

## Long-Term Effects of Land Use History on Carbon and Water Balance Final Report October 2004

The "Carbon & Water" Workshop was held at the Coweeta Hydrologic Laboratory on October 28-29, 2004. In attendance were: Larry Band (BES), Paul Bolstad (CWT), Mark Harmon (AND), Florent Hautefeuille (ZA), Olga Krankina (AND), Stephen Maberly (ZA), Jorge Ortiz (LUQ), Pascal Palu (ZA) and Ted Gragson (CWT). The framing of this workshop was the idea that land use and land-use change are among the major factors shaping carbon and water balance in landscapes and ecosystems. Carbon and water were also seen to be of great consequence as synthesis topics because they are quantifiable, important at all sites, and represent globally significant ecosystem functions that are relevant to national and international policy.

Many LTER sites and research projects outside the LTER Network are demonstrating there are common patterns to land use history. However, there is major uncertainty in our understanding of the effects of land use on the global patterns of carbon and water exchange. The LTER Network is in a unique position to address this topic because of the availability of long-term ecological and socio-economic data sets, and interdisciplinary research teams. These are not often found outside the LTER Network. The topic also lends itself to rigorous cross-site comparison with the potential for globally significant results central to current LTER synthesis efforts. At the workshop the following outline for a manuscript was developed:

Legacies and uncertainties in pools, fluxes, and trajectories:  
The Challenge of Moving from Site to Region

*Introduction:* Land use and land-use change are recognized as major factors shaping carbon and water balance in landscapes and ecosystems. We have developed site-level methods to measure the effects of land use on carbon and water balance, but moving from the site to the region or from the region to the continent has yet to be realized although we can measure effects of land use change on water balance in large catchments using rainfall-runoff information. This is unfortunate, because our interests transcend local settings and include conditions, knowledge and policy at regional to global scales.

### Statement of the problem

- What is a legacy
- Why are legacies important
- Impacts at regional scales
- Driven by land use change and disturbance phenomena
- Despite that, we're not incorporating land use change mechanisms

In different locations around the world and for various reasons, humans alter ecosystem structure and dynamics. These activities often have long-term but poorly-known consequences. For example, lands once dedicated to agriculture have been abandoned and forest and woody vegetation cover has expanded. However, our understanding of the long-term ecological consequences of this change as well as the mechanisms linking the underlying causes to their

various outcomes remains limited. Little is known about how much additional carbon storage is represented by reforesting lands, how long this carbon store will last, or, how much longer forests will continue to expand and accumulate carbon. These are crucial issues for both ecology as well as national and international policies, in this example the production and trade of carbon.

The same can be said about our water quantity and quality, which are important issues in many parts of the world. We still know very little about how different land uses and changes in land use cumulatively affect water quantity and quantity may know more here through use of long term discharge records for the gross budget – but not details of individual stores, fluxes. There have also only been limited attempts to derive process-based predictions of the cumulative temporal and spatial effects of multiple land uses and landuse change on water quantity, quality and biota. This seriously constrains efforts to forecast future ecosystem responses or to execute management strategies that anticipate the most likely outcomes of change trajectories.

A primary challenge in moving from sites to region is centered on how disturbance events and disturbance regimes relate to pools and fluxes of carbon and water. More important, the uncertainties associated with the legacies passed on from disturbance and legacy effects on subsequent processes ultimately limits how we manage of carbon and water. We can summarize the challenges of moving from site to region in regards to carbon and water pools and fluxes as follows. Humans have altered the type of disturbance events operating on and the characteristics of disturbance regimes that occur on terrestrial ecosystems, and these have substantially affected carbon and water cycles. This generates many important questions, including:

- How are these changes linked to underlying causes and ultimate consequences?
- How long will these past disturbances affect the trajectories of current and future carbon storage and fluxes?
- How stable and persistent are these changes in carbon pools?
- How do different human alterations of disturbance types and regimes cumulatively affect water quality, quantity, or aquatic biota?
- How is the distribution and productivity of forest species linked to land use?

An additional, more complicated set of questions arise because carbon and water cycles are closely linked.

- What are the essential feedback mechanisms and lag times in these linked systems?
- How does knowledge of linkage affect decision-making about atmospheric CO<sub>2</sub> accumulation?
- How does knowledge of linkage affect decision-making about fresh water supply?

These questions are particularly important, given the change in needs and increased challenges as analyses move from site or stand to landscape or region. This transition multiplies our knowledge and data requirements.

- What is the status of process-based predictions of the cumulative temporal and spatial effects of multiple land uses on water quantity, quality and biota?
- How does the lack of process-based knowledge constrain efforts to forecast ecosystem responses or execute anticipatory management strategies?

*Review of current concepts about disturbance, disturbance regimes, and response*

- Disturbance as an ecological phenomenon
- Plot level studies and stand-level analysis
- Aggregation to prediction to regions – Operations Research Methods

White and Pickett (1985) define disturbance as a relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resource pools, substrate availability, or the physical environment. Aggregating disturbance events into disturbance regimes is the basis for translating site-level results to regional- and global-level assessments. Geomorphology uses "regime theory" to describe stream balances in the removals and additions from their transported load. Regime in geomorphology refers to the magnitude and frequency of sediment transport events – providing flow conditions competent to maintain channel form. A regime stream, river or canal is one that has achieved average equilibrium between deposition and scouring (Blench 1957; Poff et al. 1997). A fire regime refers to the natural fire equilibria on a landscape in the absence of human mechanical intervention (Agee 1993; Brown 1995). It is a function of the average number of years between fires combined with the severity of the fire on the dominant overstory vegetation.

Various approaches that have been applied to estimate the carbon and water pools and fluxes across a range of scales, but only a small subset of these have incorporated disturbance and disturbance regimes, and fewer still have included legacy effects. Operations Research has a history of scaling from stand to region in a procedure comparable to that being advocated. Perhaps a bit more detail given here on these methods and how are aims are different. For example, using simple models relying on growth and yield tables they have successfully produced wood supply estimates. While the result is regional in scope, it is without reference to heterogeneity. There are three key differences between the approach we will present in contrast to that followed in operations research. First, there is an increase in complexity by incorporation pools normally ignored. Second, there is the addition of legacies expressing the transience effects of past events on present and future conditions. Finally, the application is broadened from wood supply to different and novel problem areas.

### *Problem definition*

The aggregate human impact on local-to-global carbon and water pools and fluxes leads us to focus on the concepts of disturbance events, disturbance regimes, and legacies to address the challenges of scaling up from plots to region.

***Question 1:*** *What are the temporal and spatial dimensions of carbon/water pools and fluxes, and the domain of human influence on them – how do we relate knowledge of to management of?* (Larry, Paul, Florent, Jim)

A disturbance event or regime is defined as rapid change in a pool or flux.  
Introduce important components – sketch of water cycle and carbon cycle.

Describe mass conservation.

Define input, output balance, results in fluxes and changes in storages. This may be among components (live to dead wood) or out of the bounds of the system (fire, volatilization).

Relate/expand description of disturbance as a change in input, output, flux, pool, structure.

Describe specific components – table 1 introduced – what are the categories, what are the large fluxes

Introduce notion of dominant fluxes – examples in forests or agricultural or other settings  
Discuss

Table of carbon/water stores and fluxes, additional column on magnitude of space/time scales near here

Introduce notion of balance – in a static or slowly changing framework, there is a steady state or slowly changing set of components, e.g., total ecosystem carbon, allowing for interannual variability. Notion that legacy effects are represented in nonequilibrium state.

Note that the components state variables (C and water pools) have different time and length scales of variation. Some change more slowly/quickly, some over smaller/larger areas. A lower limit of change scales may be interested, and all extend to global levels. Perhaps this is not of as much interest at global scales. Upper bound to maximum extent of disturbance or disturbance regime.

Graph of space/time domains of example key water/carbon components – note that this is for the recovery phase, e.g., carbon accrual after landslide or fire, forest regrowth.

***Question 2:*** *How do disturbance events and disturbance regimes give rise to legacies at the patch and regional level? (Jorge, Mark, Pascal)*

Disturbance events and disturbance regimes are often conflated. A disturbance event is a singular occurrence in time and place as defined by White and Pickett as noted above. Disturbance is characterized by a discrete change in one or more state variables, which leaves a system out of balance. The system will then go through an adjustment to approach an asymptote that may be the same or different. A disturbance is characterized by its size (small vs. large) and by its severity (how much structural reshaping is involved). Severity is characterized by the intensity of the event, a property of the agent, and its resistance, a property of the subject. For example, in a wind storm (disturbance event) the intensity could be measured by the maximum wind speed while the resistance might be measured by the difference between hardwoods and pines in the ability of their stems to resist bending and breaking by wind force.

Present a table of examples of disturbances

Disturbance regimes on the other hand represent a conditional probability of particular types of events occurring across the landscape. In effect, a population of events that is relatively stable over time. The regime can change the spatial distribution of states, but not the frequency distribution of states (needs rewording).

(new figure near here – parallel to figure above, focus on dist. regimes)

A regime can be characterized by its frequency and its temporality. Frequency is the rate of occurrence of particular types of events; temporality qualifies if events are clustered, synchronous, etc. Regimes reflect the constraints particular to a system – age, mortality, etc.

Because you are dealing with population of events, you don't have to track individual events (one hopes)

Challenge – where this will fail; spatial independence assumption, large number (system assumption) violated for large disturbance.

- It is easy to deal with a small and large number system. The intermediate state is more difficult to deal with.
- spatial independence assumption, for carbon the location of the disturbance is not that critical as it is for water.

Legacy – what is passed on

Legacy effects

- Quantity change/magnitude
- Memory/persistence/relaxation/duration. How quickly the system forgets/erases the legacy, i.e., approaches a process-driven asymptote?

For example, legacy might be reduced soil carbon. The legacy effect – magnitude might then be a 10% reduction relative to expected carbon stores. While the legacy effect – duration would be over which period the 10% reduction would endure and or the period of recovery to expected.

Uncertainty space

- State
- Process
- Parameter

A legacy example that combines the methodological correction for uncertainty might be weather forecasts. We seek to control or bound our uncertainty with respect to expectations on certain weather events. Through multiple realization we effectively create a population of forecasts that provide us with a probability space within which the true forecast lies. We then compare this population to local experience to detect outliers, and make further adjustments by backcasting and forecasting.

At this point we can develop examples for the relation of legacy, legacy effect and uncertainty anchored to carbon and water balance issues. The point through concrete examples that discriminate between what is passed on (i.e., legacy) from the magnitude and duration properties of the legacy in relation to the state, flux and parameter dimensions of uncertainty we are able to establish ....

Possible examples to develop:

- CWT WS7/2 or WS17/18 comparison (at the edge of human manipulation)

- Turner/Pearson/Fraterrigo on C/N in the Piedmont based on change-over-time in human manipulation
- Forest to agriculture to forest or urban
  - Baltimore lawns ~50 years
  - So. App agriculture ~150 years
  - SW France agro-pastoralism ~300 years
- (need to review, make sure effects as well...Mark's point, rapporteur incomp.)
- Brown and Lugo – paper on carbon and land use change and carbon

Legacy-severity part of disturbances control legacies

At the regime there is a legacy in spatial patterns/arrangements (example of cutting simulations-how long a spatial pattern can persist)

(inserted from question 1 – description of space/time graph for disturbance event/regime).

We need to define an operational upper bound for the component. How large a length scale to disturbance events cover, and do disturbance regimes or clusters of events cover? Need to define disturbance regimes (how do we do this? – what are the categories for a regime), and how you set spatial bounds.

Legacies often result from changes in slow pools.

Someone needs to talk about disturbance event vs. a population event/regime change. This structures much of our recommendations/analytical approach. Do we introduce this, or does it come in the next sections?

Lower (spatial) extent at which regime is valid, upper limit at which regime is valid- stationarity in the statistical property of the events. Regime content uses utility as size of event approaches size of the universe – lose help of large numbers.

Add water to this table

Type	Effect on ecosystem structure	Processes affected
Biotic		
Herbivory (bark beetles)	Live to dead; C export via respiration	Mortality and respiration, reduce NPP
Parasites and pathogens	Live to dead; C export via respiration	Mortality and respiration, reduce NPP
Invasions	Diversity (?long effect)	Change NPP, mortality?
Predators?	Herbivore biomass	Behavior, mortality
Abiotic		
Climate (winds,	Live to dead	Mortality; NPP

drought, precipitation, flooding)		
Fire	Live to dead; C export; fertility	Mortality; combustion
Earth movements	Live to dead; soil export	Erosion; sedimentation
Human		
Land cover change	Live to dead	Transpiration;
	Export o live, dead and soil	
	Infiltration	
Land use change w/o change in land cover	Live to dead	
	Export of live, dead and soil	
Fire alteration		

Multiple legacies- differences in magnitude and response

Relaxation time, persistence, decay of effects

Response-what happens immediately, vs. long-term

*Questions 3: What are the properties of legacies that make them significant at the scales of regions relative to sites or globe: legacy itself, legacy effects, uncertainty. (Olga, Brian, Stephen)*

What are the properties of legacies that make them significant at the scales of regions or globe relative to sites: legacy itself, legacy effects, uncertainty.

1. Ecosystem properties than are significant at large scales: C, H<sub>2</sub>O, radiative balance, surface roughness

2. Present conditions are insufficient to understand the above

3. Properties of legacies:

Occur over large area (especially synchronized)

Persist over long time

Influences multiple properties significant at large scales

4. Examples of perturbations that produced legacies significant at regional to global scale at present

Human

desertification

deforestation/regrowth of forest

peatland drainage

nitrogen deposition, other nutrient enrichment

irrigation (rice cultivation)

loss of native vegetation (especially forest)

Natural

ice age, little ice age

fire

insects

5. Why this is important? To project future pools and fluxes.