THE CARBON CYCLE MODEL LINKAGE PROJECT

(CCMLP)

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Overview

The global carbon cycle constitutes an important constituent of the earth system. In order to understand and predict its behavior as a function of direct anthropogenic impacts by the emissions of CO_2 from fossil fuel burning and from changes in land use, but also as an interactive component of the physical climate system necessitates the development of realistic, comprehensive simulation models of the global carbon cycle. Already since the early 1960's have simple, conceptual carbon cycle box-models been constructed, however, the establishment of process-based simulation models of the oceanic and terrestrial carbon cycle components has not begun before the late 1980's and early 1990's. This is substantially later than the corresponding development of comprehensive three-dimensional models of the physical climate system components. In part, this delay may be attributed to the relatively poorly known biochemical and ecological processes, which control the exchanges of carbon between inorganic and organic forms on land and in the oceans. The wealth of process studies conducted during the last decades, in part also by activities within the core projects of the IGBP, have now allowed the modelers to take up the challenge to build global process-based carbon cycle models, which are currently being coupled to climate models.

Any model development necessitates a careful evaluation of the model performance. In order to rigorously evaluate the performances of comprehensive global carbon cycle models the IGBP-GAIM task force, as part of its activity "The Coupled Atmosphere-Land-Ocean Carbon System 1980-2000", helped to initiate of the "Carbon Cycle Model Linkage Project" (CCMLP) in the early 1990's. Since its beginning, substantial funding support

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During phase I of the project, CCMLP focused particularly on a rigorous evaluation of recently developed models of the terrestrial carbon cycle (terrestrial biochemical models, TBMs). A significant effort went into the establishment of a series of model simulation tests, which permit an integrative and quantitative assessment of the model's performance on global and regional scales. As an example, by coupling TBMs with oceanic components (prescribed model derived sea-air CO_2 fluxes) and an atmospheric transport model, the simulated temporal and spatial atmospheric CO_2 concentration patterns may be compared to the observations from the global monitoring networks, e.g. of the Climate Monitoring and Diagnostics Laboratory of the U.S. National Oceanic and Atmospheric Administration, (NOAA-CMDL) [Convay et al., 1994].

CCMLP is not a model intercomparison project. It was intended as a pilot study to explore model predictions in as many ways as possible, which may be compared to integral observations of the carbon cycle (e.g. measurements of atmospheric CO_2 concentration, isotopes and other coupled tracers, data compilations from statistics, results from deconvolution studies etc.). Some of the experiments conducted within CCMLP, however, have now found their way into other, specific model intercomparison studies (e.g. the Potsdam NPP model intercomparison study [Cramer et al., 1999]).

CCMLP included a series of additional studies beyond the evaluation of model simulations. These included the development of tools to represent the global behavior of complex TBMs by means of simple pulse substitute models [Joos et al., 1996], the investigation of the effects of biomass burning on the atmospheric concentration variations of CO_2 [Wittenberg et al., 1998] and the use of radiocarbon in the evaluation of global TBMs [Meier et al., in preparation]. In the following, a few results from two of the studies conducted within CCMLP are briefly presented.

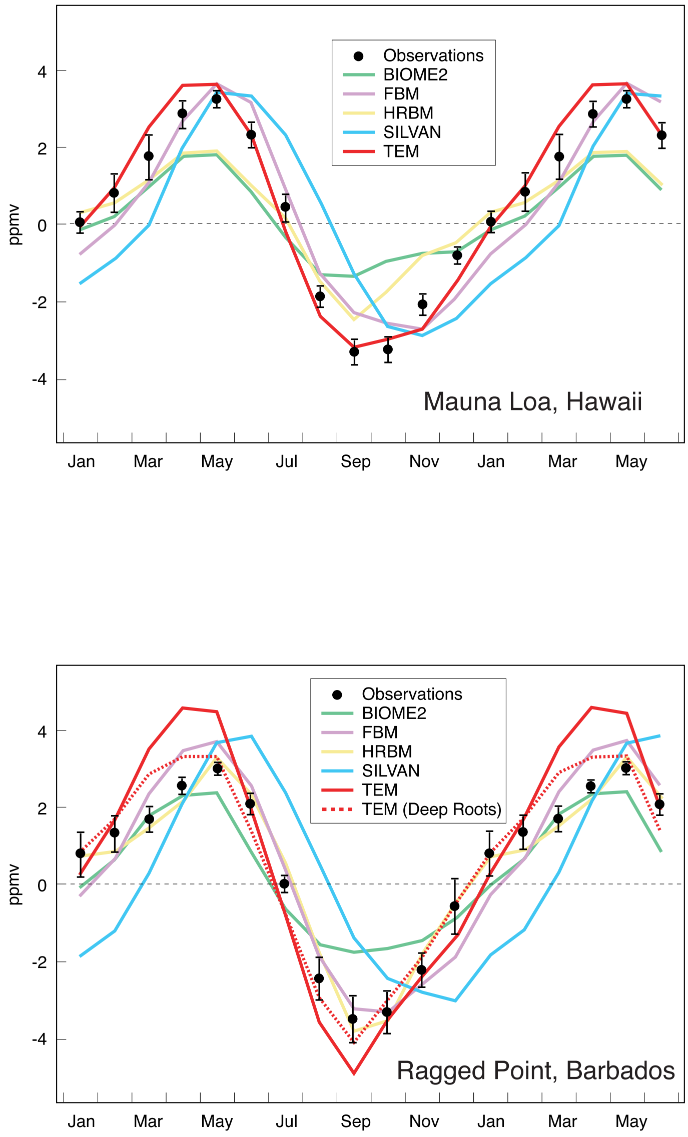

Figure 1. Seasonal cycle of atmospheric CO_2 predicted by five TBMs at Mauna Loa, Hawaii (upper panel) and Ragged Point, Barbados (lower panel) [from Heimann et al., 1998]. The observations (monthly mean and one standard deviation) are from Conway et al., 1994.

Seasonal Cycle Study

As an example of a coupled model evaluation experiment, Figure 1 [Heimann et al., 1997], shows the modeled and observed seasonal cycle of atmospheric CO_2 at two monitoring stations: Mauna Loa, Hawaii and Ragged Point, Barbados. The black symbols denote monthly mean observations and standard deviation [Conway et al., 1994] while the colored curves indicate the seasonal cycle predicted by model configurations in which different TBMs were included (indicated by the acronyms – for a description of the models see Heimann et al., 1998).

Obviously, there is significant scope for improvement. Some of the models seriously mismatch amplitude and phase of the observed seasonal cycle. The panel of the Ragged Point station also displays the results of a sensitivity study: The red dotted line shows the prediction of a variant of the TEM model, in which the standard rooting depth has been significantly increased. With this modification the subtropical vegetation is less susceptible to water stress during the dry season, leading to a less pronounced seasonality of CO_2 exchanges and thus reduced atmospheric seasonal CO_2 amplitude in subtropics, which is more compatible with the observations.

Clearly, a single evaluation such as the seasonal cycle test cannot comprehensively validate the correctness of a complex TBM. Furthermore, the predicted atmospheric CO_2 signals do not only depend on the TBM, but to some limited extent also on the specified air-sea fluxes and the atmospheric transport model. Nevertheless the test allows a quantitative assessment of the modeled net CO_2 surface flux patterns of the Northern Hemisphere, where the terrestrial seasonal signal is dominant.

The “Grand Slam” Experiments

Building on the expertise from early part of CCMLP, at the end of phase I a series of so-called “Grand Slam” Experiments were conducted [McGuire et al., submitted to GBC]. In these experiments, four terrestrial biochemical models were subjected to the observed historical perturbations of three factors over the last 150 years: (i) the rising atmospheric CO_2 concentration as determined from ice-core measurements, (ii) monthly spatio-temporal variations of temperature [Jones, 1994] and precipitation [Hulme, 1994] and (iii) historical changes in land use by deforestation of natural vegetation and abandonment of crop lands [Ramankutty and Foley, 1999].

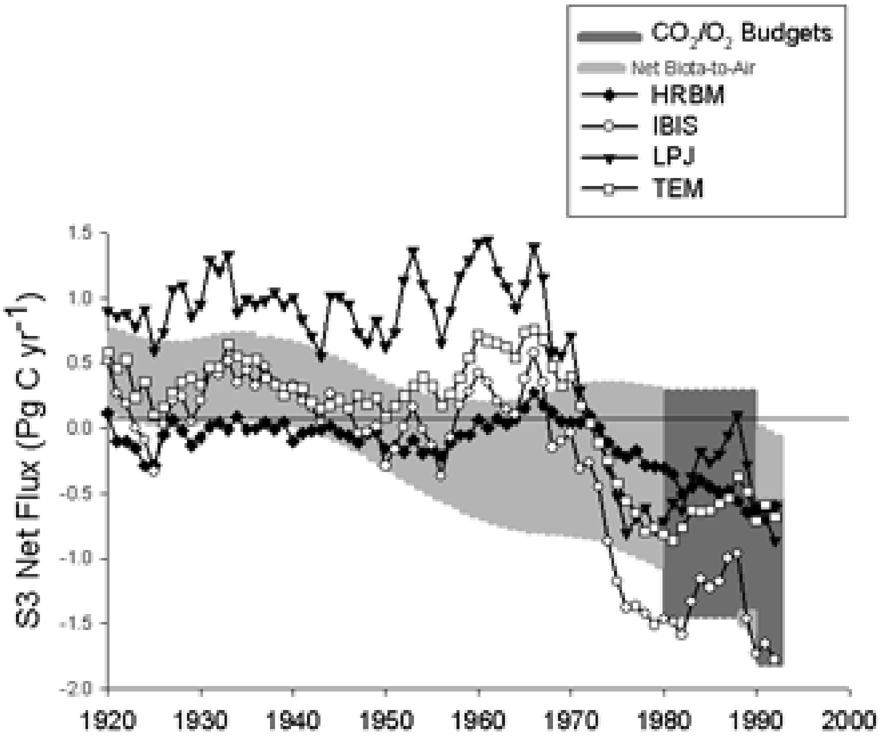

Figure 2. History of net land to atmosphere flux of carbon as simulated by four terrestrial ecosystem models of CCMLP driven by observed changes in atmospheric CO_2, climate and land use [from McGuire et al., submitted to GBC]. The light-gray shaded region denotes the range of estimates from a global atmospheric CO_2 deconvolution study [Bruno and Joos, 1997]. The dark gray areas denote estimates from atmospheric O_2/N_2 measurements for the 1980's and 1990's [updated from Keeling et al., 1996, and Langenfelds et al., 1999].

These experiments built upon the results obtained in previous CCMLP studies on the effects of the rising CO_2 concentration [Kicklighter et al., 1999] and on the interannual, climate driven variability in TBMs [Heimann et al., in preparation]. The inclusion of the crucial effects caused by land use change in the simulation allowed a much more comprehensive evaluation against contemporary global carbon cycle data.

The "Grand Slam" experiments were performed by two TBMs with prescribed vegetation: the High Resolution Biosphere Model [HRBM, Esser et al., 1994], and the Terrestrial Ecosystem Model [TEM, Tian et al., 1999], and two dynamical global vegetation models: the Integrated Biosphere Simulator [IBIS, Foley et al., 1996] and the Lund-Potsdam-Jena Dynamic Global Vegetation Model [LPJ, Sitch, 2000].

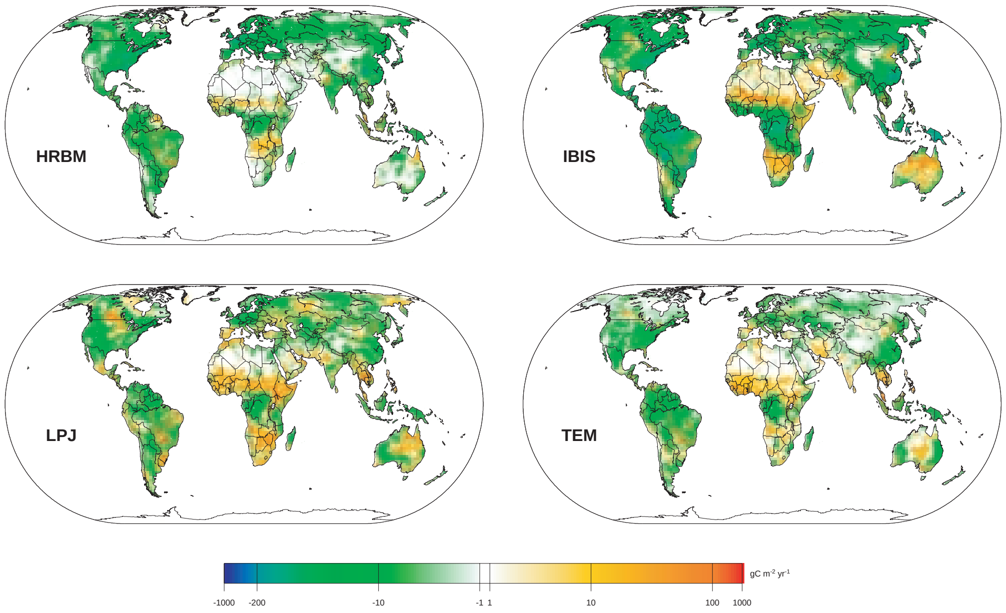

Figure 3. Global map of predicted net land-air CO_2 flux averaged over 1980-89, simulated by four terrestrial ecosystem models of CCMLP driven by observed changes in atmospheric CO_2, climate and land use [from McGuire et al., submitted to GBC].

Figure 2 shows the temporal evolution of the modeled terrestrial carbon budget over the simulation period. Because the models were initialized with inadequate climate data for the time period prior to 1900, only the results after 1920 can be regarded as significant. In Figure 2 the model predicted net land to air fluxes of CO_2 are compared against independent estimates: from a CO_2 deconvolution study [Bruno and Joos, 1997] and, over the 1980's and the early 1990's, from O_2/N_2 measurements [updated from R. F. Keeling et al., 1996, and Langenfelds et al., 1999]. Overall, it is seen that during the last decades the TBM simulations are broadly consistent with the independent estimates. Nevertheless, there are still large differences among the models, even when driven with the same forcing data

Figure 3 shows global maps of the simulated net CO_2 fluxes during the 1980's (1980-89). The 4 models of the study predict substantial uptake of carbon (green colors) in the tropics and temperate latitudes, which are contrasted by

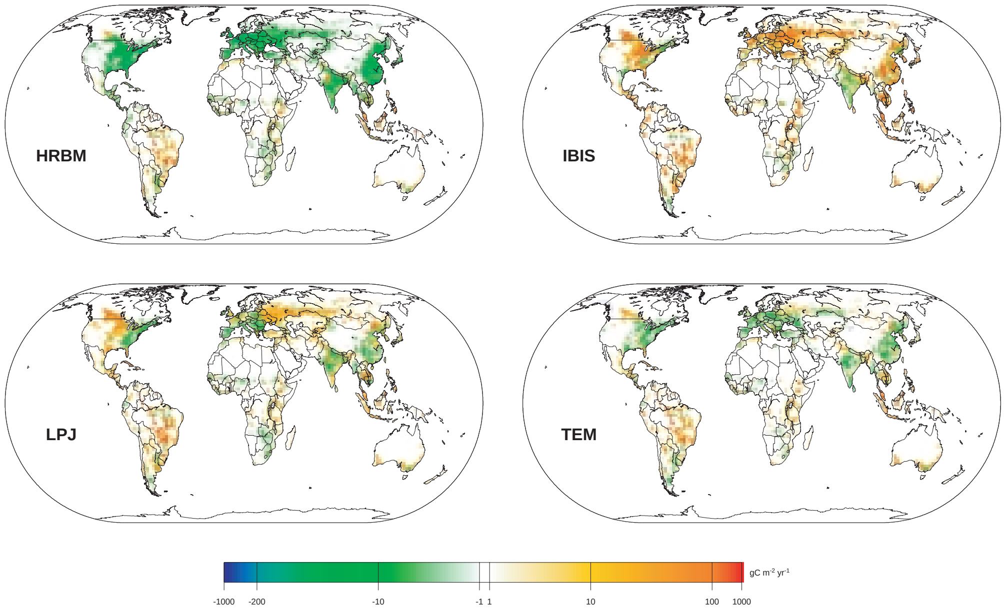

Figure 4. Global maps of net CO_2 flux induced by changes in land use, averaged over 1980-89, predicted by four terrestrial ecosystem models of CCMLP [from McGuire et al., submitted to GBC].

deforestation hotspots, in particular in the Sahel region in Africa, representing a net source of CO_2 to the atmosphere (brown-red colors).

The experiment protocol included also a simulation run without changes in land-use. Hence, the effects of the latter may be assessed by difference of the model results. (It was independently verified that the effects of the three forcing factors on the predicted fluxes were almost additive.) The effects of land use changes during the 1980's are shown in Figure 4 and as global time series in Figure 5. All the models predict substantial areas with vegetation regrowth (Figure 4, green colors), but the modeled geographical patterns are not very robust except, perhaps, in Europe, the eastern United States, parts of India and China. Overall, however, the effects of changes in land use lead to a net source of CO_2 into the atmosphere. The global history of the emissions due to changes in land use (Figure 5) are compared against the independent, canonical land use CO_2 flux estimates of Houghton [1999]. After the 1970's all the TBMs significantly deviate from Houghton's estimates. It is believed that this difference is due to the fact that the land use patterns of the present study only included conversions from natural vegetation to agriculture and vice versa, but did not include any conversion to pasture land.

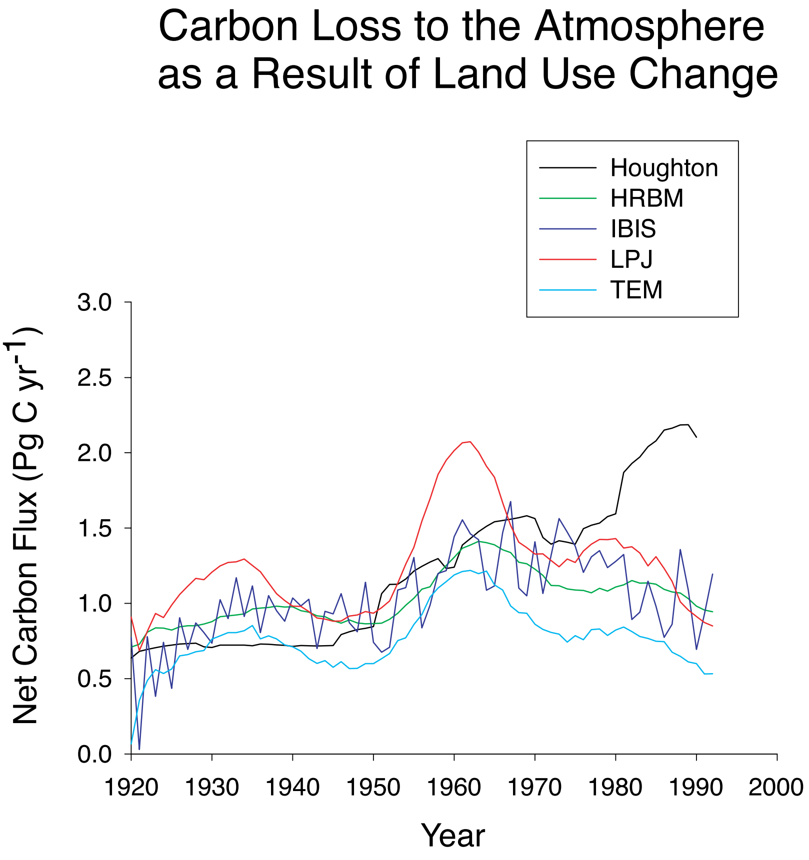

Figure 5. History of globally integrated land-atmosphere CO_2 flux induced by changes in land use [from McGuire et al., submitted to GBC]. Also shown for comparison are the estimates from Houghton [1999].

By considering each perturbation factor alone, the contribution of each factor to the net terrestrial carbon budget can be inferred. Table 1 lists the resulting breakdown of the global terrestrial carbon budget as simulated by the different models, averaged over 1980-89. According to these simulations, the CO_2 fertilization effect dominates the response, leading to a modest carbon uptake over the 1980's. The differences between the models, however, are substantial. It is interesting to note, that the model with the smallest CO_2 senstitivity, TEM, was the only one with an explicitly modeled nitrogen cycle. This results demonstrates the role of nitrogen limitation [Kicklighter et al., 1999].

Table 1. Simulated global terrestrial carbon budget averaged over 1980-89 and breakdown of balance into the three perturbation factors: impact of CO_2 fertilization, climate variations and changes in land use. Units: $10^{12}kgCa^{-1}$, negative values: carbon uptake. [McGuire et al., submitted to GBC].

TBM	HRBM	IBIS	LPJ	TEM
CO_2	-1.6	-3.1	-2.1	-0.9
Climate	0.0	0.8	0.9	-0.2
Land Use	1.0	0.8	0.9	0.6
Total	-0.6	-1.5	-0.3	-0.5

An intriguing feature of the atmospheric CO_2 record of Mauna Loa is the observed increase of the amplitude of the seasonal cycle over the last 40 years [C. D. Keeling et al., 1996] by more than 25%. This increase, presumably caused by changes in the "breathing" of the Northern Hemisphere terrestrial biosphere, is also predicted by the models that conducted the "Grand Slam" experiments. In Figure 6 the relative changes in the seasonal amplitude as predicted by the four models are shown against the observations (black line with square symbols). Two of the models are able to predict rather convincingly the observed increase including the broad features of its interannual variability. This result demonstrates again the power of the atmospheric observations, a central aspect of the model evaluations explored within CCMLP.

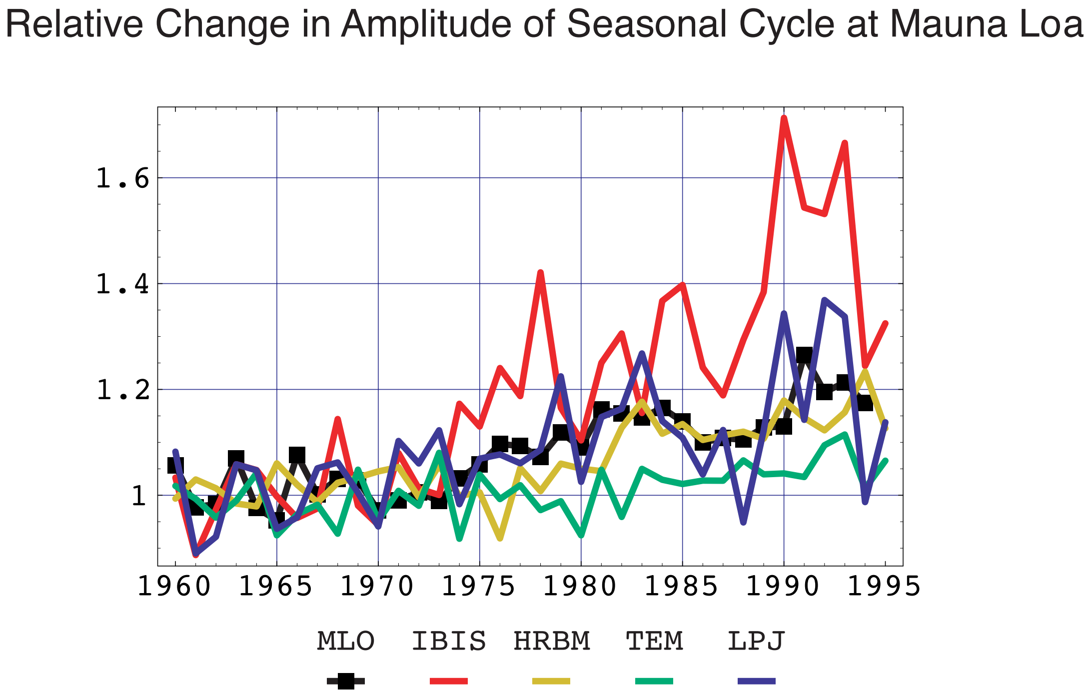

Figure 6. Relative change of the amplitude of the seasonal cycle of atmospheric CO_2 at the Mauna Loa, Hawaii, monitoring station. The observations (from Keeling et al., [1996]) are indicated by the black squares. The CCMLP model predictions are indicated by the colored lines [from McGuire et al., submitted to GBC].

The Future of CCMLP – Phase II

After the first phase the project has been reorganized with a change in objectives and project participants. The overall objective of phase II is the development and evaluation of carbon cycle modules (land and sea) as integral components of the Earth System. This implies a close collaboration with climate model developers and a major effort directed at coupling the carbon cycle components to climate models.

At present, CCMLP II is structured among four main tasks:

1. **The contemporary comprehensive carbon cycle.** This task includes an in-depth evaluation of the terrestrial ecosystem models. This includes a revisit of the experiments conducted during CCMLP phase I but extended with a series of site specific model evaluations against local process

information such as the observations from eddy covariance flux towers, FACE studies, Nitrogen fertilization studies, and regional assessments against hydrological data and forest inventories. In addition, a comprehensive model study of the cycles of the carbon and oxygen isotopes will be conducted.

2. **Human impacts: Land-use, land cover and Nitrogen deposition.** This task addresses a more comprehensive compilation and modeling of the impacts from cropland and pasture creation and abandonment, forest harvest and regrowth and Nitrogen deposition.

3. **"Grand Slam" experiments revisited.** With the new and improved models and driving data sets the "Grand Slam" experiments will be revisited.

4. **"Great Leap" experiments and evaluation.** Ultimately, the model components as developed and evaluated within CCMLP phase II will be coupled to climate models for participation in the new GAIM activity of simulation experiments with fully coupled carbon-climate earth system models (the "Flying Leap", Fung et al., 2000).

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