Earthcasting the Future of the Critical Zone

S. L. Brantley

The “Critical Zone” is the zone extending from the outer limits of the vegetation canopy to the lower limits of groundwater.

Studying the Critical Zone leads to development of models to quantify evolution over time.

Modelling the CZ

Interpreting the Record

Atmospheric Response
River/Ocean Response
Soil/Sediment Response
If we can read the depth records of the Critical Zone using models, we can use the models to predict the future (Earthcasting)
Critical Zone Science Mission:

- Learn to measure the fluxes occurring today
- Learn to read the geological record of the cumulative effect of these fluxes over time
- Develop quantitative models of Critical Zone evolution

Critical Zone Science Vision:

By measuring what is happening today and reading what happened yesterday, we will learn to project what will happen tomorrow.
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Welcome to the Anthropocene

“The Earth is a big thing; if you divided it up evenly among its 7 billion inhabitants, they would get almost 1 trillion tonnes each. To think that the workings of so vast an entity could be lastingly changed by a species that has been scampering across its surface for less than 1% of its history seems, on the face of it, absurd. But it is not. "Humans have become a force of nature reshaping the planet on a geological scale – but at a far-faster-than-geological speed."

From: The Economist: May 28, 2011
Syncrude mine in Athabasca tar sands

• Moving 30 billion tonnes of earth – twice the amount of sediment that flows down all rivers in world per year
• (or did flow...that sediment flow is shrinking due to the 50,000 large dams over the last 50 y that have cut the flow by 1/5)

From: The Economist: May 28, 2011

Syncrude - a joint venture of oil and gas companies mining the Athabasca oil sands - holds eight leases covering 258,000ha, 40km north of Fort McMurray. It is ranked as the world's largest producer of synthetic crude from oil sands and the biggest single source in Canada. The consortium runs three separate mines – the original Base Mine and the North Mine, both near to Mildred Lake on lease 17, together with the Aurora mine some 35km to the north. The upgrader facility, also located on lease 17, treats oil sands from all three.

http://www.mining-technology.com/projects/syncrude/
Historic Mill Dams in Centre County PA

Map from Dorothy Merritts, Franklin and Marshall Univ
How will humans change the earth into the future?

- We will experience huge pressures to grow food and provide clean water to growing numbers of humans (growth of pressure for water and food)
- We will continue to expand the human impact (growth of the human footprint)
- We are going to drill a lot more holes: and inject a lot more stuff (growth of drilling and injecting)
- We are going to increasingly mine from what we have already mined or used (growth of recycling)
- We are going to increasingly live in a built environment, sequestered from the natural environment (growth of urban earth)
- We will increasingly live “on line” (growth of the separate, online world)
- We will share more: rooms, cars, movies, music (growth of the sharing economy)
- We will see push back against technology, threatening the social license for development (growth of the No-society)
- We will try to engineer our global environment (growth of geoengineering)
- More...
Rough outline of the talk

- **Part I.** How we have touched the CZ from canopy to “the bottom of groundwater”
- **Part II.** How we are moving toward the ability to **Earthcast**

Riebe, Hahm and Brantley, in prep.
“The Grand Nutrients”
Carbon, Nitrogen, Phosphorus, Sulfur

Lerman and Wu, 2008
Earth's global Ag, Al, Cr, Cu, Fe, Ni, Pb, and Zn cycles

By Thomas S. Jones

**Manganese Material Flow Patterns**

Solid portions indicate pre-human/present-day
dashed portions indicate human activities.

Source: Reference 24, pp. 778-79.

Figure 16.—Pre-human/present-day global fluxes of manganese in thousand metric tons per year.

1994 USGS publication
Susquehanna Shale Hills Critical Zone Observatory

- Soils are enriched in Mn relative to the parent shale

Herndon, Jin, Brantley (2011) ES&T.
What was the rate (A) and timescale of Mn deposition?

- Use a simple mass balance model to estimate rates and time durations of deposition

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**Soil, $m_{Mn,w}$**

Atmospheric Deposition  \[\uparrow\]  Erosion

Chemical Weathering  \[\downarrow\]  Soil production from bedrock

Herndon, Jin, Brantley (2011) *ES&T.*
Mn enrichment consistent with past industrial inputs

Derived atmospheric inputs consistent with historical deposition near urban/industrial sources

Herndon, Jin, Brantley (2011) ES&T.
• Surface soils throughout the US and Europe contain the legacy of Mn emissions (but data are very very sparse and soils heterogeneous)
• Over >60% of U.S. soils (n = 455) and >50% of European soils (n=778) analyzed and reported in public databases have net Mn enrichment (warm colors) relative to their parent materials

Herndon, Jin, Brantley (2011) *ES&T.*
What are the sources of Mn?

Point Source CO₂ releases in 2000 (kton/year)

- 100 – 1,000
- 1,000 – 3,000
- 3,000 – 6,000
- 6,000 – 12,000
- 12,000 – 24,000

Mn addition or removal from soil

- 7.1 kg/m² (Mn Addition)
- 0 (No change)
- - 5.9 kg/m² (Mn Removal)

Data From USGS
Cumulative Mn emissions 1988-2010 (US EPA) superimposed on integrated Mn mass flux values
Carter, M. Masters thesis Penn State 2013

Figure 14. Total Mn air releases from facilities reported for the time period 1988-2010 superimposed on integrated Mn mass flux values ($m_{Mn}$) calculated from 455 soil cores in Herndon and Brantley (2011) and Herndon et al. (2011). Purple symbols are primary metals facilities, which were responsible for 50% of U.S. Mn air emissions from 1988-2010. Green symbols are smaller Mn emitters.
What happens to the emitted manganese?
Some deposited in the oceans:
Trace metals in north Atlantic

Figure from William Landing, Florida State University
What happens to the emitted manganese? Some deposited in soils, then weathered into rivers

Herndon, Beth PhD Thesis Penn State
Some Mn taken up into vegetation

Leaves

Stems

Roots

Herndon, Beth PhD Thesis Penn State
Schematic timescales of change of Mn in Air, Soil, Vegetation, Water

Beth Herndon, Penn State University graduate student, now professor at Kent State
How deep is the critical zone?
One definition might be the depth of human impact.

Riebe, Hahm and Brantley, in prep.
Using this definition, the public is actually arguing about the depth of the Critical Zone.
1987 gas well fracked in WV alleged to have contaminated a nearby water well
In 1982, Kaiser Gas Co. drilled a gas well on the property of Mr. James Parsons. The well was fractured using a typical fracturing fluid or gel. The residual fracturing fluid migrated into Mr. Parson’s water well (which was drilled to a depth of 416 feet), according to an analysis by the West Virginia Environmental Health Services Lab of well water samples taken from the property. Dark and light gelatinous material (fracturing fluid) was found, along with white fibers. The gas well is located less than 1000 feet from the water well. The chief of the laboratory advised that the water well was contaminated and unfit for domestic use, and that an alternative source of domestic water had to be found. Analysis showed the water to contain high levels of fluoride, sodium, iron, and manganese. The water, according to DNR officials, had a hydrocarbon odor, indicating the presence of gas.
Pennsylvania DEP estimates that 350,000 oil and gas wells have been drilled in PA. The location of maybe 100,000 of them are unknown. **Red** = active, **Blue** = inactive, **Black** = abandoned
Locations of unconventional shale gas wells – more than 7000 PA well pads today
THE NSF-FUNDED SHALE NETWORK

The ShaleNetwork is creating a central and accessible repository for geochemistry and hydrology data collected by watershed groups, government agencies, industry stakeholders, and universities working together to document natural variability and potential environmental impacts of shale gas extraction activities.
Screen Shot showing ShaleNetwork Data Sites with chemistry for injection and/or flowback water (data from Hayes)
Benzene in flowback/production water chemistry plotted versus time after hydrofracking from ShaleNetwork (data from PA wells as cited by Hayes (2009) that are available in ShaleNetwork)

No confirmed reports in PA of constituents in hydrofrack fluids going into drinking waters due to hydrofracturing itself.

There have been spills that have contaminated soils and surface waters.

Graph from Carl Kirby, Bucknell Univ
In contrast to low concentration constituents such as hydrofracking compounds, salts are present in flowback/production waters at much higher concentrations. **A spill or leakage would therefore most likely be identified by analyzing salts.** Here are all 22 locations where PA DEP determined that shale gas development could be presumed responsible for contamination of drinking water supplies with dissolved salts between 2008 and 2012.

In many of these cases, salts may derive from natural brines in subsurface.

Brantley et al., 2013, subm. Int. J. Coal Geology
Methane concentrations in groundwaters

Most data are in ShaleNetwork database; figure made by PSU grad student Paul Grieve

What would Earthcasting the Critical Zone look like?
We would have all the data we need at our fingertips.
Where do we stand? Critical zone data types (trains) moving down tracks at different rates

LiDAR data
Hydrologic data
Geochemical data
Geophysical data
Microbiological data
Geomorphological data
Biological data
Hydroservers are computers around the world that post online data. HydroDesktop is the computer program that helps you pull the metadata and data onto your home computer.

One of the most advanced: CUAHSI’s Hydrologic Information System

HIS Central is the computer that houses the metadata for online datasets.

First you grab metadata

Then you grab data

HydroDesktop and other clients

Data Access

HydroServer

Data Publication

Data Services

Water and Spatial Data

Search Services

Geographic Semantic Time and Network Search

Metadata Services

Service Registration and Catalog Harvesting

CUAHSI
universities allied for water research
NSF CUAHSI HIS Timeline

HIS Pilot  HIS Development  HIS Prototype

2002  2007  2012

Number of Time Series Downloaded

Data Sources Registered in HIS

Production Quality Resources

Water Data Center


0  20  40  60  80  100  120

2008  2009  2010  2011  Present

28  39  56  77  97

1,200,000

2002  2007  2012

Number of Time Series Downloaded

Data Sources Registered in HIS

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0  20  40  60  80  100  120

2008  2009  2010  2011  Present

28  39  56  77  97

1,200,000
All Shale Network sites, May 2013

Time Series: 58,133
Sites: 22,904
Variables: 121
Total Values: 669,774
Earthcasting will likely include cascades of models

GCM
- Atmospheric CO₂
- Rainfall
  - Air temperature
  - Continental vegetation
- Soil CO₂
- Soil drainage
- Land use changes

DGVM
- Enhanced erosion
- Weathering reactions
  - Cation biogeochemical cycles
  - Water pH
  - Nutrient cycle

Godderis and Brantley, Elementa, 2014
Models would be used to interpret the geologic record... e.g., we have modelled soil formation in Peoria loess
Peoria loess: Deposits of dust along the Mississippi valley

Parent loess -- roughly constant in composition -- began pedogenesis about 13,000 y ago
Climate model used with a vegetation model drives a weathering model.

Godderis, Williams, Schott, Pollard, Brantley, 2010
CO$_2$ solubilizes and acidifies soil solutions that flow through the soils, dissolving away carbonates.

Fastest dissolving mineral in the soil is dolomite (Ca,Mg carbonate): can model the retreat of the dolomite from 10000 y ago, to 5000 y ago, to today.
How will weathering along the transect change in the future as CO₂ increases?

ARPEGE GCM
(Meteo-France Toulouse)

Climate scenario to 2100
Temperature Precipitation,
Wind speed Humidity,
Cloudiness

CARAIB (LPAP Belgium)

Vegetation, NPP
Root depth
Evapotranspiration
Runoff
Drainage
Soil CO₂ estimated from autotrophic & heterotrophic respiration

WITCH

Water chemistry

Modelling by Yves Godderis,
Toulouse, with S Brantley
A1B scenario from IPCC

Very rapid economic growth, global population peaks mid century and then declines, rapid introduction of new and efficient technologies, balance across energy sources.
Earthcasting future weathering along the Mississippi valley, USA (northern pedon)

Godderis and Brantley, Elementa, 2014
Calculated dolomite retreat rate

Godderis and Brantley, Elementa, 2014
Temperature increases along the transect

Modelling by Yves Godderis, Toulouse
Soil $\text{CO}_2$ varies with position

T increases rate of diffusive loss of $\text{CO}_2$
Drainage decreases
Fertilization does not compensate

Larger $\text{CO}_2$ diffusive loss
Drainage increases
$\text{CO}_2$ fertilization increases NPP (and autotrophic and heterotrophic respiration)

Modelling by Yves Godderis, Toulouse
Rainfall increases N and S
ET increases N and S
Drainage up 14% in S, down 40% in N

ET calculated from T and CO$_2$, includes CO$_2$ fertilization effects, stomatal closure, etc.

Modelling by Yves Godderis, Toulouse
Proposed Network of Critical Zone Observatories

SS  Southern Sierra CZO  (California)
CZO  (Colorado)
SH  Susquehanna-Shale Hills CZO  (Pennsylvania)
(Pennsylvania/Delaware)
Jemez River Basin – Sta. Catalina CZO  (New Mexico/Arizona)
ER  Eel River CZO  (California)
Reynolds Creek CZO  (Idaho)
IML  Intensively Managed Landscapes CZO  (Illinois/Iowa)

BC  Boulder Creek
Christina River Basin CZO
LM-Luquillo CZO  (Puerto Rico)
CH  Calhoun CZO  (South Carolina)
The CZO Network is an audacious experiment aimed at using the CZ as a “time telescope” that looks back in time to see forward.
Conclusions: Challenges for Earthcasters

• Measuring the data ...sharing the data..assimilating different types of data together
• Developing the conceptual models that allow projections across time for highly **coupled** systems
• Developing the conceptual models that allow projections across space for highly **heterogeneous** systems
• Developing the numerical models to quantify the highly heterogeneous and coupled chemical – physical - biological systems across space and time
• Parameterizing the models
• Developing scenarios of human behavior
• Testing the models back in time and earthcasting forward in time

I acknowledge many years of funding especially from NSF EAR (especially the Critical Zone Observatory program directed now by E. Barrera); DOE OBES (directed now by N. Woodward), as well as NASA Astrobiology
Coming soon on cable... the Earth Channel?

data show enhanced erosion and weathering across southeastern Asia

Landslide occurs

Next year’s flooding from next year’s hurricane
Human appropriation of net primary productivity

Fig. 1. Maps of the human appropriation of net primary production (HANPP), excluding human-induced fires. (a) Land-use-induced reductions in NPP as a percentage of NPPo. (b) Total HANPP as a percentage of NPPo. Blue (negative values) indicates increases of $\text{NPP}_{\text{acc}}$ (a) or $\text{NPP}_t$ (b) over $\text{NPP}_o$. Green and yellow indicate low HANPP, and red to dark colors indicate medium to high HANPP.
The need for such models is increasing as humans change global climate.

Calculated temperature (top) and soil organic carbon concentration (bottom) for a simulation of 2 x present atmospheric CO₂ using the Genesis climate model and Century soil model (D. Pollard, unpub., Penn State)
Climate change 10 kry BP to present day: Northern pedon

2 x rise

45% drainage rise

CO₂ x 4
Temperature increases along the transect

North

South

Modelling by Yves Godderis, Toulouse
Rainfall increases N and S
ET increases N and S
Drainage up 14% in S, decreasing 40% in N

ET calculated from T and CO₂, includes CO₂ fertilization effects, stomatal closure, etc.

Modelling by Yves Godderis, Toulouse
Soil CO$_2$

T increases rate of diffusive loss of CO$_2$. Fertilization does not compensate.

Larger CO$_2$ diffusive loss but CO$_2$ fertilization increases NPP (and autotrophic and heterotrophic respiration).

Modelling by Yves Godderis, Toulouse
pH changes

General increase in pH from 6.5 to 6.8...low drainage promotes high pH

pH oscillates around 6.65

Modelling by Yves Godderis, Toulouse
Albite chemical saturation

$\text{CO}_2$ consumption by dissolution of feldspars either increases or stays roughly constant from 1950 to 2100.

Solution is equilibrated with albite mainly below dolomite front at 2.8 m.. but after 2000, even upper solutions are saturated. Droughts become common.

Equilibrium with albite is episodic below 1 m, and permanent below 2.8 m (spikes of high saturation are spikes of low drainage).

Modelling by Yves Godderis, Toulouse
Largely due to CaMgCO$_3$ (dolomite) weathering, CO$_2$ consumption due to weathering decreases in both N and S from 1950 to 2100.
Bicarbonate outfluxes (CO$_2$ consumption) decrease with time in N and S

$\text{CO}_2$ increases into the future but solubilization into rivers does not keep up
Measured bicarbonate outfluxes in the Mississippi river actually have increased with time.
Change in runoff 2100 vs today

IPCC 2008
Land use change from 1700 to 1990

Green = primary vegetation, yellow = crops, blue = pasture)

U.S. land use and total carbon 1700-1990, kg/m2 (Sarmiento+Gruber, 2002)
Global geochemical cycle of lead: humans mobilize about half the metal mass of the global elemental Pb cycle (also true for Ag, Al, Cr, Cu, Fe, Ni, Zn)
Manganese in industry

US Mn Consumption and Steel Production

- Steel Production (thousand short tons)
- Mn Consumption (thousand short tons)

Year
- 1900
- 1920
- 1940
- 1960
- 1980
- 2000

Peak Steel Production

Methylcyclopentadienyl manganese tricarbonyl (MMT) fuel additive in use

Slide by Megan Carter, PSU
More from EPA report

• Not unusual to find high alkalinity, F, Na, TDS in water from that county
• Unusual to find gelatinous material and presence of hydrocarbons indicative of petroleum type products which were both detected
• Microscopic examination ruled out bacterial populations
• Dark and light gelatinous material, large glossy gelatinous masses, rod-shaped particles which did not appear to be bacteria, odor of putrefying description
• Amer Petroleum Institute argues this damage resulted from a malfunction of the fracturing process
Parenthetically, this is not unlike CO$_2$ flowing into oceans and acidifying the oceans.

Observed anthropogenic CO$_2$ in oceans (top: Sarmiento + Gruber, 2002)
Data gathering

Questions about how the system works

Deep system-level understanding emerges

Model development, testing, and refinement

Cross-site and cross-discipline hypotheses

Data sharing

The Science of NSF Critical Zone Research
Integrated, process-based, predictive modeling?

- Soil carbon
- Terrestrial water & energy cycles
- Microbial processes
- Soil formation & landscape evolution

Slide from Henry Lin