# Continued Search for the Carbon Sink:
# Considering Interactions in an Integrated Assessment Framework

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Feedback scenarios are critical when looking at land use/land cover (LULC) change as a driver of climate change because LULC affects albedo and vegetation characteristics, which leads to surface energy balance change, which leads to surface temperature change, which is associated with changes in evapotranspiration and surface hydrology, which lead to changes in rates of terrestrial net primary productivity (NPP), which lead to changes in vegetation characteristics, which completes the feedback loop and takes us back to the beginning.

Not considering the LULC feedbacks will leads to flawed carbon management policy, failure of climate change management policy, unintentional drought and other hydrological effects, and the jeopardizing of integrated assessments and international negotiations and scientific credibility.

Hydrology and the carbon cycle are linked at a huge range of scales, from the cell (where carbon is assimilated) to the entire ecosystem (net heat exchange, atmospheric convergence resulting from landscape heterogeneity). Figure 1 illustrates land-atmosphere feedbacks at different scales. Transpiration, hydrology/radiation feedbacks, and precipitation changes lead to vegetation changes that cause feedbacks. Carbon assimilation is greatly affected by such environmental feedbacks. It is important to understand each of the individual components that make up the net impact.

[insert Figure 1 - slide 9 from Powerpoint]

*Tropics versus Mid-latitudes*

Land surface properties (LSPs) differ between the tropics and the mid-latitudes.

- LSPs affect both of these domains
- Direct effects are similar

- Interactions/feedback pathways are different
- Vegetation interactions are key in semiarid tropics while mid-latitudes are dominated by soil moisture-related interactions
- Mid-latitudinal case shows both vegetation and soil interactions
- Tropical case does not show vegetation and soil interactions (i.e., surface acts as independent mosaic of vegetation and soil acting interacting with atmosphere)
- More interactions -> more resilience -> lesser vulnerability?
- Possible to review carbon–hydrological feedback process as an econometric/resource allocation approach in future analyses
- (Additional studies with detailed regional atmospheric modeling system in future)

Why do land surface changes in the tropics matter so much? Soil moisture changes alter albedo and emissivity and these changes effect the system. In mid latitudes, the system is more interactive. In the tropics, surface changes have a more direct effect on the atmosphere (with complex interaction avoided). The logic is that more interactions lead to more resilience, leaving the tropics more vulnerable to land surface changes.

In the tropics, there is little connection between vegetation and soil moisture, while in mid latitudes, there is more connection between the two - the system works together more. The "optimization" tools of the system are different, and thus there are different impacts in the two systems. It is as if the system in the mid-latitudes is acting to conserve itself, while in the tropics, it doesn't seem to care.

Modeling Studies

When trying to determine effective climate policy, it is important not to simplistically focus on what vegetation type to plant. We must also consider how the change in land use will affect soil moisture and thus climate. Not considering these feedbacks can lead to unintended consequences. The modeling studies discussed here yielded the following results.

For the "broadleaf" trees (SiB2 vegetation types 1, 2 and 3):

- Each vegetation type has characteristic response to the biotic and abiotic changes
- $CO_2$ Enrichment will lead to
    - Enhanced net primary productivity

  - Moderately decrease stomatal resistance
  - Marginally increase evapotranspiration (but increase WUE)
  - No significant effect on air temperature
- $CO_2$-Soil Moisture interactions are active and often equal to the lesser dominant effect.

Limiting soil moisture controls biospheric response irrespective of $CO_2$ levels; high soil moisture availability synergistically assist $CO_2$ effects (which are then dominant)

For the "needleleaf" trees (SiB2 types 4 and 5):
- Each vegetation type has characteristic response to the biotic and abiotic changes
- Many of the features are similar as discussed for the "Broadleaf" trees, but with
  - Significantly lowered both ETR, and NPP (WUE not changed)
  - Significantly higher soil moisture and $CO_2$ interaction effect

Respiration losses dominated by soil moisture availability

For the C4 vegetation types (SiB2 type 6):
- Results similar to Nie et al. (1992) closed - chamber experiments
- Highest NPP values seen for doubling of $CO_2$ under limiting soil moisture conditions
- $CO_2$ increase reduced ETR significantly (opposite to broadleaf trees)
- Active and dominant $CO_2$ - Soil Moisture interactions
- Role of C4 grasslands as a source/sink carbon pathway will depend on the soil moisture availability (higher the moisture, more the respirative losses)
- Doubling of $CO_2$ increased air temperature by 1.5K but if accompanied by increasing soil moisture, induced relatively cooling, instead!

And for the C3 grass and shrubs (SiB2 types 7, 8 and 9):
- Each vegetation type has characteristic response to the biotic and abiotic changes
- Many of the effects are opposite to those seen for C4 grass
- C3-C4 shrub/grassland ecotone dominance will depend on the soil moisture availability
- NPP is highest for resource "unlimiting" conditions (high soil moisture and doubling of $CO_2$ conditions)

- Interactions tend to balance the response and hence the outcome will not be as dramatic as seen in many one-at-a-time studies

*Relevance of the results to BAI studies*

- Process-based analysis of the physical parameterizations for every vegetation type
- Extracted direct as well as interactive feedbacks
- Interaction effects can be equated to the indirect effects of $CO_2$ doubling (though not causally, often as empirical corrections)
- Previous studies suggested, $CO_2$ doubling will affect C3 vegetation and may not affect C4. This may be true only for the direct effects but considering interactions, both C3 and C4 vegetation appears to be significantly affected by $CO_2$ changes
- $CO_2$ doubling effects should not be discussed without considering soil moisture status
- $CO_2$ doubling is intrinsically linked with soil moisture availability
    - Used coupled GEM based outcome over all the nine SiB2 vegetation types to prove the hypothesis
    - landscape can be a source / sink depending on the soil moisture status
    - Need to consider interactions explicitly while analyzing BAI

*Future research directions*

Because we won't know where we are going until we get there, we need to be prepared for diverse scenarios. This requires understanding and accounting for the feedback effects and the resulting vulnerability using models as assessment tools) to help aid in integrated assessment of global change. Any LULC change, even with the best of management and mitigation interests in mind, may prove to be a failure and even harmful unless we explicitly consider the feedback processes affecting the $CO_2$ (and hydrological interactions) for an effective, resilient policy

In order to make future research more robust we must incorporate LULC change as a critical driver of global climate change. There is a need to develop projects and approaches for validating the testable hypotheses. Scaling (time and space based) still remains the biggest disconnect. There is a need for intelligent adaptive models, combining processes with optimization concepts for process simulations e.g. drought adaptation and invasion.