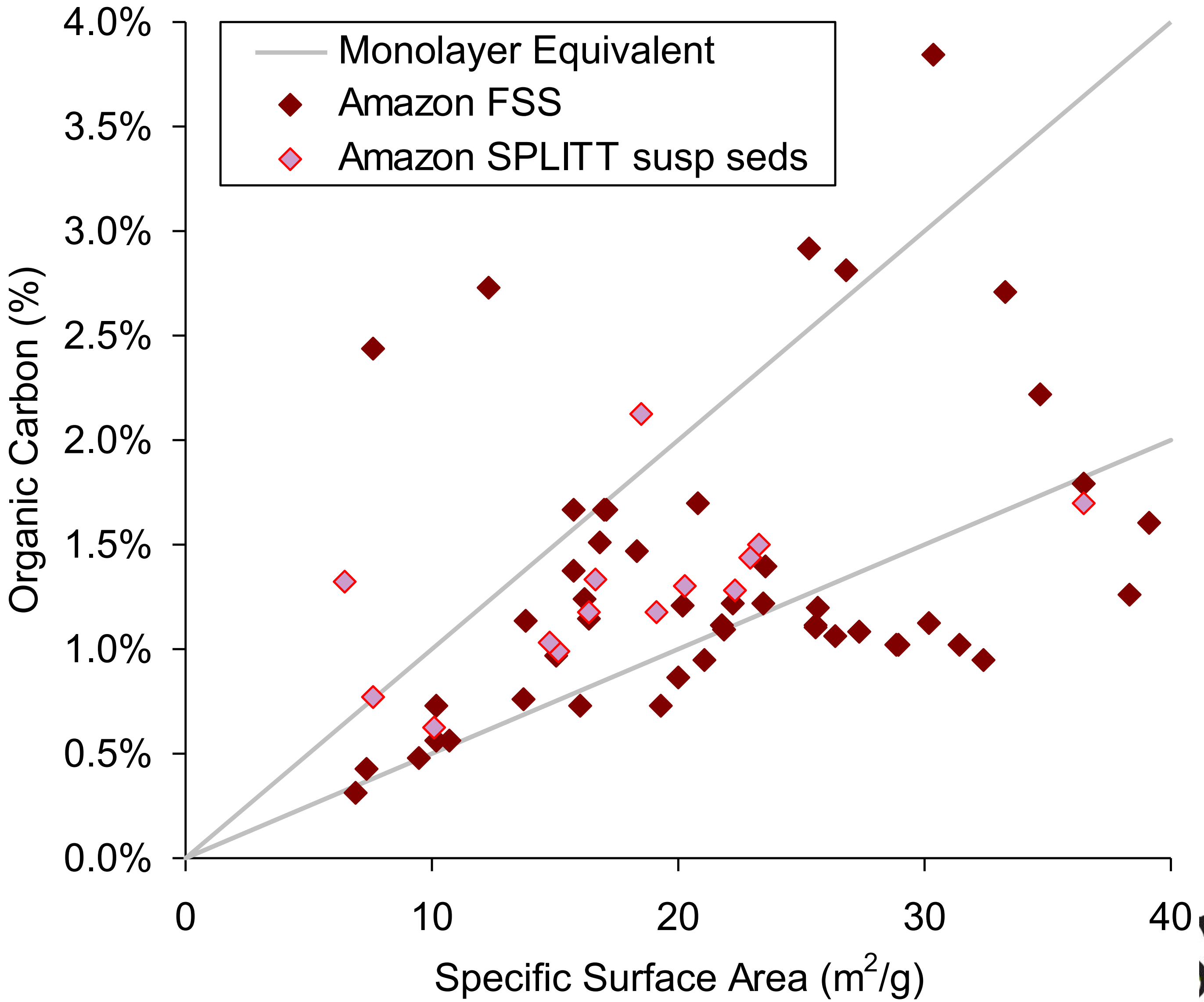
Van Oost *et al*. 2007

measured SOC
replacement

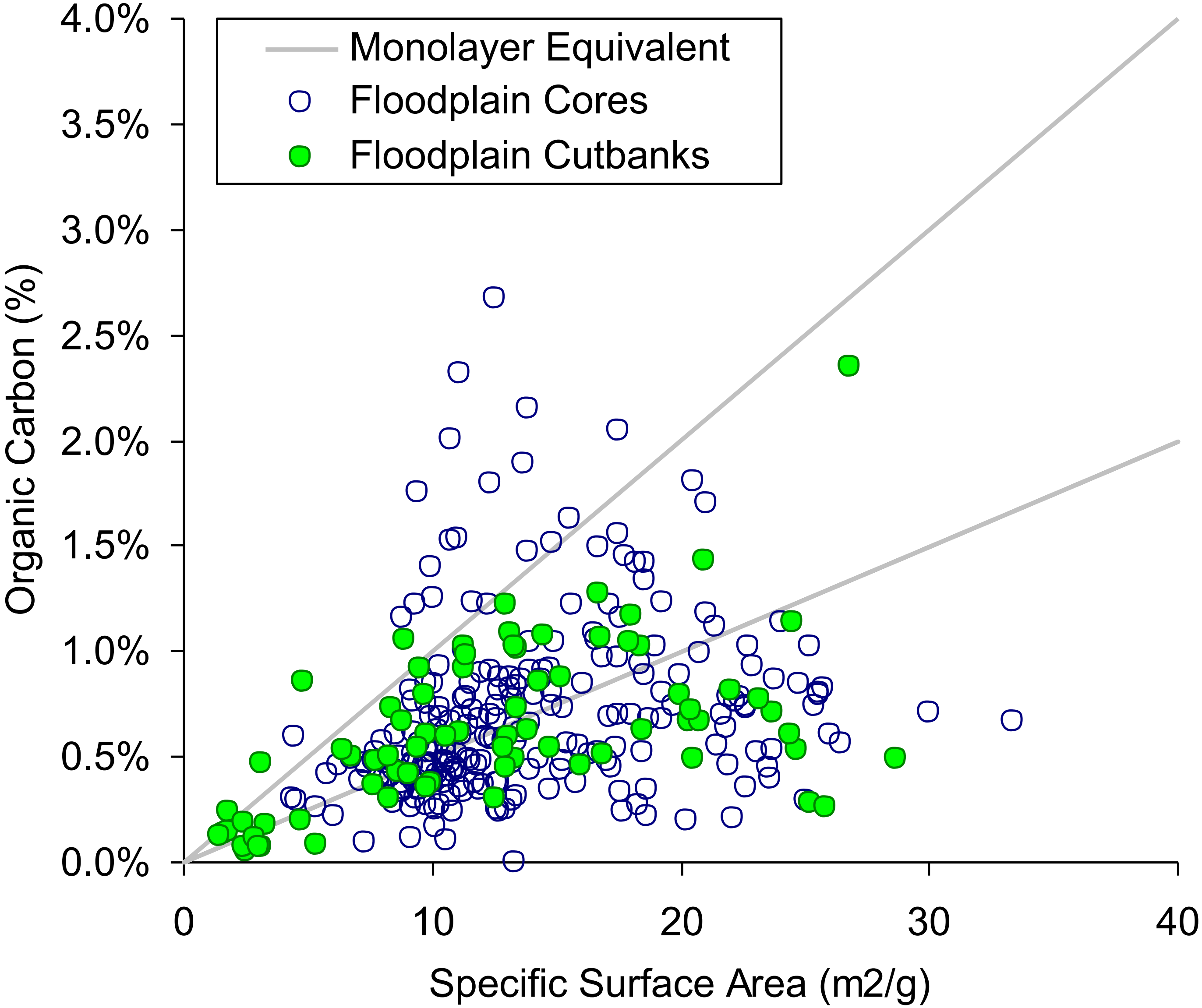
Sediment Sources: 0.03-0.15 mg OC m^{-2}



Suspended Sediment: 0.29-3.2 mg OC m^{-2}



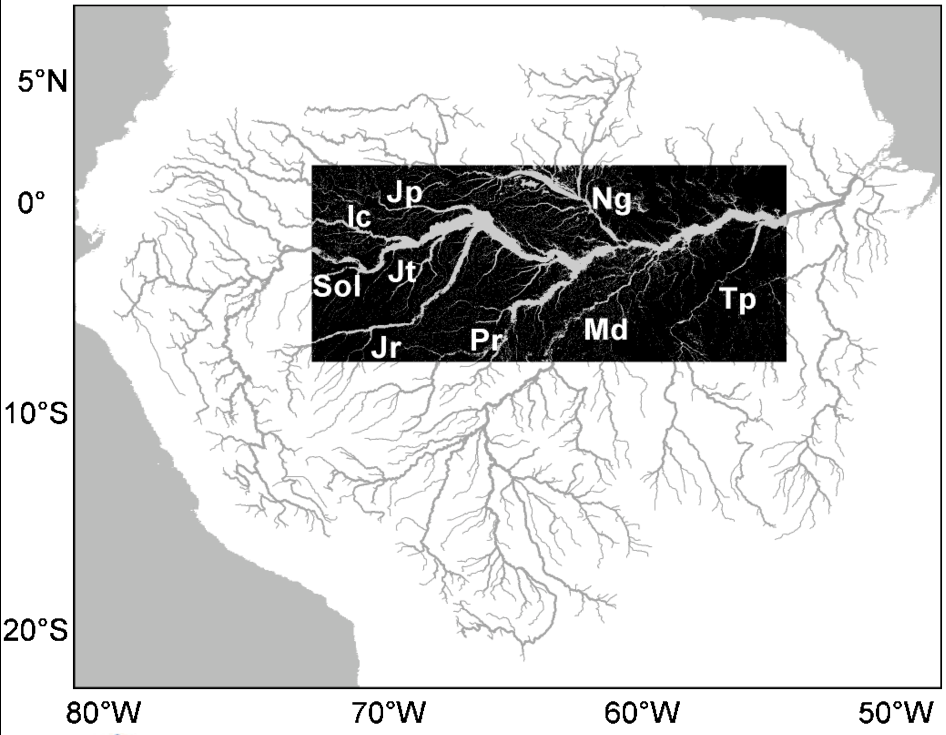
Sediment Deposits: 0.21-1.2 mg OC m^{-2}




South Beach
ORVIS

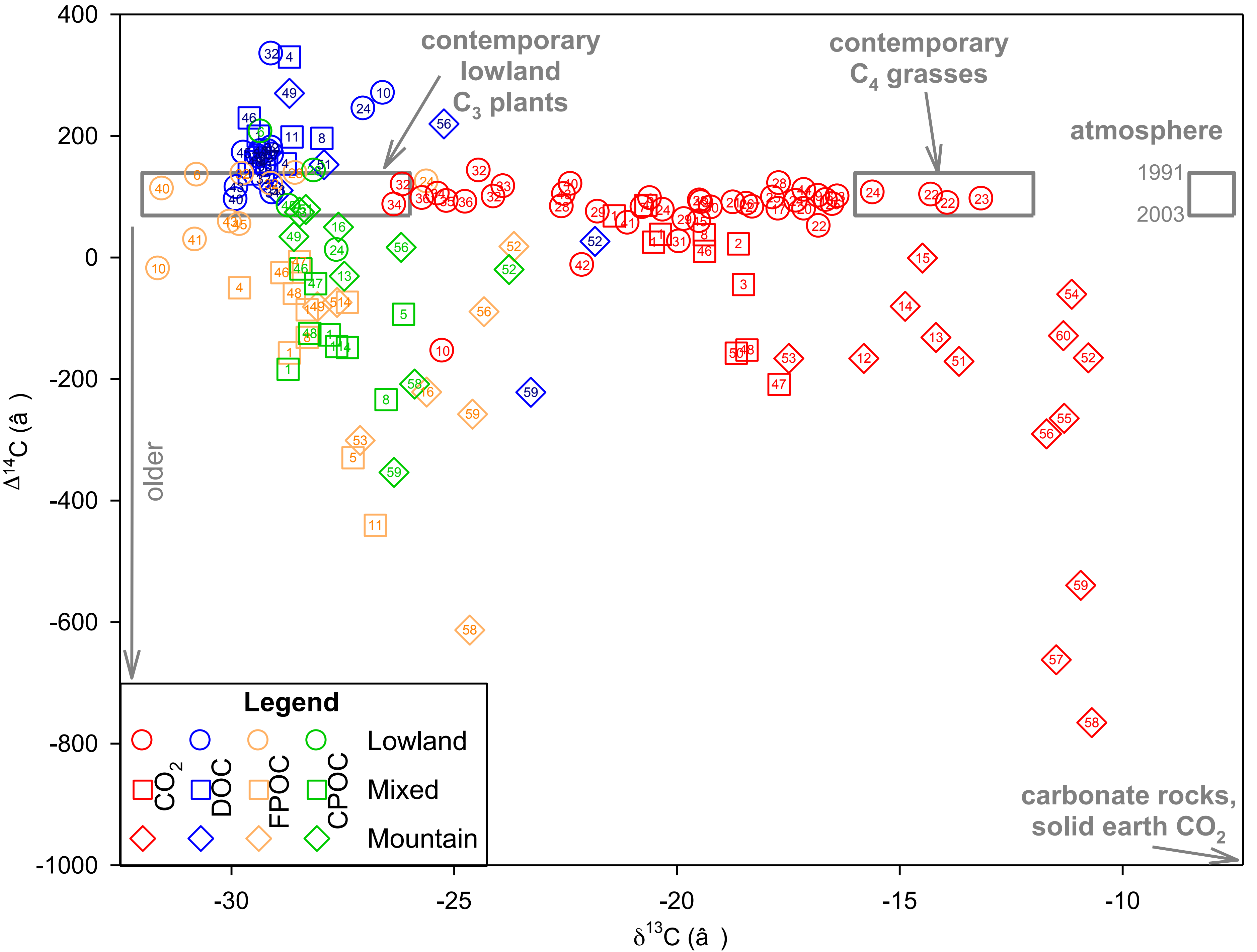
4. An excess of fresh OM is mobilized into freshwaters, with 50-95% being respired

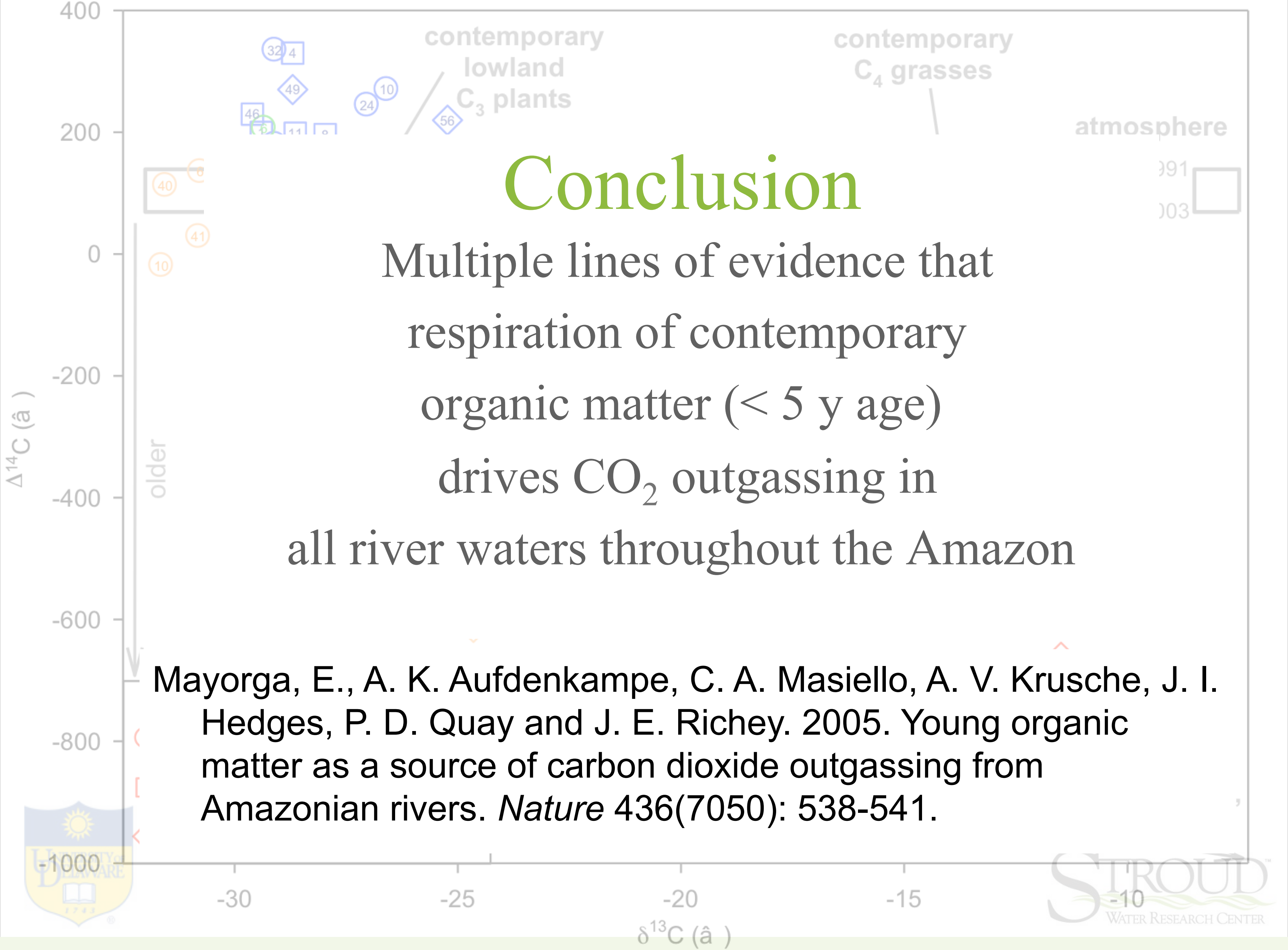
Tropical Rivers Outgas 10-15x more than Discharge



- ~ 0.2 Gt C y^{-1} evades from central Amazon waters
  - ≈ biomass accumulation in rain forest
- 0.9 Gt C y^{-1} from all waters in humid tropics
  - Recent data show that values are at least twice as large!

Richey, J. E., Melack, J. M., Aufdenkampe, A. K., Ballester, V. M., and Hess, L. L. (2002). Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO_2. *Nature*, **416**, 617-620.


contemporary lowland C_3 plants
contemporary C_4 grasses
atmosphere
1991
2003
older
carbonate rocks, solid earth CO_2
Legend
CO_2
DOC
FPOC
CPOC
Lowland
Mixed
Mountain
Δ^{14}C (â)
δ^{13}C (â)
400
200
0
-200
-400
-600
-800
-1000
-30
-25
-20
-15
-10



Conclusion

Multiple lines of evidence that respiration of contemporary organic matter (< 5 y age) drives CO_2 outgassing in all river waters throughout the Amazon

Mayorga, E., A. K. Aufdenkampe, C. A. Masiello, A. V. Krusche, J. I. Hedges, P. D. Quay and J. E. Richey. 2005. Young organic matter as a source of carbon dioxide outgassing from Amazonian rivers. *Nature* 436(7050): 538-541.

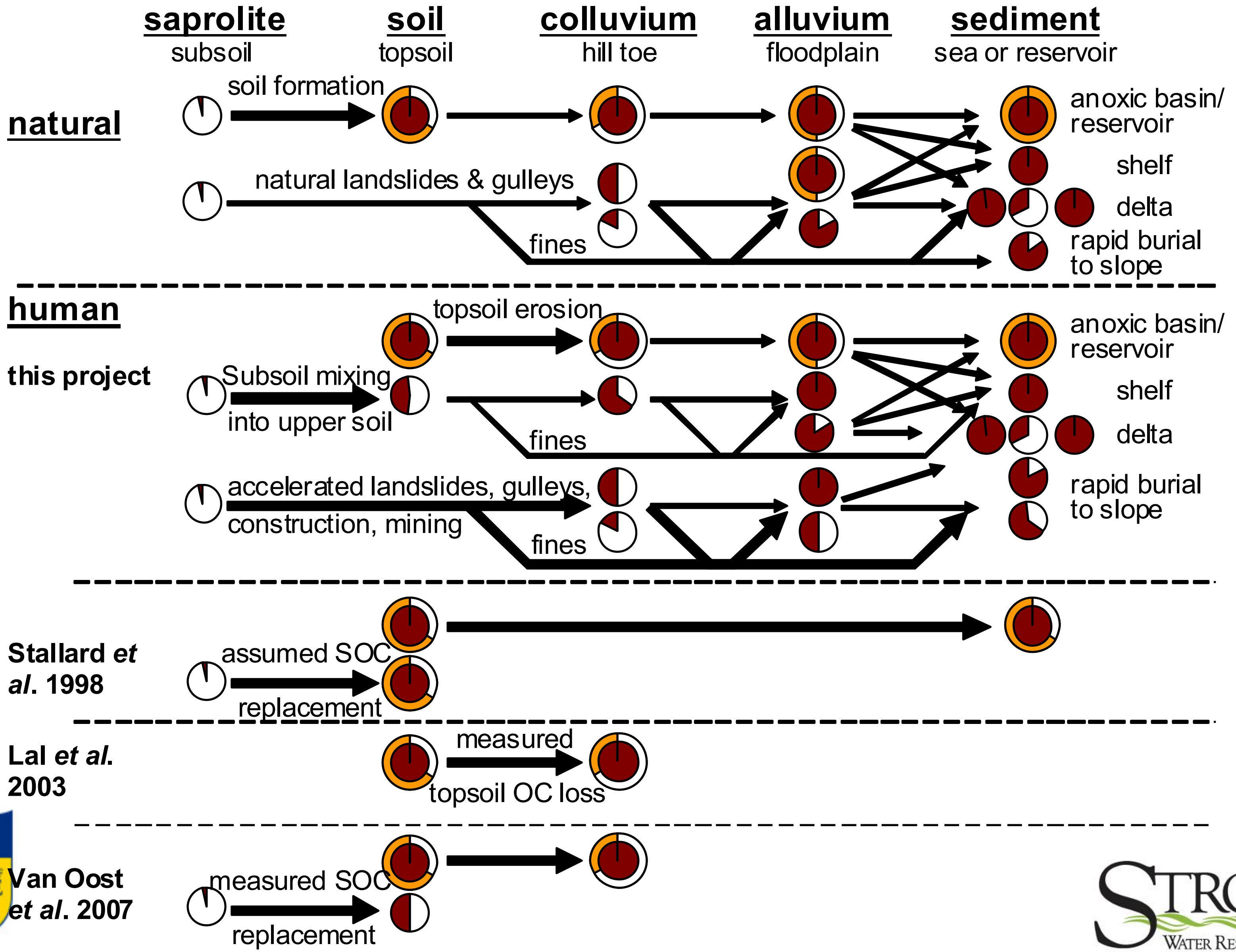
Obj. 4: Watershed Integration of Erosion-Driven Carbon Sequestration

4.1: Mass balance calculation for mineral surface area and mineral-complexed organic carbon

$$\frac{d\left(OC_{complexed}\right)}{dt} = \underbrace{\left(\frac{OC}{SA}\right)_{dep} SSA_{dep} Q_{dep}}_{\text{Deposition flux}} + \underbrace{\left(\frac{OC}{SA}\right)_{export} SSA_{export} Q_{export}}_{\text{Stream export}} - \underbrace{\left(\frac{OC}{SA}\right)_{source} SSA_{source} Q_{source}}_{\text{Upland \& bank erosion}}$$

$$\frac{d\left(OC_{sequestered}\right)}{dt} = \frac{d\left(OC_{complexed}\right)}{dt} + \begin{array}{c}\text{burial of young,}\\ \text{non-complexed}\\ \text{OC}\end{array} - \begin{array}{c}\text{respiration of old,}\\ \text{non-complexed}\\ \text{OC}\end{array}$$

Whole Watershed Approach



saprolite
subsoil

soil
topsoil

colluvium
hill toe

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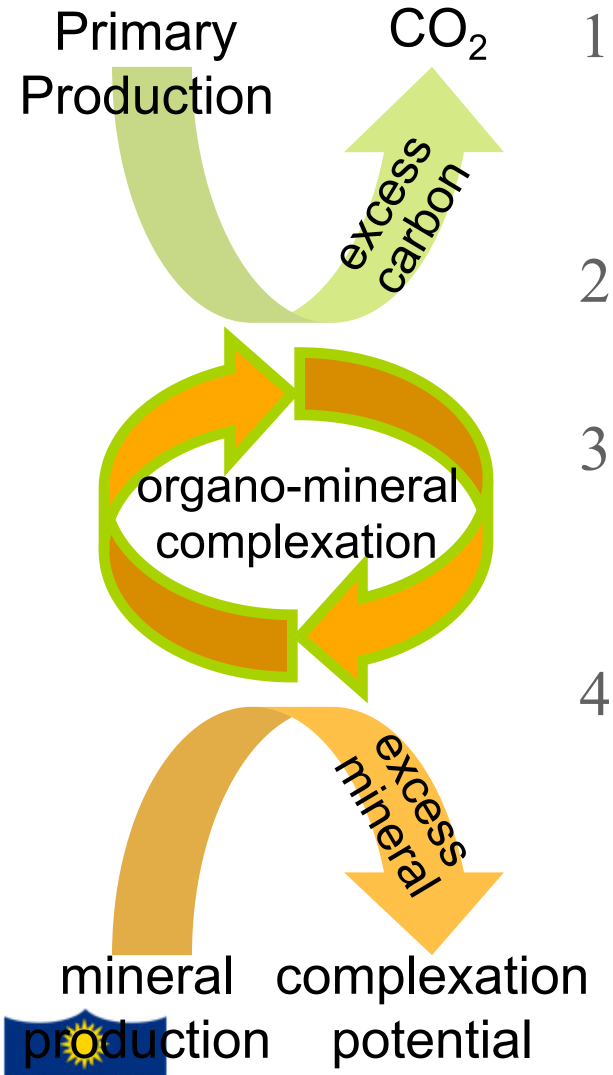
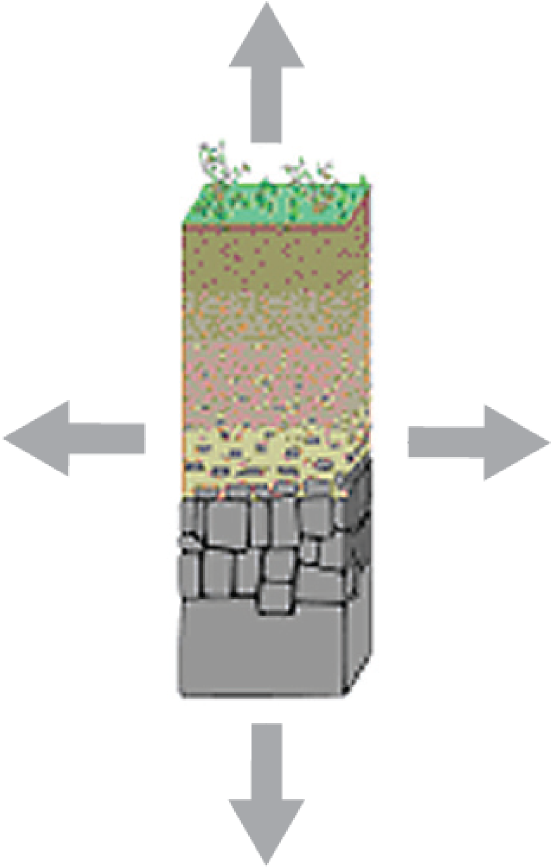
Basis for Hypothesis



1. Organic matter (OM) complexation to fine minerals is a critical factor to stabilizing and sequestering carbon
2. OM production and fine mineral production are spatially separated
3. Minerals will rapidly acquire normal carbon loadings when well-mixed with fresh OM
4. An excess of fresh OM is mobilized into freshwaters, with 50-95% being respired before the ocean

The Critical Zone



Atmosphere

Landforms

Ecosystems

Water

NSF Critical Zone Observatory National Program

- Goal: Establish long-term watershed-scale “observatories” in different physiographic regions of USA
  - with state-of-the-art monitoring and cyber-infrastructure, and
  - as a resource for multi-disciplinary teams of scientists from around the nation
- 3 CZO’s funded in 2007
- 3 CZO’s funded in 2009, with stimulus funds