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Agricultural Land Use and the Transformation of Planet Earth: Investigating the Effects of Land Use Practices on the Ecological, Biogeochemical and Hydrological Systems of the Planet

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Abstract.

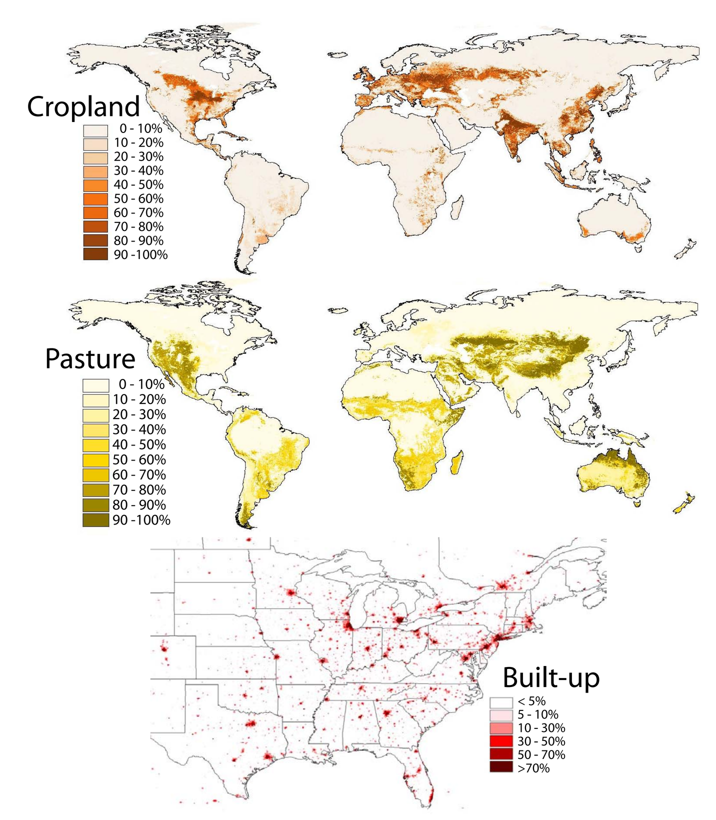
The rise of modern agriculture, coupled with the massive population increases and technological developments of recent decades, has transformed about one-third of the Earth's land surface into croplands and pastures. In addition, the widespread use of fertilizers and irrigation has drastically affected water and nutrient balances across large regions of the globe. Such changes to the land have driven fundamental shifts in the ecological, biogeochemical and hydrological systems of the planet. Even future climate change may not have such a major transformative effect on the environment and on human society. However, despite the importance of agriculture on environmental systems, we still know relatively little about how these domains interact across local, regional and global scales.

During the next three years, our research team will investigate how a variety of human and environmental drivers affect the condition of agroecosystems and freshwater systems on regional and global scales. We will work at the global scale to identify and better document agricultural land cover and land use practices, and their consequences on large-scale water, carbon and nitrogen budgets. We will also conduct more detailed regional-scale studies in the Mississippi Basin to improve our understanding of the linkages between atmospheric, ecological, biogeochemical and hydrological processes in agriculturally dominated regions.

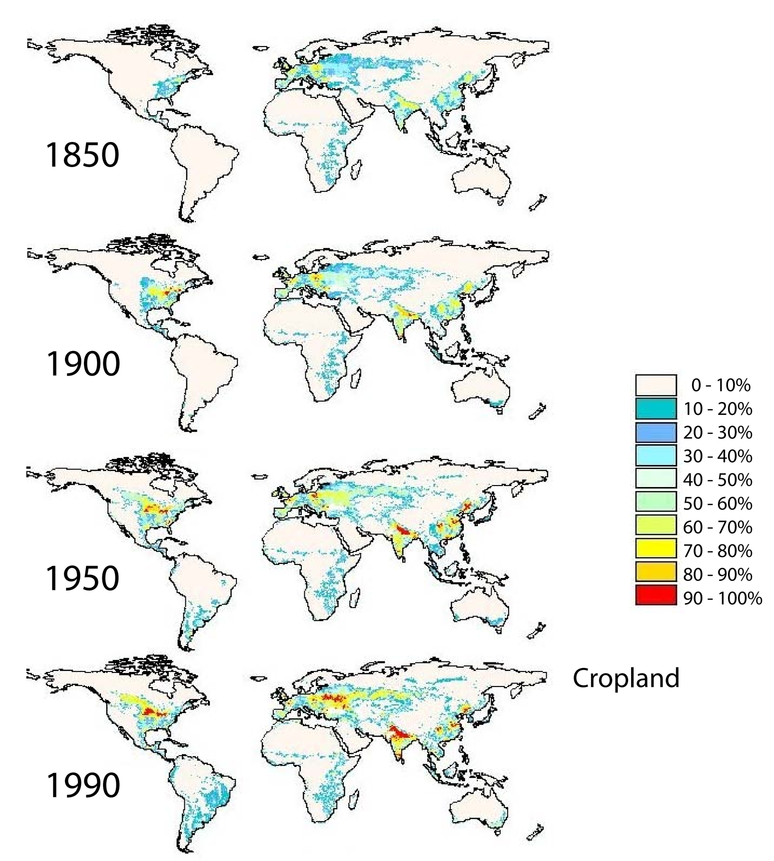
Our IDS project has four major objectives: 1) Document Global Agricultural Land Use Practices. 2) Examine Agroecosystem Dynamics at Regional Scales. 3) Examine the Dynamics of Freshwater Systems at Regional Scales. 4) Explore Changes in Agroecosystems and Freshwater Systems at Global Scales.

Global Land Use Data.

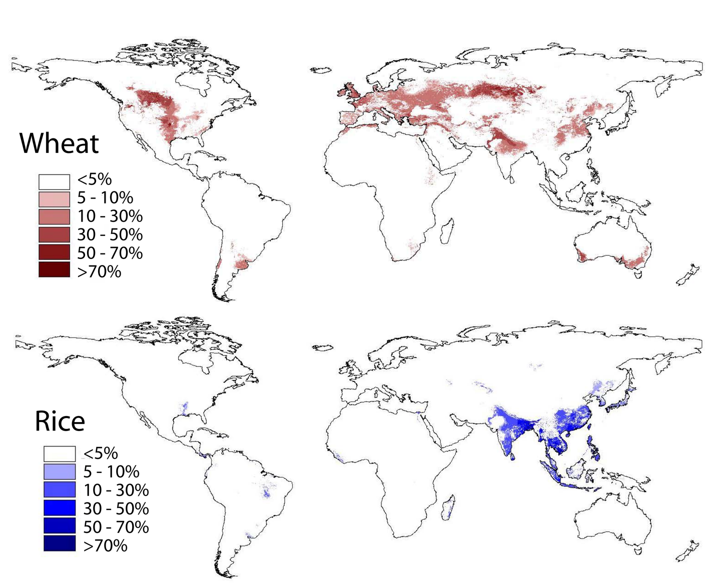
Using a combination of satellite-based measurements (from MODIS) and detailed agricultural census data, we will derive new spatially explicit, global datasets of contemporary agricultural land cover (for croplands, pastures and natural ecosystems) and land use practices (cropping systems, irrigation, and fertilizer inputs). Using historical census data and a simple land use / land cover change model, we will then "back-cast" land cover and land use datasets through the period 1961-2000.

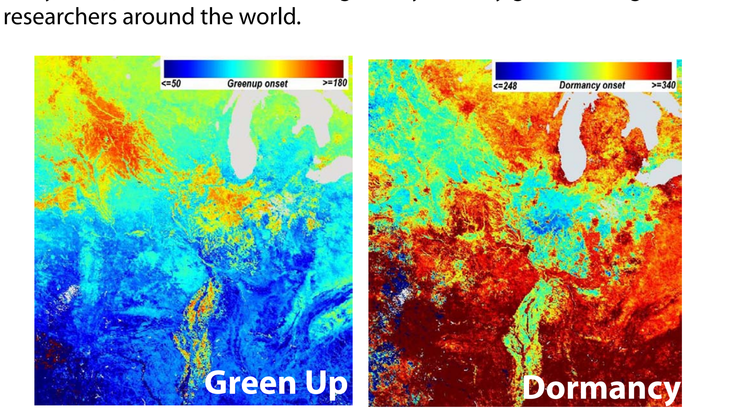


We have developed a statistical data-fusion technique to combine satellite data and census data to create a global data set of croplands, pastures, and built-up areas. In this project, we will further refine this data using emerging MODIS products, and better spatial statistical techniques.

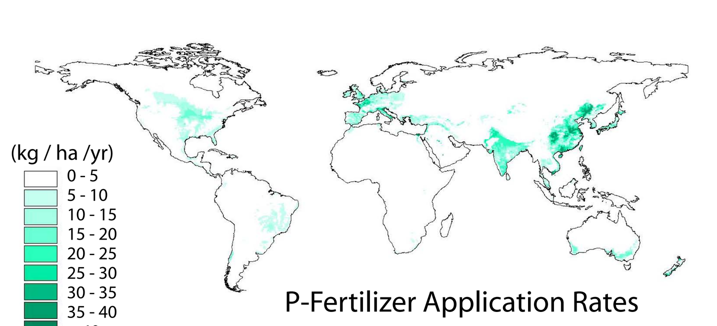


Using a backcasting approach and a historical land cover inventory database, we have reconstructed the historical changes in croplands over the last 3 centuries (1850 onwards shown here) (Ramankutty and Foley, 1999). This database is being widely used by global change researchers around the world.

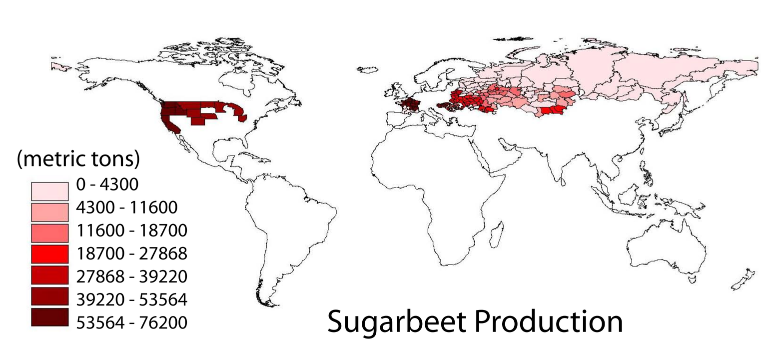




We have further subdivided our croplands data set into 18 major crop types (two examples shown here, at left) (Leff *et al.*, 2003). We propose to refine this data set further using MODIS data. Indeed, MODIS derived phenology (above; Mark Friedl, personal communication, Boston Univ.) is able to detect agricultural lands in the Mississippi Basin and the upper Midwest very well because those lands green up later, and are harvested earlier than surrounding natural vegetation. MODIS will help define planting/harvest dates for crops.



By combining national and subnational data on fertilizer application rates for various crops, with our global distribution of major crop types, we can derive spatially-explicit maps of fertilizer application rates. Here we show a preliminary product of global phosphorus fertilizer application rates created using national level data distributed on our croplands map.



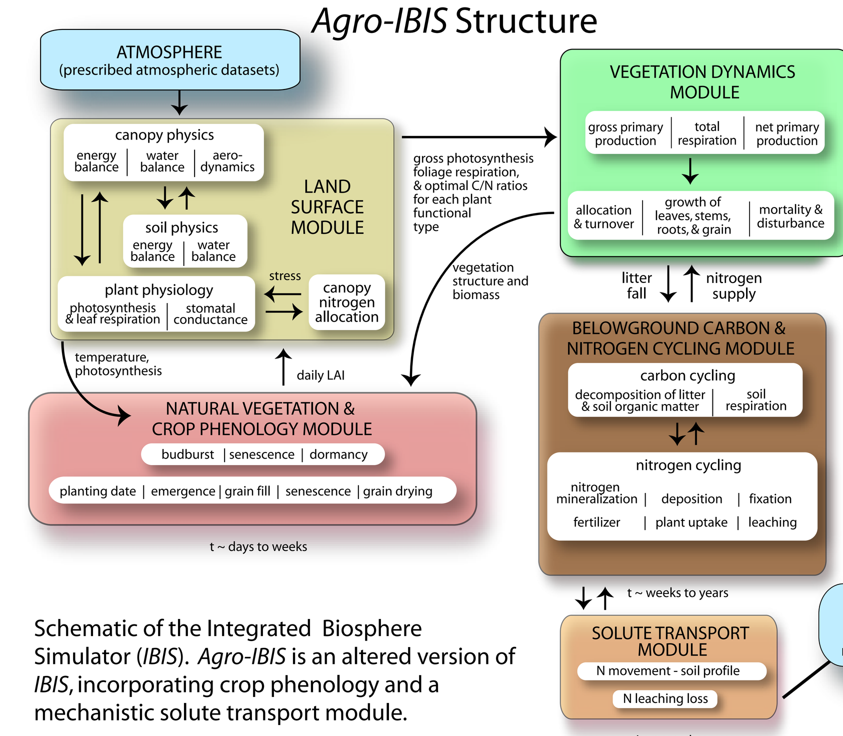
In collaboration with IFPRI and FAO, we are compiling subnational data sets of harvested area, yield, and production for major crops of the world, and for major crop growing nations. SAGE is responsible for compiling data for the OECD nations, while our partners are compiling data for the developing nations. Here we show a preliminary product from this project. This data can be used along with our data fusion technique to create spatial maps of yield and production for the major crops of the world.

Regional Modeling: Agriculture and Freshwater Systems.

Using a new set of ecological and agroecosystem models (IBIS and Agro-IBIS), combined with new collections of field and satellite data, we will examine how natural ecosystems, croplands and pastures in the Mississippi Basin responds to multiple, potentially interacting drivers (land cover change, land use practices, climatic variability). We will specifically consider regional-scale changes in productivity (from each ecosystem, crop and pasture type), carbon storage (in biomass and soil pools), soil nutrient stocks (especially nitrogen) and environmental losses (CO_2 and N_2O to the atmosphere, NO_3^- through runoff and groundwater).

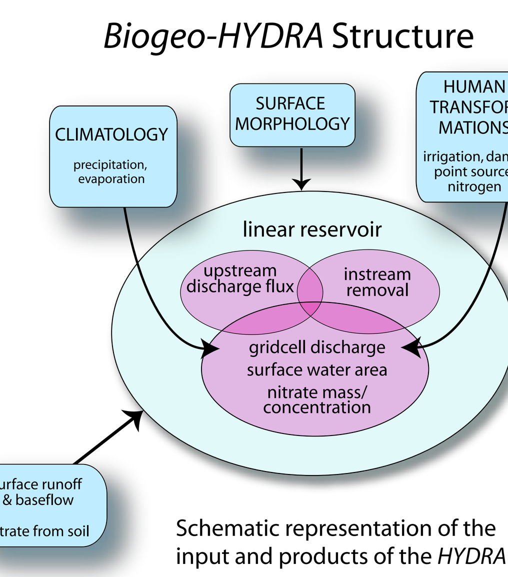
Using a new terrestrial hydrology and aquatic biogeochemistry model (Biogeo-HYDRA), we will consider how human and environmental drivers (land use, land cover change, climate and climatic variability, and water management practices) affect the hydrology and aquatic biogeochemistry of the Mississippi Basin. We will focus our study on regional-scale changes in water balance (evapotranspiration, runoff and recharge), water availability (in soil moisture, river networks and groundwater) and water chemistry (NO_3^- concentration and flux, N_2O efflux).

Agro-IBIS Structure



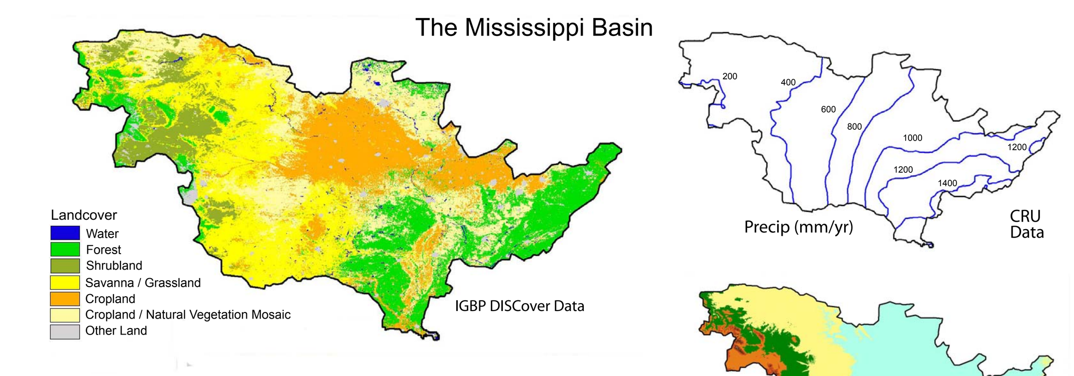
Schematic of the Integrated Biosphere Simulator (*IBIS*). *Agro-IBIS* is an altered version of *IBIS*, incorporating crop phenology and a mechanistic solute transport module.

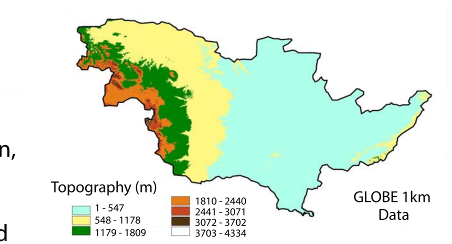
Biogeo-HYDRA Structure



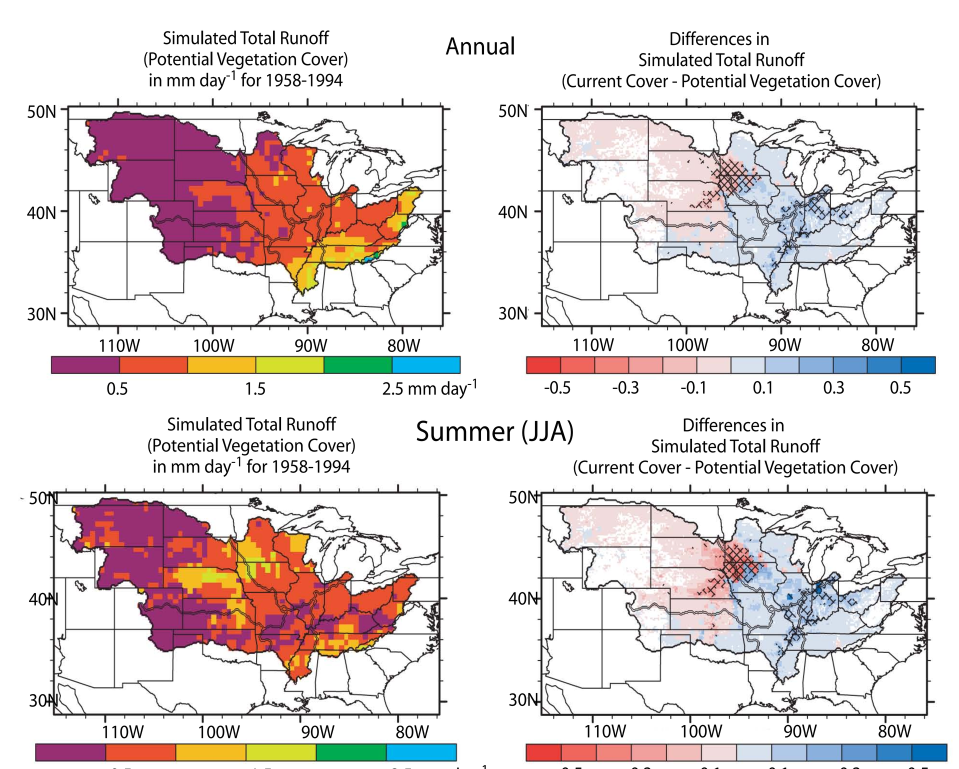
Schematic representation of the input and products of the *HYDRA*

The Mississippi Basin

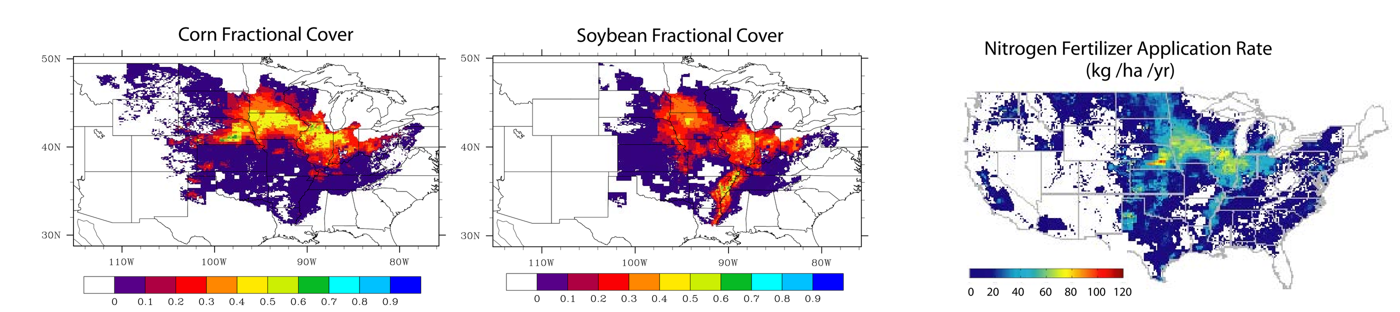




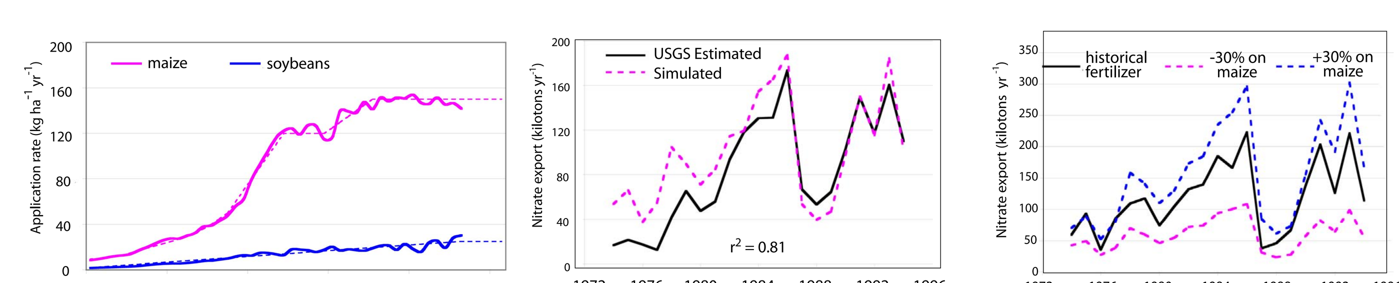
The Mississippi River basin, the world's third largest, is home to some of the most productive farmland on the planet. The river drains some 3.2 million km^2, and is home to 70 million people plus a $100 billion annual agricultural economy. Rainfed corn and soybean cropping systems, grasslands, pastures, and forests dominate the eastern half of the basin. The western half (primarily less than 500 mm of annual precipitation) is dominated by a mix of rainfed (wheat) and heavily irrigated (corn, soybean) cropping systems, grasslands, and shrubland. The region has been subjected to significant land-use change since the 1800s, causing significant losses of soil organic matter. The region produces approximately 40% of the world's corn, and is responsible for about 70% of the total global exports, but does so on only 20% of the total global acreage devoted to corn (USDA-NASS, 2003). However, these rapid gains in productivity have not come without significant environmental costs and losses; nitrate export by the Mississippi River to the Gulf of Mexico almost tripled from 1955 to 1999, primarily due to a six-fold increase in fertilizer application and an increase in runoff (Goolsby et al., 2000). This has led to an increase in the severity and extent of hypoxia in the northern Gulf of Mexico, which may contribute to increased benthic mortality and fisheries decline.



Our modeling results suggest that the effects of land cover change on the water balance are strongly dependent on the location, and on the particular land cover transition (e.g., from forest to summer crops, or from grasslands to winter crops). In the eastern part of the basin, conversion from forests to summer crops causes significant decreases in annual mean runoff (top at left) due to changes in late spring, summer (bottom at left), and early fall. A decrease in runoff is found in the northern plains where the residue layer of dormant grasses is eliminated upon conversion to crops and the bare crop fields evaporate more water than the former dormant grass cover. Conversion of grasslands to winter wheat in the southern plains causes season-dependent changes that eliminate any annual change.

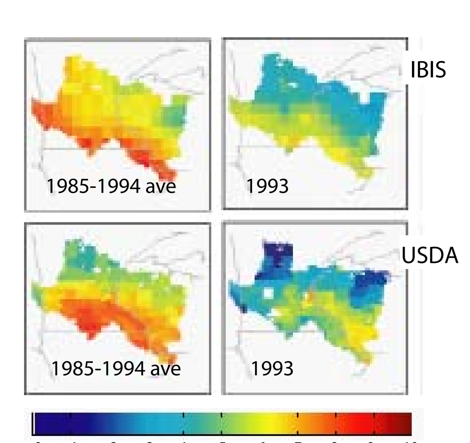


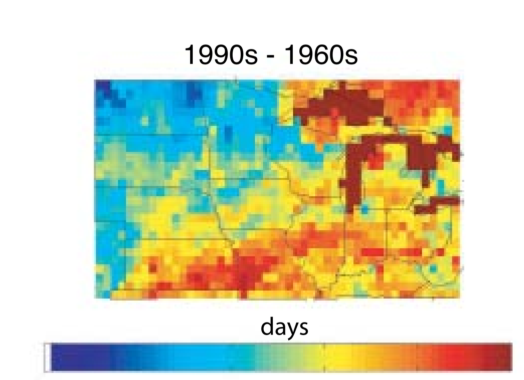
Fractional area of maize and soybean (above left and middle) and nitrogen fertilizer application rate (above right) at 5′ x 5′ spatial resolution in the United States (from Donner, in press). The data sets are created by combining state and county data on fertilizer application rates and planted area (USDA, 2001) with the satellite-derived fractional cropland data set of Ramankutty and Foley. Maize and soybeans are the dominant crops in the Mississippi River basin, planted on over 75% of the permanent croplands in Minnesota and Wisconsin (Lander and Moffitt, 1996); maize also receives the vast majority of the N-fertilizer applied (Goolsby et al., 1999). For completeness, representation of fractional coverage of spring, winter, and durum wheat were also created (not shown). In two recent studies we have used the explicit fractional crop cover and fertilizer application rate maps with our IBIS and HYDRA models to investigate the impact of human transformations on the water resources of the Mississippi River basin (summarized in the figures below).



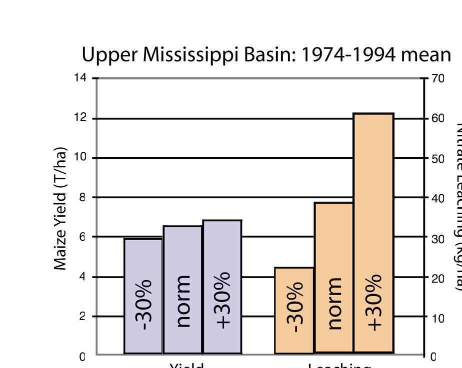
The application of industrial fertilizers (above left) and the introduction of nitrogen fixing plants (such as soybean, middle) greatly impact the chemistry of many of the world's rivers. Our simulations of the nitrogen flux in the Upper Mississippi River system (Donner and Kucharik, in press) show strong agreement with the USGS estimated annual nitrate export for the Mississippi River at Clinton, Iowa (above middle). These simulations illustrate the capability of our models to simulate the dynamics of nitrogen cycling within the soil/vegetation/water system. Simulations in which the fertilizer application rate in IBIS is varied by +/- 30% reveal the non-linearities of the system (above right). At higher levels of N-fertilizer use, DIN loading to rivers and river nitrate export become increasingly sensitive to the hydrologic conditions, particularly when there is ample residual nitrogen in the soil.

Comparison of *Agro-IBIS* simulated maize yields (top) with USDA (bottom) county level data (values are in T/ha), for a 10-year average period (1985-1994) and a wet year (1993).





Agro-IBIS simulations of changes in optimum planting date of maize from the 1960s to the 1990s. This figure shows how the simulated optimum planting date for corn is about 10-14 days earlier in the 1990s across NW Iowa, Minnesota into the Dakotas. However, potentially cooler and wetter conditions across eastern Kansas through Missouri and Illinois may have caused optimum planting dates to be 3-5 days later in some regions.

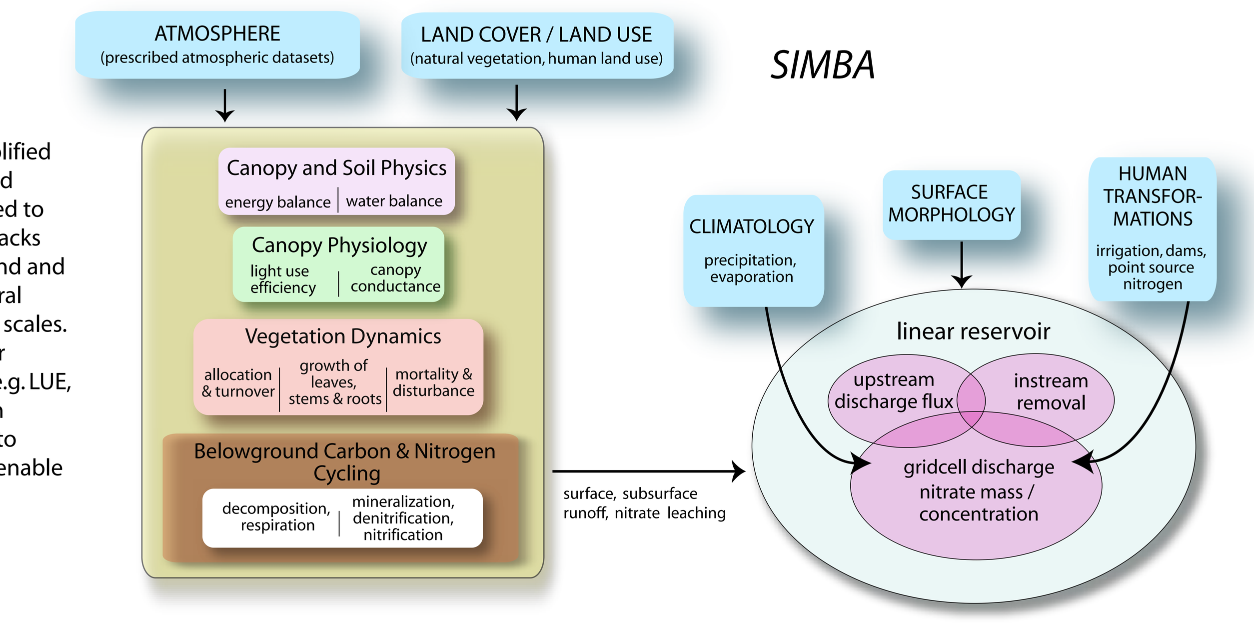


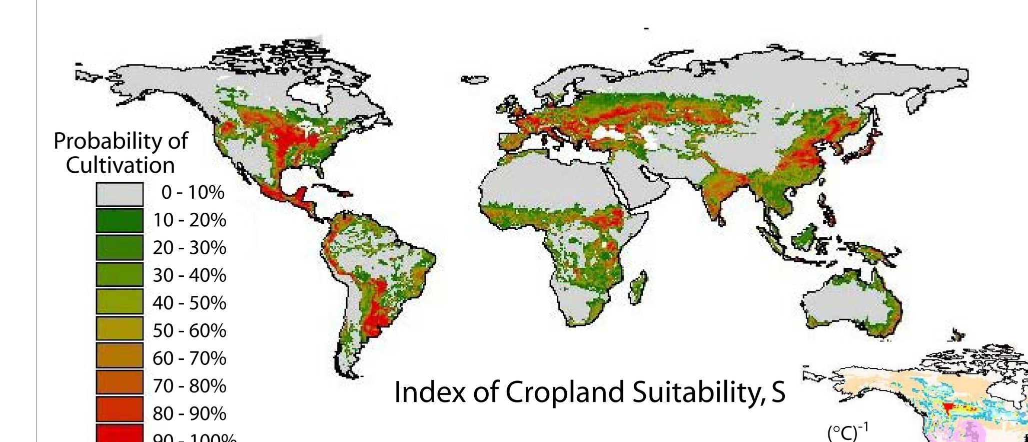
Agro-IBIS simulated sensitivity of maize yield and average annual nitrate leaching over the Upper Mississippi basin taking into account +/- 30% changes in estimated historical applications of N-fertilizer during the 1974-1994 time period. Adapted from Donner and Kucharik, in press.

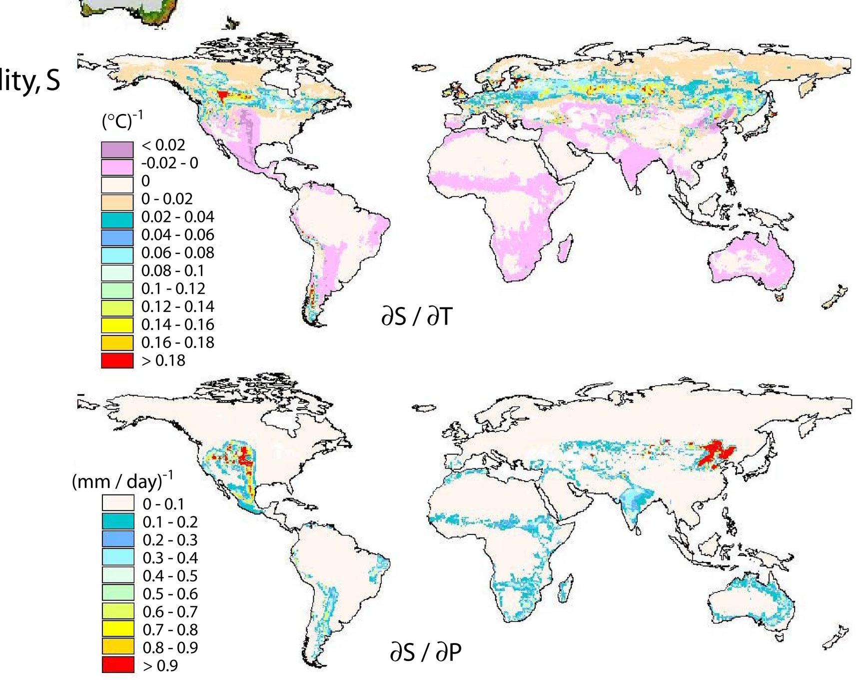
Global Modeling: Synthesis.

We are developing a simplified model (SIMBA – SImple Model of the Biosphere and Agriculture) of global agroecosystems and freshwater systems. Using SIMBA, we will explore the sensitivity of agroecosystem and freshwater conditions to a wide range of environmental drivers, and determine where "hot spots" of change may occur. We will also apply the model to policy-relevant scenarios of global environmental change (including the IPCC and Millennium Ecosystem Assessment scenarios of future climate, land cover, land use, and atmospheric composition).

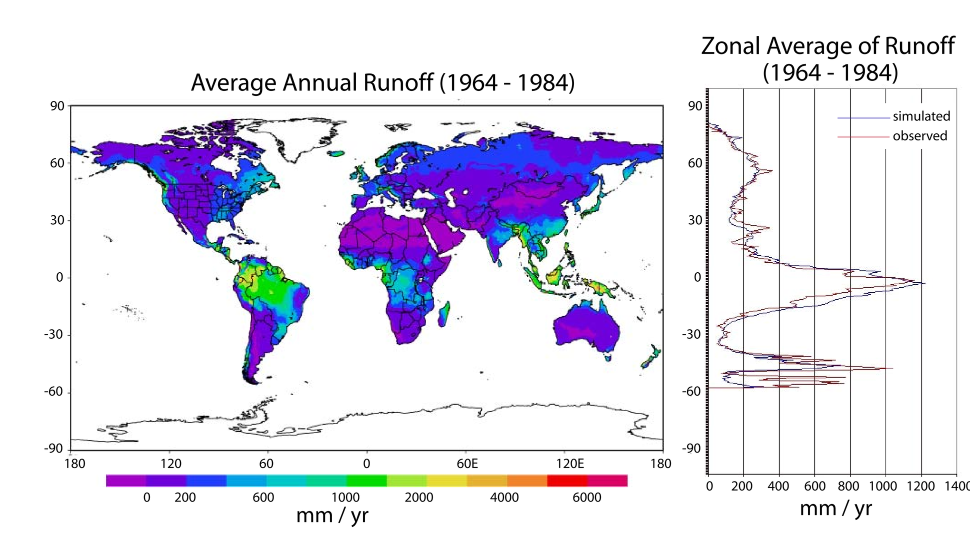
SIMBA framework. Simplified versions of Agro-IBIS and Biogeo-HYDRA are linked to enable studies of feedbacks between agricultural land and water use, and the natural resource base, at global scales. SIMBA uses fewer, major drivers and processes (e.g. LUE, land cover, precipitation bucket model), chosen to optimize accuracy and enable global coverage.

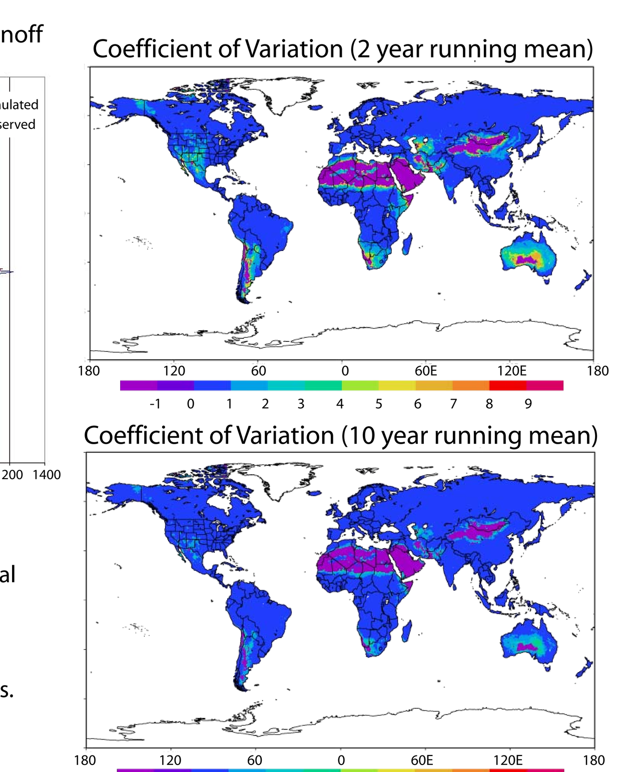






We derive the overall index of cropland suitability (above) as a product of the climate and soil quality limits on cultivation (Ramankutty *et al.*, 2002). The suitability index map is similar to the actual distribution of croplands in 1992. Panels at right show sensitivity of the suitability index to change in temperature (above) and precipitation (below). Often, regions at the edges of the most suitable lands are most vulnerable to climate change.





Global patterns of total runoff (surface runoff and groundwater recharge) and its spatial and temporal variability. Left panel shows global mean runoff, an index of water availability. Center panel shows the relationship between runoff and latitude (high runoff in the tropics, low in temperate regions). Right panels show the variability (coefficient of variation) of runoff at interannual (top) and decadal (bottom) time scales.