Effects of Land Use on Climate and Water Resources

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Project Summary

The IPCC Third Assessment Report identifies land cover and land use change as an important global climate forcing. This forcing is thought to cool climate globally, primarily by increasing surface albedo, but the climate effect varies regionally, with past studies indicating tropical deforestation warms climate while temperate deforestation cools climate. Our scientific understanding of the forcing is poor, and uncertainty in both the sign and magnitude of the forcing is high. Previous studies showed conversion of forest and grassland to cropland in the U.S. has cooled surface air temperature, primarily in summer and autumn, and has reduced diurnal temperature range through greater cooling at mid-day than at night (Bonan, 1997, 1999, 2001). The goal of this study is to refine the land cover and land use change forcing for the U.S. through better models and surface datasets and to begin to treat land cover and land use change in an integrated manner, including forcings associated with surface energy fluxes, hydrology, and biogeochemistry.

The research supported the development of the Community Land Model (CLM) for the Community Climate System Model (CCSM). This model is being developed in coordination with the CCSM Land and Biogeochemistry Working Groups. The work consisted of three components: *surface datasets* – improved present-day land cover and leaf area index datasets were developed from satellite data products; *model development* – the Community Land Model for the Community Climate System Model was further developed to better represent land cover and land use change as a climate forcing; *climate model experiments* – simulations with the Community Land Model coupled to the Community Atmosphere Model examined the impact of historical land cover change on the climate of the U.S.

Accomplishments

Satellite-Derived Plant Functional Types

Land surface models developed for climate models typically represent vegetation as biomes, often allowing for several biomes tiled within a grid cell. Vegetation parameters determining leaf physiology and leaf optical properties vary among biomes. This approach fails in mixed life-form biomes such as savanna (grasses, trees), grasslands (C_3, C_4 grasses), and mixed forests (needleleaf evergreen tree, broadleaf deciduous tree), where plants in the landscape differ greatly in their ecology and physiology. To better represent landscape heterogeneity in a way that is consistent with ecological theory and ecosystem models and to take advantage of high resolution (1-km) satellite data products such as "continuous fields", we developed an alternative to the classification approach that represents landscapes as patches of co-existing plant functional types.

A ½° dataset of the fractional cover of 15 plant functional types (PFTs) was derived from available 1-km satellite data and climate rules (Bonan et al., 2002a). The 7 primary PFTs are needleleaf evergreen or deciduous tree, broadleaf evergreen or deciduous tree, shrub, grass, and crop. One-half degree maps of the abundance of each primary PFT (Figure 1) were derived from the 1-km IGBP DISCover dataset of natural and anthropogenic land cover and the 1-km University of Maryland tree cover dataset of evergreen, deciduous, broadleaf, and needleleaf tree cover. Temperature and precipitation data were then used to derive physiological variants of these PFTs. The seasonal course of leaf area index (LAI) for each PFT present in a grid cell was derived from 1-km AVHRR red and near infrared reflectances (Figure 2).

Community Land Model

This proposal supported the development of the Community Land Model (CLM) for the Community Climate System Model (CCSM). This model was developed in coordination with the CCSM Land Working Groups from the NCAR LSM, BATS, and IAP94 land surface models (Oleson et al., 2004a). A river routing model routes runoff downstream to oceans to close the hydrologic cycle in the coupled land-atmosphere-ocean system. Climate model simulations with the CLM showed significant improvements in surface air temperature, snow cover, and runoff for CLM compared to the NCAR LSM (Bonan et al., 2002b). The CLM generally warms surface air temperature in all seasons, reducing or eliminating many cold biases. The annual cycle of runoff is greatly improved, especially in arctic and boreal regions where the model has low runoff in cold seasons when the soil is frozen and high runoff during the snow melt season. Surface albedo is well simulated over snow-free regions compared to MODIS white sky and black sky albedos for visible and near-infrared wavebands except most noticeably over North Africa (Oleson et al., 2003).

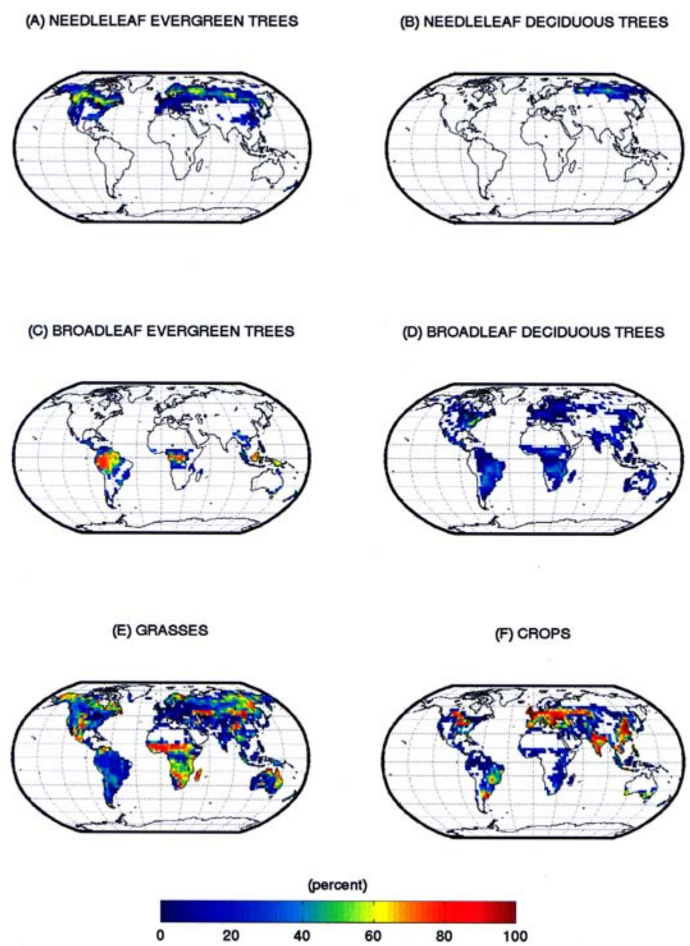

Figure 1. Distribution of needleleaf evergreen trees, needleleaf deciduous trees, broadleaf evergreen trees, broadleaf deciduous trees, grasses, and crops. Maps show the percent of the grid cell occupied by each plant functional type.

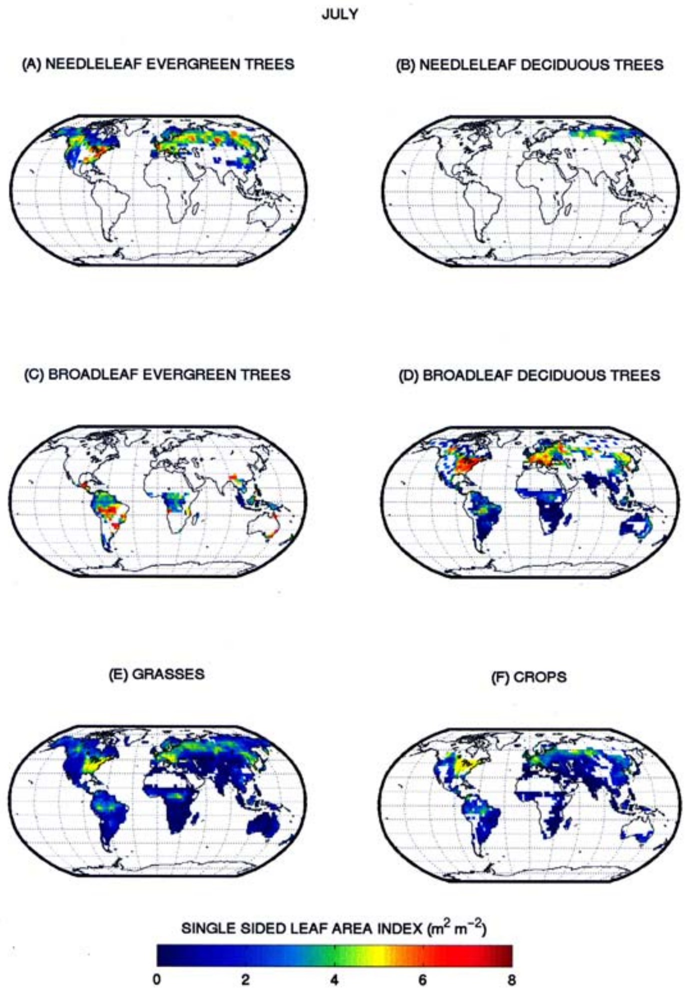

Figure 2. July satellite-derived leaf area index for needleleaf evergreen trees, needleleaf deciduous trees, broadleaf evergreen trees, broadleaf deciduous trees, grasses, and crops.

Additionally, development of the model from the traditional hydrometeorology represented in land surface models allows for integrated assessment of natural and human changes in land cover and their effects on climate, water resources, and biogeochemistry. Biogenic emissions of volatile organic compounds (BVOCs) are an important determinant of ozone and atmospheric chemistry. The emission of BVOCs varies greatly with photosynthetically active radiation, temperature, leaf area index, and plant type. A parameterization of BVOC emissions was implemented in the CLM so that the model can be used to study how changes in land cover affect BVOC emissions (Levis et al., 2003). Dust emissions also depend greatly on surface climate and land cover type. A dust emissions model was implemented in the CLM (Zender et al., 2003).

Changes in vegetation structure and biogeography in response to climate change have important feedbacks on climate. We used ecological concepts from the Lund-Potsdam-Jena dynamic global vegetation model to grow plants in the CLM (Bonan et al., 2003; Levis et al., 2004). This allows the model to contrast the importance of natural changes in land cover from human land uses. Vegetation is represented as spatially independent patches of plant functional types. Each plant type is represented by an individual plant with the average biomass, crown area, height, and stem diameter of its population, by the number of individuals in the population, and by the fractional cover in the grid cell. Plant mass, density, and coverage are updated once a year in response to establishment, resource competition, growth, mortality, and fire. Leaf area index is updated daily to a maximum value set by the annual vegetation dynamics. The coupling approach is successful. The model simulates dynamics of tundra, boreal forest, northern hardwood forest, tropical rainforest, and savanna ecosystems that are consistent with observations (e.g., Figure 3). The model also simulates global biogeography that is consistent with observations (Figure 4).

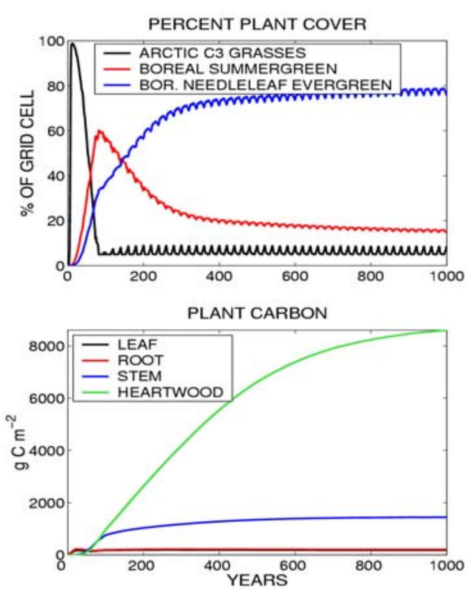

Figure 3. Simulated vegetation dynamics for a grid cell in northern Canada from initially bare ground. Community composition and carbon pools are representative of a boreal forest.

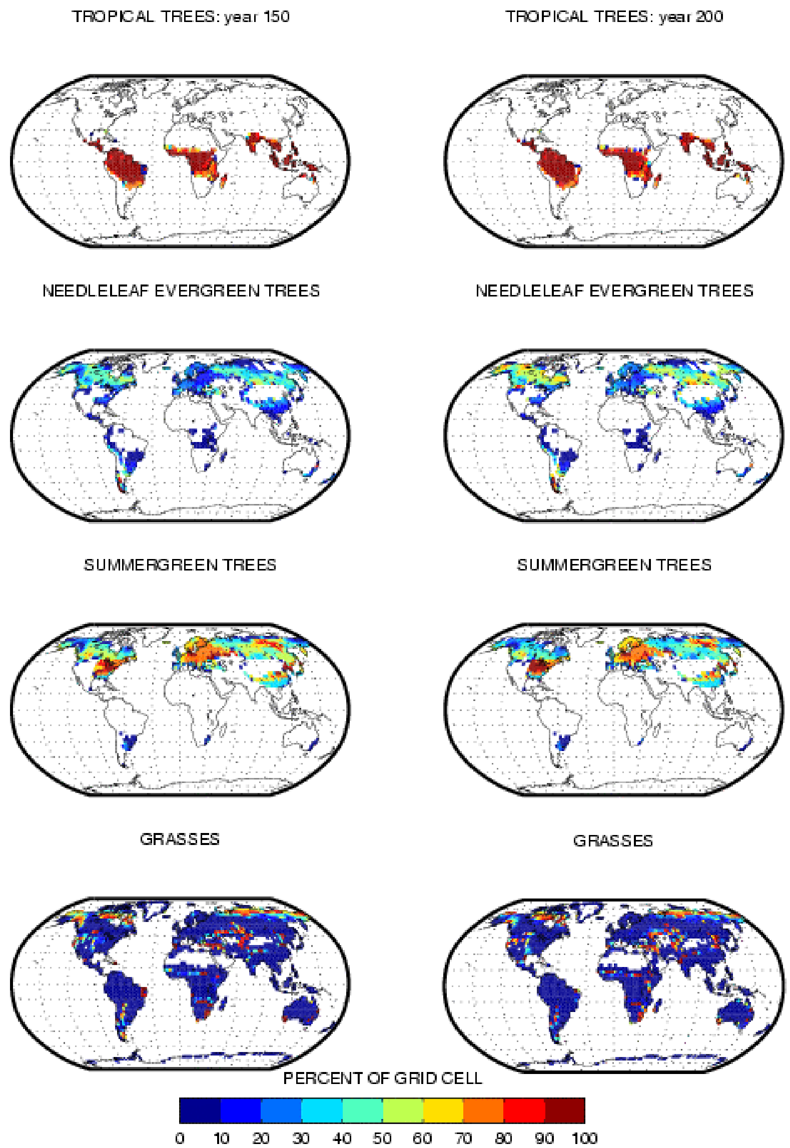

Figure 4. Biogeography of plant functional types (as a percent of the grid cell) simulated at 150 and 200 years. The simulation was initialized from bare ground.

Climate Effects of Land Cover Change

To study the impact of historical land cover change on climate, CLM surface datasets representing the potential natural vegetation and actual vegetation at 1800, 1850, 1900, 1950, and 2000 were prepared for the United States and southern Canada (Figure 5). These datasets show farm abandonment and reforestation in New England and the rise of agriculture in the Midwest.

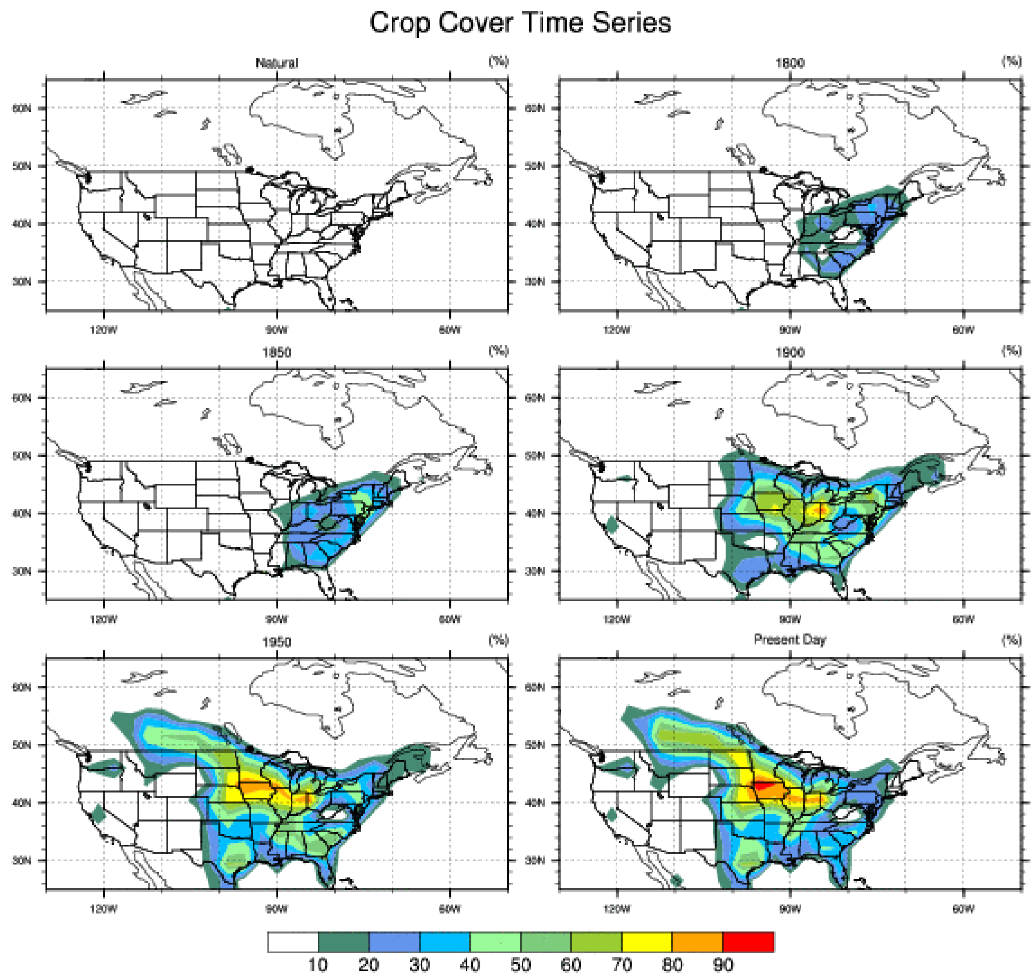

Figure 5. Geographic distribution of croplands (as a percent of a grid cell) at 1800, 1850, 1900, 1950, and 2000.

These datasets were used in a study that examined the impact of historical land cover change on North American surface climate, focusing on the robustness of the climate signal with respect to representation of sub-grid heterogeneity and land biogeophysics within a climate model (Oleson et al., 2004b). We performed four paired climate simulations with the Community Atmosphere Model using two contrasting land models and two different representations of land cover change. One representation used a biome classification without subgrid-scale heterogeneity while the other used the high-resolution satellite dataset of multiple plant functional types within a model grid cell. Present-day and natural vegetation datasets were created for both representations. All four sets of climate simulations showed that present-day vegetation has cooled the summer climate in regions of North America compared to natural vegetation (Figure 6). The simulated magnitude and spatial extent of summer cooling due to land cover change was reduced when the biome-derived land cover change datasets were replaced by the satellite-derived datasets. The diminished cooling is partly due to reduced intensity of agriculture in the satellite-derived datasets. Comparison of the two land surface models showed that the use of a comparatively warmer and drier land model in conjunction with satellite-derived datasets further reduced the simulated magnitude of summer cooling. These results suggest that the cooling signal associated with North American land cover change is robust but the magnitude and therefore detection of the signal depends on the realism of the datasets used to represent land cover change and the parameterization of land biogeophysics.

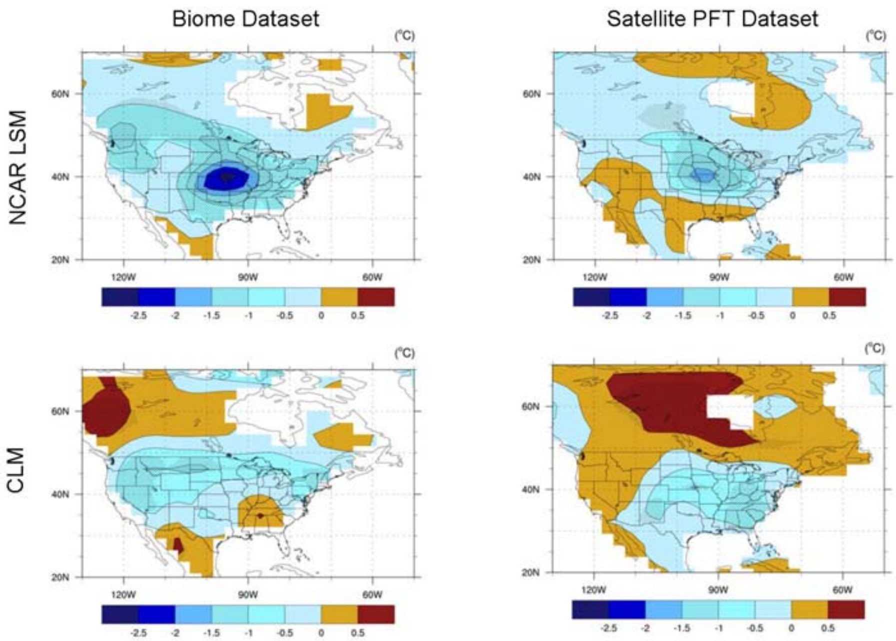

Figure 6. Effects of croplands on summer surface air temperature. Each panel shows the difference in surface air temperature between two climate model simulations that used different surface datasets – one of present-day vegetation with croplands and the other natural vegetation without croplands. Simulations were performed with CAM using both the NCAR LSM and CLM as the land model and with biome and satellite plant functional type datasets.

Ongoing Work

An urban land cover parameterization is being developed for the CLM to include the effects of cities on surface energy fluxes and the hydrologic cycle. This parameterization utilizes the concepts of an urban canyon consisting of roof, wall, and road surfaces to simulate the radiative balance (Masson, 2000; Masson et al., 2002). As the ratio of building height to street width increases, the albedo of the urban canyon decreases due to greater trapping of radiation within the canyon (Figure 7). The amount of solar radiation absorbed by elements within the canyon (road, walls) also declines due to shading. Work is continuing to parameterize turbulent fluxes (sensible heat, latent heat) and hydrology for the urban canyon.

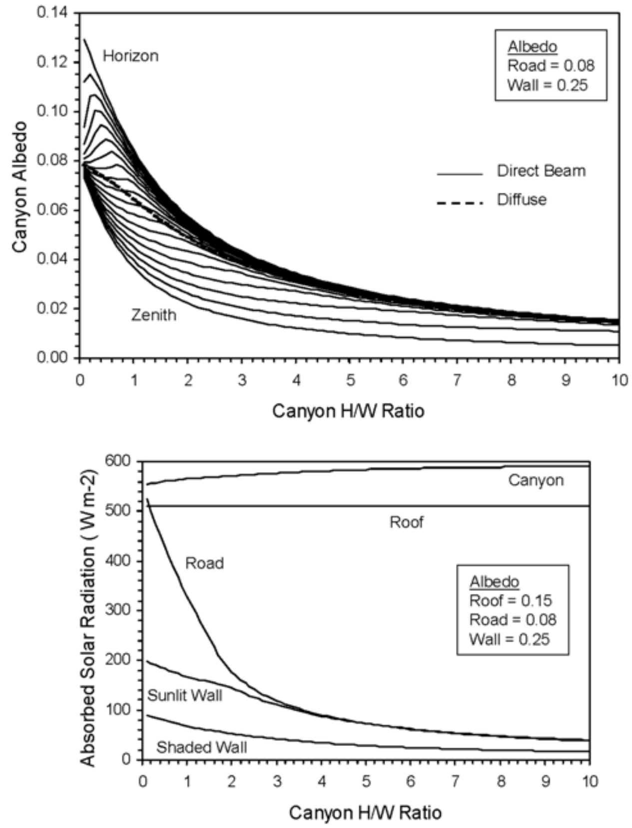

Figure 7. Albedo of an urban canyon (top) and solar radiation absorbed by surface elements in the canyon (bottom) in relation to increasing ratio of building height-to-street width. Albedos are shown for sun angles ranging from overhead (zenith) to horizon. Solar radiation is for a zenith angle of 30 degrees.

Agricultural land in the CLM is currently represented by a single crop type. The phenology of crops is parameterized by satellite-derived leaf area index. The CLM is being modified from this single crop type to include corn, wheat (winter, spring), and soybean (Kucharik et al., 2001; Kucharik, 2003). This will provide a first order look at the sensitivity of climate to better specification of croplands. In addition, the crop model allows for prognostic growth and development of crops so that crops are an interactive component of the climate system, affecting and responding to climate variability and climate change. For example, Figure 8 shows the simulated daily leaf area index for corn in central U.S. After planting, the corn reaches maximum leaf area index in 60-90 days and is then harvested. Temporal changes in leaf area index and crop height due to planting, growth, and harvesting alter surface energy fluxes and climate.

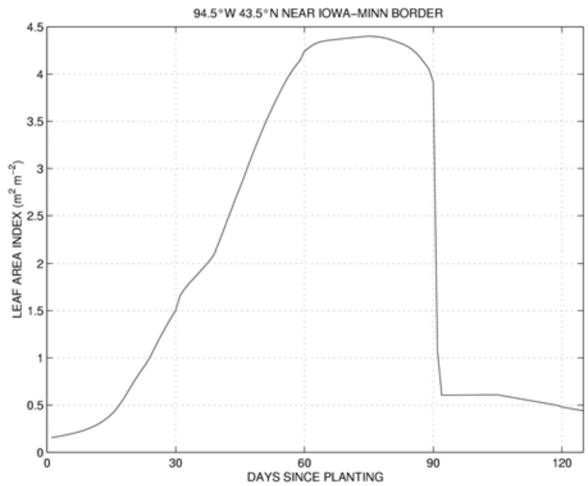

Figure 8. Simulated daily leaf area index for corn in central U.S.

Conclusions

This study produced the following significant results. The model and datasets are available as part of the publicly released Community Climate System Model (http://www.ccsm.ucar.edu/).

1. A new satellite derived dataset of the fractional cover and leaf area index of plant functional types for use with the Community Land Model. This is a unique representation of land cover for land surface models. Compared to the traditional biome-based land cover classification, it better represents the spatial scale at which land cover and land use occurs and is consistent with ecosystem models.

2. The Community Land Model for the Community Climate System Model was further developed to parameterize natural and human-induced changes in land cover and their effects on climate.

3. Datasets of natural vegetation and vegetation at 1800, 1850, 1900, 1950, and 2000 were prepared for North America. These datasets were used in climate model simulations that assessed the impact of croplands on the climate of the U.S. The simulations showed that land cover change has cooled the climate of the U.S. This cooling is robust, but the magnitude depends on the realism of the datasets used to represent land cover change and the parameterization of land biogeophysics.

4. This work was published in six journal articles, two book chapters, and two NCAR technical notes (ten publications total).

Publications

Review Articles

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