Available online at www.sciencedirect.com

ScienceDirect

Global and Planetary Change 54 (2006) 79 – 93

GLOBAL AND PLANETARY CHANGE

www.elsevier.com/locate/gloplacha

Feedbacks between agriculture and climate: An illustration of the potential unintended consequences of human land use activities

Navin Ramankutty *, Christine Delire [1], Peter Snyder [2]

Center for Sustainability and the Global Environment (SAGE), Gaylord Nelson Institute for Environmental Studies,
University of Wisconsin, 1710 University Avenue, Madison, Wisconsin 53726, USA

Received 29 April 2005; received in revised form 21 September 2005; accepted 21 October 2005
Available online 11 July 2006

Abstract

Agriculture has significantly transformed the face of the planet. In particular, croplands have replaced natural vegetation over large areas of the global land surface, covering around 18 million km^2 of the land surface today. To grow crops, humans have taken advantage of the resource provided by climate — optimum temperature and precipitation. However, the clearing of land for establishing croplands might have resulted in an inadvertent change in the climate. This feedback might, in turn, have altered the suitability of land for growing crops. In this sensitivity study, we used a combination of land cover data sets, numerical models, and cropland suitability analysis, to estimate the degree to which the replacement of natural vegetation by croplands might have altered the land suitability for cultivation. We found that the global changes in cropland suitability are likely to have been fairly small, however large regional changes in cropland suitability might have occurred. Our theoretical study showed that major changes in suitability occurred in Canada, Eastern Europe, the Former Soviet Union, northern India, and China. Although the magnitude, sign, and spatial patterns of change indicated by this study may be an artifact of our particular model and experimental design, our study is illustrative of the potential inadvertent consequences of human activities on the land. Moreover, it offers a methodology for evaluating how climate changes due to human activities on the land may alter the multiple services offered by ecosystems to human beings.

Keywords: land use; land cover; agriculture; climate; modeling

1. Introduction

Over the last few decades, numerous studies have highlighted the importance of considering the interactions between terrestrial vegetation and climate (Bonan et al., 1992; Prentice et al., 1992; Woodward et al., 1995; Brovkin et al., 1998; Foley et al., 2003). Climate influences the types of vegetation that can grow in a given location (Holdridge, 1947; Box, 1981; Woodward, 1987). In turn, the vegetation types, by modifying land surface characteristics such as albedo, the partitioning of sensible heat and latent heat, and surface roughness,

---

* Corresponding author. Department of Geography, McGill University, Room 627, Burnside Hall 805 Sherbrooke St. W., Montreal, QC H3A 2K6, Canada. Tel.: +1 514 398 8428; fax: +1 514 398 7437.
E-mail address: navin.ramankutty@mcgill.ca (N. Ramankutty).
URL: http://landuse.sage.wisc.edu/~navin/pub/Navin_Ramankutty/ (N. Ramankutty).

[1] Current address: Institut des Sciences de l'Evolution (UMR CNRS 5554), Université Montpellier II - pl. E. Bataillon, case postale 61, 34095 Montpellier cedex 05 France.

[2] Current address: Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, 105 South Gregory Street, Urbana, IL 61801, USA.

0921-8181/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.gloplacha.2005.10.005

influence regional climate (Foley et al., 2003) and sometimes through teleconnections, global climate as well (Henderson-Sellers et al., 1993; Sud et al., 1996; Chase et al., 2000; Gedney and Valdes, 2000; Werth and Avissar, 2002). Indeed, some authors have suggested broadening the definition of climate to incorporate the influence of terrestrial vegetation (Kabat et al., 2004). In the remainder of the paper we will use climate in the more traditional sense, describing only atmospheric processes.

Direct anthropogenic modifications of the land surface, through land use practices, might also influence the climate system. Agriculture, one of the most widespread human land use activities, currently covers roughly a third of the global land surface (Ramankutty and Foley, 1998; Klein Goldewijk, 2001). Several observational or model simulation studies have estimated the influence of agricultural land use practices, deforestation, or other types of land use and land cover change on climate of North America (Copeland et al., 1995; Bonan, 1997; Stohlgren et al., 1998; Chase et al., 1999; Baidya Roy et al., 2003; Kalnay and Cai, 2003; Marshall et al., 2003; Cooley et al., 2005), the tropics (Shukla et al., 1990; Henderson-Sellers et al., 1993; Costa and Foley, 1999; Delire et al., 2001; Snyder et al., 2004b), China (Fu, 2003), Australia (Narisma and Pitman, 2003; Pitman et al., 2004), and global climate (Betts, 1999; Brovkin et al., 1999; Govindasamy et al., 2001; Zhao et al., 2001; Bounoua et al., 2002; Pielke et al., 2002; Matthews et al., 2004; Snyder et al., 2004a).

On the other hand, it is very difficult to examine the converse question — how does climate influence land use practices? While the climate system provides a constraint on what land use practices can take place, humans through their technology and innovation (mechanization, new cultivars, irrigation, fertilization, etc.) have overcome some of the limitations. Land use change is driven by a complex combination of factors (Geist and Lambin, 2001), including the global economy, fuel price, fertilizer price and availability, genetically modified crops, influence of invasive species and pests, and societal cultural practices. Nevertheless, the broad patterns of land use are constrained by climate. The cultivation of crops, for example, is critically dependent on the temporal and spatial patterns of temperature and precipitation. On this basis, a few studies have examined the climate-regulated suitability of the land surface for growing crops (Leemans and Solomon, 1993; Fischer et al., 2000; Ramankutty et al., 2002).

The concept of “ecosystem service” was recently developed to describe and evaluate the various provisioning and regulatory services provided by terrestrial ecosystems to human beings (Daily et al., 1997; Daily, 1997). These include provisioning services such as food, freshwater, and fiber, regulating services such as climate regulation and water purification, supporting services such as soil formation and nutrient cycling, and cultural services such as recreation and tourism, spiritual, and cultural heritage benefits (Millennium Ecosystem Assessment, 2003). Using this concept, we can say that the climate system offers a service to humans by providing an adequate growing season to grow crops. However, as discussed earlier, the terrestrial vegetation itself regulates the climate system to some degree. We can therefore say that the *regulation of climate by terrestrial vegetation is an ecosystem service*.

By growing crops, humans have modified the land surface characteristics, and in turn altered regional and global climate. How has this climate modification, in turn, influenced our ability to grow crops? Could we inadvertently have altered the effectiveness of the climate regulation process? In other words, by growing crops, might humans have unintentionally modified the climate system in a way that has changed our ability to continue growing crops? Is this feedback positive or negative, and what is the magnitude of change? This is the central question we are addressing in this study, and it is an illustration of the broader question: *Are human activities changing the environment in ways that may jeopardize our ability to continue deriving resources in the future*?

To answer this question, we use a combination of data analysis and numerical modeling tools, as presented in the next section.

2. Methods

We first introduce some earlier work on global cropland suitability analysis (Ramankutty et al., 2002). Here we build on this earlier work to estimate the ecosystem service provided by climate for growing crops. We then present our experimental design, followed by brief descriptions of the numerical modeling tools.

2.1. Land suitability for cultivation

Several studies, with varying degrees of sophistication, have attempted to evaluate the suitability of the land surface for cultivation in general (Cramer and Solomon, 1993), or for growing various crops (Leemans and Solomon, 1993; Fischer et al., 2000). These studies evaluated the large-scale suitability of the global land surface for growing crops as constrained by climate, soil, and physiographic features. Using similar methods, Ramankutty et al. (2002) used a combination of two climatic indices and two soil quality indices to define the land suitability for cultivation. They derived empirical relationships between the four indices and the global distribution of croplands in 1992 from Ramankutty and Foley (1998) and applied it over the globe. At the global scale, climate and soils adequately describe the major constraints on agricultural land as will be shown below. The climate constraints are growing degree days (GDD) and the ratio of actual to potential evapotranspiration (α) (these are calculated using the simple water balance model described in detail later, which uses as inputs, the observed CRU05 monthly-mean climatological data sets (New et al., 1999) of temperature, precipitation, and cloudiness over the 1961–1990 period). The soil constraints are soil carbon density, C_{soil}, and soil pH, $\mathrm{pH}_{\mathrm{soil}}$, obtained from the IGBP-DIS (1998) global soil data set.

Thus land suitability for cultivation, S, is given by,

$$S = f_1(\mathrm{GDD}) f_2(\alpha) g_1(C_{\mathrm{soil}}) g_2(\mathrm{pH}_{\mathrm{soil}}),$$

where $f_1(\mathrm{GDD})$, $f_2(\alpha)$, $g_1(C_{\mathrm{soil}})$ and $g_2(\mathrm{pH}_{\mathrm{soil}})$ are empirical functions determined by curve fitting to the existing relationships between cropland areas, GDD, α, C_{soil}, and $\mathrm{pH}_{\mathrm{soil}}$. (See Ramankutty et al. (2002) for more details on the empirical fitting.)

The empirical functions based on climatic parameters are given by,

$$f_1(\mathrm{GDD}) = \frac{1}{[1 + e^{a(b-\mathrm{GDD})}]}, \text{ and}$$

$$f_2(\alpha) = \frac{1}{[1 + e^{c(d-\alpha)}]},$$

where $a=0.0052$, $b=1334$, $c=10.808$, and $d=0.3562$. (Note that the values of c and d are slightly different from that in Ramankutty et al. (2002) because of some corrections to the water balance model code.)

The empirical functions based on soil parameters are given by,

$$g_1(C_{\mathrm{soil}}) = \frac{a}{[1 + e^{b(c-C_{\mathrm{soil}})}]} \frac{a}{[1 + e^{d(e-C_{\mathrm{soil}})}]},$$

where $a=3.9157$, $b=1.3766$, $c=3.468$, $d=-0.0791$, and $e=-27.33$, and

$$g_2(\mathrm{pH}_{\mathrm{soil}}) = \begin{cases} -2.085 + 0.475\ \mathrm{pH}_{\mathrm{soil}}, & \text{if } \mathrm{pH}_{\mathrm{soil}} \le 6.5 \\ 1.0, & \text{if } 6.5 < \mathrm{pH}_{\mathrm{soil}} < 8 \\ 1.0 - 2.0\mathrm{pH}_{\mathrm{soil}}, & \text{if} \mathrm{pH}_{\mathrm{soil}} \ge 8 \end{cases}$$

The suitability estimate captures the dry and cold boundaries of agriculture, as well as the highly fertile organic matter rich (chernozem) grassland soils (Mollisols) of the Midwestern U.S., Ukraine, and the Pampas of Argentina (Fig. 1). Much of the suitable cropland of the world is already in croplands by 1992. Nevertheless, there is an additional ~ 115% potentially available for cultivation (18 million km^2 in 1992 compared to a suitable area of 39 million km^2). Roughly half of this remaining cultivable land lies in tropical South America and Africa. This result is consistent with earlier studies (Buringh and Dudal, 1987; Alexandratos, 1995; Fischer et al., 2000).

Our global cropland suitability analysis ignores many of the finer details normally invoked in local-scale cropland suitability analysis, including the consideration of topography, micro-climate, climate variability (climate during critical growth phases, probability of climate hazard including frost, hail, winds, etc.), more detailed considerations of soil suitability (including nutrient availability, drainage, levels of toxicity, etc.), erosion hazard, etc. Furthermore, cropland suitability is only one of several components, including crop cultivar development, irrigation, fertilizer use, pesticide use,

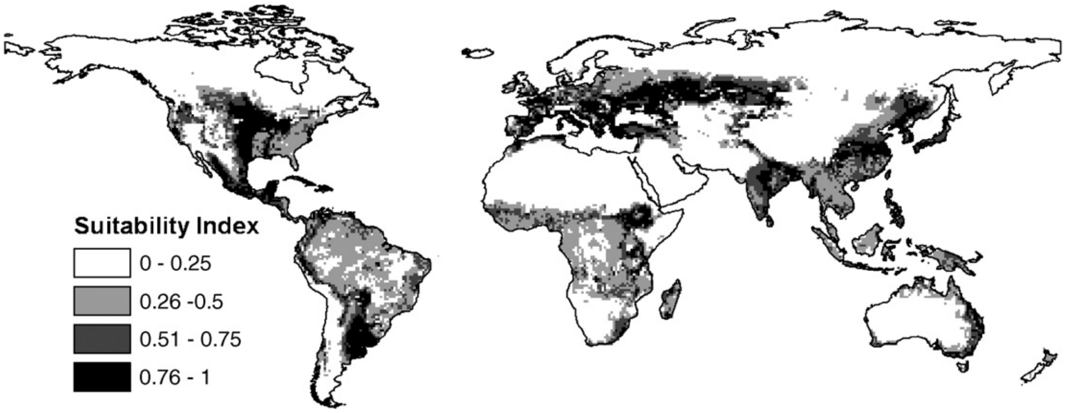

Fig. 1. Global land suitability for cultivation, as estimated by Ramankutty et al. (2002). This index is calculated using a combination of climate and soil parameters (see text for details). It captures the major climate and soil constraints on a global scale.

mechanization, etc., that combine to form the ecosystem service of food production. Nevertheless, growing season length and moisture stress are major constraints on the food production system, as evidenced by how well they combine to describe the present-day distribution of croplands (Fig. 1).

Our estimate of cropland suitability is one measure of the ecosystem service provided by the climate system for continued cultivation. The principal question of this study is how the ecosystem service of land suitability for cultivation, has changed since the onset of agriculture. We use numerical models, in conjunction with land cover data sets and cropland suitability analysis, to answer this question.

2.2. Experimental design

In this study, we use a combination of numerical models and the cropland suitability analysis described above. The major component of our analysis is a coupled climate–vegetation model — CCM3/IBIS (the National Center for Atmospheric Research (NCAR) Community Climate Model, coupled to the University of Wisconsin's Integrated Biosphere Simulator) (Delire et al., 2002). This model is described in greater detail in the next section. We ran two separate simulations with the coupled climate–vegetation model forced with two different boundary conditions for the land cover — modern vegetation cover and potential natural vegetation cover (Figs. 2, 3). Potential natural vegetation (PNV) cover is derived from a study by Ramankutty and Foley (1999). PNV represents the vegetation that would exist in a location in the absence of human intervention. We resampled the PNV map, originally at 0.5° resolution, to the Gaussian T31 resolution of CCM3/IBIS (approximately 3.75° × 3.75°). Modern vegetation cover is derived here by overlaying the Ramankutty and Foley (1998) global cropland data set over the PNV data set, and replacing natural vegetation with croplands wherever croplands dominate. To do this, we also convert the "continuous" fractional croplands map at 0.5° resolution to a Boolean croplands map at T31 resolution by using an approach described in McGuire et al. (2001).

Crops have replaced tropical, temperate and mixed forest, savanna, shrubland and grassland (Fig. 3) and alter the land surface properties that can affect climate (Snyder et al., 2004a). Crops are shorter than trees, and therefore decrease surface roughness thereby affecting turbulence. They usually have lower leaf and stem area indices compared to trees and can be snow covered in winter. As a result, the surface albedo (the fraction of sunlight reflected by the surface) is usually higher in croplands compared to natural vegetation. Finally, crops, especially the newly bred varieties used in the developed countries, tend to have higher stomatal conductances than natural vegetation.

Because our CCM3/IBIS model does not explicitly represent croplands, in this study we use grasslands to represent croplands. This is an approximation, because cultivated ecosystems differ from grasslands in multiple ways, including their physiognomic, physiologic, and management characteristics. For example, Twine et al. (2004) concluded that the changes in energy and water balance at the land surface depends on the season, the crop type (including whether it is spring, summer, or winter crop), the management practice, and the type of natural vegetation being replaced. Chase et al. (1999) suggested that conversion of grasslands in the plains of northern Colorado to agricultural land may have altered the weather in the plains and in the adjacent mountains. However, in general, it is likely that grasses as imple-

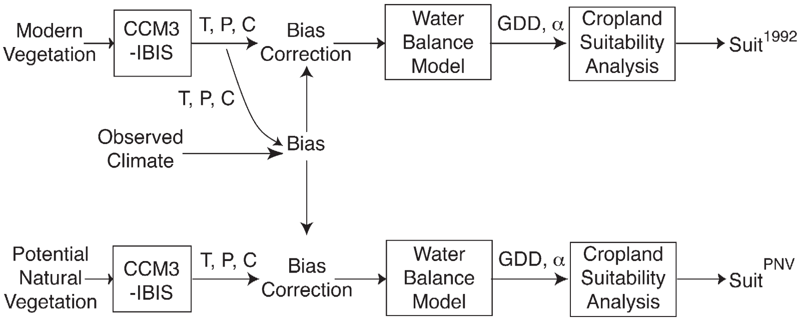

Fig. 2. Flow chart showing the experimental design used in this study. The modern vegetation simulation is run first. The climate model bias calculated from this run is then used in the potential natural vegetation run. Monthly output from the climate model — temperature (T), precipitation (P), and cloudiness (C) — are fed into the water balance model after being bias corrected. The output from the water balance model — Growing Degree Days (GDD) and the ratio of actual to potential evapotranspiration (α) is then used by the cropland suitability analysis.

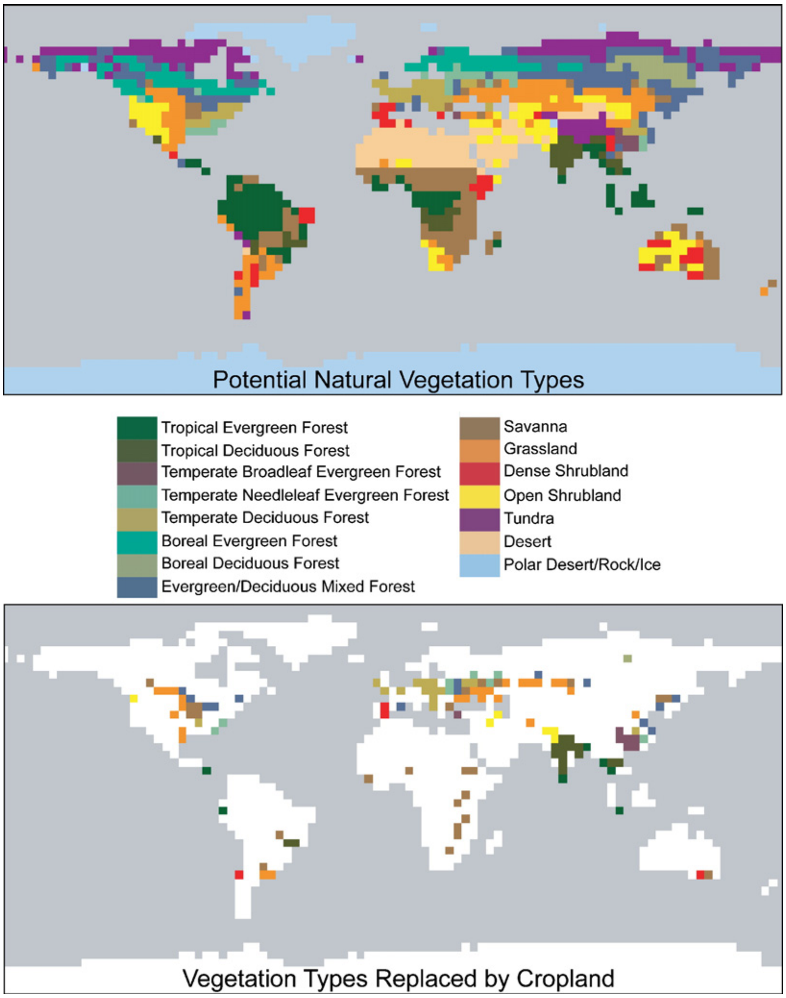

Fig. 3. (top panel) The global potential natural vegetation data set derived by Ramankutty and Foley (1999). The data set describes the spatial patterns of 15 major natural vegetation types. Here we show the data at the T31 Gaussian resolution used by the CCM3/IBIS model. (bottom panel) Map showing the global distribution of croplands at T31 resolution, in Boolean format. The colors indicate the vegetation types that are replaced by croplands in the Modern Vegetation simulation (see Fig. 2). Please note that because we represent croplands using grasslands in this study, the grassland to cropland conversions should be ignored.

mented in IBIS comes closest to the behavior of croplands in terms of the different ways in which the vegetation affects the atmosphere. Similar to crops, grasses are shorter than trees, have lower leaf and stem area indices and can be snow covered. Moreover, the focus of this study was not to *predict* climate, but rather to analyze the sensitivity of the ecosystem service offered by the coupled climate–vegetation system to perturbations in the land surface.

In this study, we run the CCM3/IBIS model at T31 Gaussian resolution. The models are run with prescribed climatological sea surface temperatures, and with prescribed land cover as described above. The coupled model is run for 15 years and the last 10 years of the simulated climate data is used in this study (the first 5 years are neglected because they represent the climate model spinup, to allow the model to overcome the influence of initialization and achieve dynamic equilibrium). The simulated years do not correspond to a specific calendar period, but rather are generic with identical boundary conditions for every year of simulation, and provide a measure of model interannual variability. The output of the climate model runs (monthly-mean temperature, precipitation, and cloudiness) are then "bias corrected" in order to account for well-recognized errors in climate model simulations (Fig. 2)(Chen et al., 2000). The bias correction adjusts the climate model output from the modern vegetation run to statistically match the observed climate data (CRU05 data set of New et al. (1999, 2000)). The same bias (or error) estimated from the modern vegetation cover run is then used to correct the climate from the potential vegetation run (the bias correction is explained in detail later). The simulation with modern vegetation cover is run first because of the need to estimate the climate model bias.

The bias corrected climate output from the last 10 years of the simulation is then fed into a simple water balance model (described in detail below) to derive estimates of Growing Degree Day (GDD) and α (the ratio of actual to potential evapotranspiration). The GDD and α values are used to estimate land suitability for cultivation for 10 years. The soil characteristics C_{soil} and $\mathrm{pH}_{\mathrm{soil}}$ are left unchanged between the two simulations. We then calculate an average suitability over the 10-year period. Because the climate of the modern-day simulation is bias corrected to match the present-day climate, the cropland suitability estimated from this simulation is nearly identical to that estimated from observed climate (shown in Fig. 1). The second simulation performed using PNV provides us an estimate of the climate that existed before the onset of agriculture, and the corresponding land suitability for cultivation for the pre-agriculture time (not shown). The difference between the suitability estimates from the two simulations provides us with an estimate of how the climate-derived ecosystem service for cultivation has been changed due to the very fact of cultivation (Fig. 4). We also estimate the statistical significance (at the 95% confidence level) of the change in cropland suitability by adapting the Pool-Permutation Procedure (PPP) of Preisendorfer and Barnett (1983) by applying it to each grid cell. PPP constructs a reference distribution from random samples of the input data sets themselves, and overcomes the limitation of standard methods that assume a normal, student-*t*, chi-square or other distributions.

The CCM3/IBIS model operates using a Gaussian grid at T31 resolution, while the land cover data, climate data, and soils data are at 0.5° in latitude by longitude resolution. This requires interpolation when we pass variables between the various models. We chose to calculate land suitability for cultivation at 0.5° resolution and we interpolate input data to the climate model (land cover) to T31 resolution, and interpolate climate model output to 0.5° resolution.

2.3. Coupled climate–vegetation model

CCM3/IBIS uses the National Center for Atmospheric Research (NCAR) Community Climate Model version 3 (CCM3, Kiehl et al., 1998) for its atmospheric component and an updated version of the Integrated Biosphere Simulator (IBIS) of Foley et al. (1996) and Kucharik et al. (2000) for the vegetation component. CCM3 was coupled to IBIS and used to simulate the present-day climate (Delire et al., 2002), the carbon cycling in vegetation and soil (Delire et al., 2003), to study the importance of individual vegetation types on climate (Snyder et al., 2004a) and the effects of vegetation dynamics on climate variability (Delire et al., 2004).

CCM3 (version 3.6) is a fully dynamic numerical model of the atmospheric general circulation with spectral representation of the horizontal fields. It simulates the large-scale physics (radiative transfer, hydrologic cycle, cloud development, thermodynamics) and dynamics of the

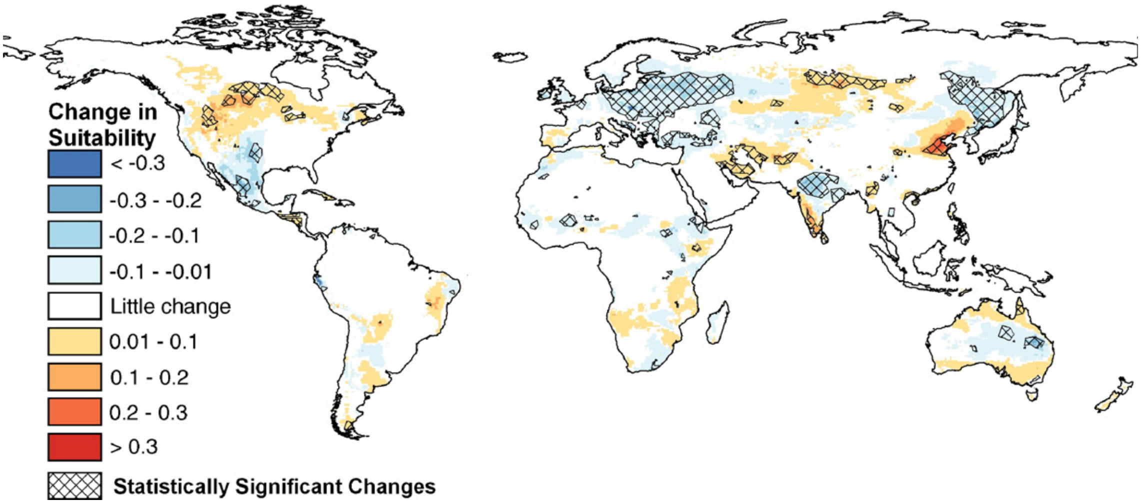

Fig. 4. Suitability from the Modern Vegetation run minus suitability estimated for the Potential Natural Vegetation condition. The changes in suitability that are significant at the 95% level, calculated using the Pool Permutation Procedure (see text), are indicated by the cross hatching.

atmosphere, using a set of "primitive equations" (a modified form of the Navier–Stokes equations of fluid dynamics). We ran the model at a resolution of T31 (the spectral representation of the horizontal fields is truncated at the 31st wavenumber using a triangular truncation; horizontal fields are converted to a ~ 3.75° × 3.75° grid). The model has 18 levels in the vertical and operates at a 20-minute timestep. The oceans are represented by monthly averaged fixed sea-surface temperatures that serve as boundary conditions for the atmosphere.

IBIS (version 2) is a global model of terrestrial biospheric processes, and simulates land-surface physics (the exchange of water, energy and momentum between the soil, the vegetation and the atmosphere), canopy physiology (photosynthesis and respiration), plant phenology (budburst and senescence), vegetation dynamics (accumulation and turnover of carbon, and competition between plant functional types), and carbon cycling for natural vegetation. In the simulations presented here IBIS operates on the same T31 spatial grid as the CCM3 atmospheric model and uses a constant vegetation map as the boundary condition. The vegetation dynamics module is not called and competition between plant functional types is not simulated. A complete description of the model can be found in Foley et al. (1996) and Kucharik et al. (2000).

IBIS was explicitly designed to work within atmospheric models. IBIS includes a land surface module based on the LSX land surface package (Thompson and Pollard, 1995a,b) that simulates the essential characteristics of the land-atmosphere interactions important for the climate (Bonan, 1997). These are mainly (i) the surface albedo (the fraction of solar radiation reflected by the land surface) affecting the energy balance, and (ii) the partitioning of net radiation into sensible heat loss and latent heat loss (cooling by evapotranspiration). These two heat fluxes depend on multiple characteristics of the soil and vegetation. Soil hydraulic properties, vegetation density, leaf phenology and stomatal physiology all affect evapotranspiration. The height and density of the vegetation also influence the surface roughness, affecting the efficiency of the sensible heat flux and latent cooling.

2.3.1. Climate model bias correction

Since our study is performed in a "modeling world" we have to deal with some of the deficiencies inherent in the models. Our first simulation using the coupled CCM3/IBIS model is forced with an estimate of modern land cover as boundary condition. The simulated climate, which should be representative of present-day conditions, has a bias in comparison to observed climate data. This type of climate simulation bias is well known and is normally corrected when performing experiments using the model results (Chen et al., 2000). Climate model bias correction is also routinely used when simulating paleo-environments, in comparing the simulation results to paleo-data (e.g., François et al., 1998; Braconnot, 2000). Here we compare the model simulated temperature, precipitation and cloudiness data to the observed CRU05 climate data over the 1961–1990 period from New et al. (2000), and apply a bias correction such that the means and standard deviations of the simulated climate match the observed for the present day simulation. The bias corrections are applied separately for each of the 12 months.

Let Obs(i,y,m), for grid cell i, y = 1961, 1962,…, 1990; for month m; be the observed monthly-mean climate data (of temperature, precipitation, and cloudiness) for years 1961 to 1990 from New et al. (2000). μ_{obs} (i,m) is the mean and σ_{obs} (i,m) is the interannual standard deviation of the observed climate data for each month over the 1961–1990 period.

Let Sim92(i,y,m), for grid cell i, y = 1, 2,…, 10 years of simulation; for month m; be the model simulated monthly-mean climate data for years 6 to 15 from the modern vegetation cover run. μ_{sim92} (i,m) is the mean and σ_{sim92} (i,m) is the interannual standard deviation of the simulated climate data over the 10 year period. Similarly, let SimPNV(i,y,m) be the model simulated data for years 6 to 15 from the control run with potential natural vegetation, and μ_{PNV} (i,m) be the mean and σ_{PNV} (i,m) be the standard deviation of this data set.

The bias correction for the modern vegetation run is given by

$$\mathrm{Sim92}'(i,y,m) = \frac{\mathrm{Sim92}(i,y,m) - \mu_{\mathrm{sim92}}(i,m)}{\sigma_{\mathrm{sim92}}(i,m)}\sigma_{\mathrm{obs}}(i,m) + \mu_{\mathrm{obs}}(i,m).$$

This bias correction ensures that the means and standard deviations of the simulated climate from the modern vegetation cover run matches that of the observed climate data, applied separately for each month.

The bias correction for the PNV run is given by

$$\mathrm{SimPNV}'(i,y,m) = \frac{\mathrm{SimPNV}(i,y,m) - \mu_{\mathrm{sim92}}(i,m)}{\sigma_{\mathrm{sim92}}(i,m)}\sigma_{\mathrm{obs}}(i,m) + \mu_{\mathrm{obs}}(i,m).$$

Thus, for the PNV run, the same bias correction is applied as for the modern vegetation run. Note that the bias correction method still allows the climate to change since it is simply removing the bias inherent in the model, but not the change due to the differences between the two experiments.

2.4. The simple water balance model

To calculate GDD and α, we use a very simple surface energy and water balance model (Prentice et al., 1993; Foley, 1994; Haxeltine and Prentice, 1996). The model is driven using observed data on monthly-mean surface air temperature, precipitation, and potential sunshine hours (New et al., 1999). The monthly-mean climate data are linearly interpolated to derive daily-mean values. The model uses a daily time step (except for evapotranspiration which is calculated quasi-hourly).

GDD is calculated as the annual accumulation of daily mean temperatures (T_i) over a base temperature of 5 °C, i.e.,

$$\mathrm{GDD} = \sum_{i=1}^{365} \max(0, T_i - 5)\mathrm{day}-\oint C.$$

The availability of water to plants is expressed using a moisture index,

$$\alpha = \frac{\mathrm{AET}}{\mathrm{PET}},$$

where AET is the actual evapotranspiration, which is the quantity of water that is actually removed from the land surface through evaporation and transpiration, while PET, the potential evapotranspiration, indicates the ability of the atmosphere (through its radiative energy demand, winds, etc.) to remove water from the surface. Therefore, the ratio of the two terms is an indication of the level of moisture stress in a given region. These terms are functions of soil moisture (calculated using a simple bucket model) and net radiation, and are calculated following Monteith (1995) and Prentice et al. (1993). (See Ramankutty et al. (2002) for more details.)

In this study, we ran the water balance model for 15 years forced with climate output from the CCM3/IBIS model (after bias correction). We used results from the last 10 years in our analysis. Note that the simple water balance model is only used as a diagnostic tool to calculate the GDD and α values that are inputs to the estimate of land suitability for cultivation. As noted earlier, for the actual climate change simulations, the comprehensive ecosystem model, IBIS, is used as the land surface package, as it is coupled to the CCM3 model. In other words, the semi-empirical cropland suitability analysis incorporating the simple water balance model is used only to *diagnose* how the climate-vegetation feedbacks influence land suitability for cultivation; the feedbacks themselves are simulated using the comprehensive CCM3/IBIS model.

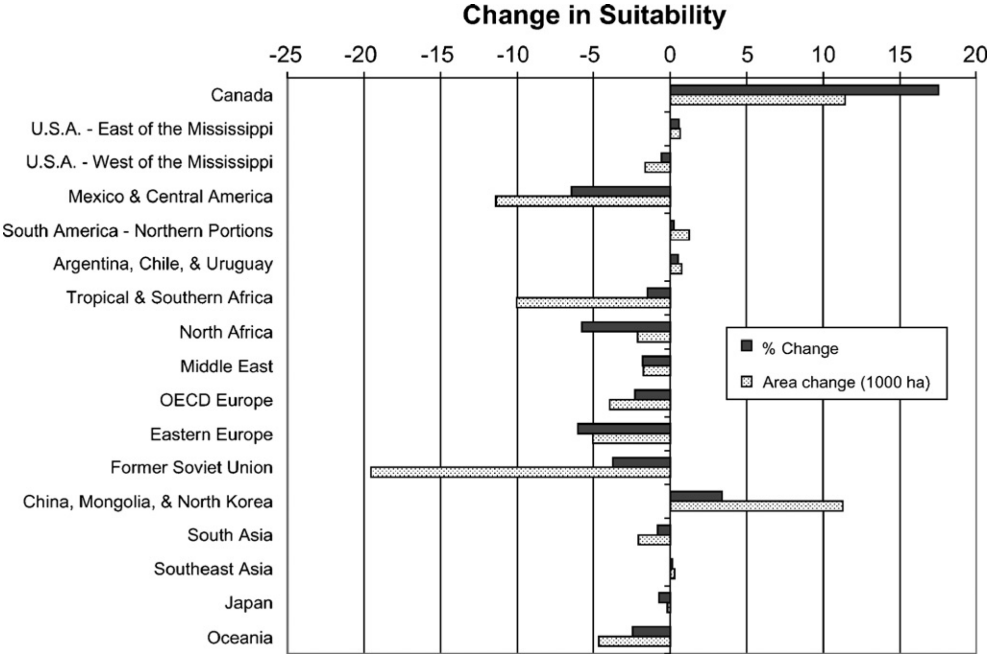

Fig. 5. Changes in suitability averaged over 17 different regions of the world. Both the actual changes in suitable area (in 1000 ha), as well as the percent change for each region are shown.

3. Results

We find that replacing natural vegetation with present-day croplands might have resulted in increased land suitability for cultivation in some parts of the world and decreased suitability in others (Figs. 4, 5; statistical significance of the changes are calculated using the PPP). Globally, cropland suitability decreases by ~ 0.9%. The largest change in suitability is found over Canada, with a ~ 18% increase in suitability. The largest decreases, of ~ 6%, occur over northern and Eastern Europe (from Denmark to the Ural Mountains and southern Finland to Turkey and the Caspian sea), and over Mexico and central America. The other regions of the world with significant increases in suitability are Mountain-West USA, central America, northern Kazakhstan and Southern Siberia West of Lake Baikal, portions of Iran and Afghanistan, western India, northern Myanmar, and the North China Plain. The other regions of the world with decreases in cropland suitability are the U.S. Great Plains, northern Mexico, the Sahel, Ireland, northern India, Manchuria and eastern Australia. In general, South America and Africa have relatively small areas of cropland suitability change.

Next, we analyze the reasons for the changes in suitability. In general, we find that changes in Northern Hemisphere high latitude regions are related to changes in GDD, while changes elsewhere are related to changes in α (Fig. 6; Table 1). This makes intuitive sense because, in general, cultivation in the Northern Hemisphere high latitudes is temperature limited, while cultivation in the tropics and subtropics is moisture limited. Changes in GDD are directly related to changes in temperature during the spring and summer season (vegetation cover does not play much of a role in the winter because of low levels of incoming solar radiation), while changes in α result indirectly from changes in precipitation and the evaporative demand of the atmosphere (the latter is a function of net radiation, and therefore temperature and cloudiness as well). Changes in climate in a region can be the result of the local changes in land cover or can arise from non-local effects caused by shifts in the general circulation of the atmosphere (Henderson-Sellers et al., 1993; Sud et al., 1996; Gedney and Valdes, 2000; Snyder et al., 2004a,b). Indeed, we find that while suitability changes in some regions can be explained by local changes in land cover, there are other regions that experience suitability change with no local land cover changes. Furthermore, there are also a few regions with large land cover change, but no local suitability change (Table 1). In the next several subsections, we discuss suitability changes in detail, region-by-region, except for South America (while some statistically significant changes in suitability are seen over South America, they are not extensive).

3.1. Suitability changes in North America

The temperature increase over Canada occurs in summer and fall, and is likely related to the replacement of mixed forests in Canada and savannas in the Mid-western USA by croplands. This results in increased albedo and decreased net radiation. This would normally result in a cooling, but in our model, there is an additional effect of reduced transpiration as well as reduced intercepted evaporation from crops compared to savannas, leading to a decrease in the latent cooling from the surface. This reduced heat loss from the surface exceeds the

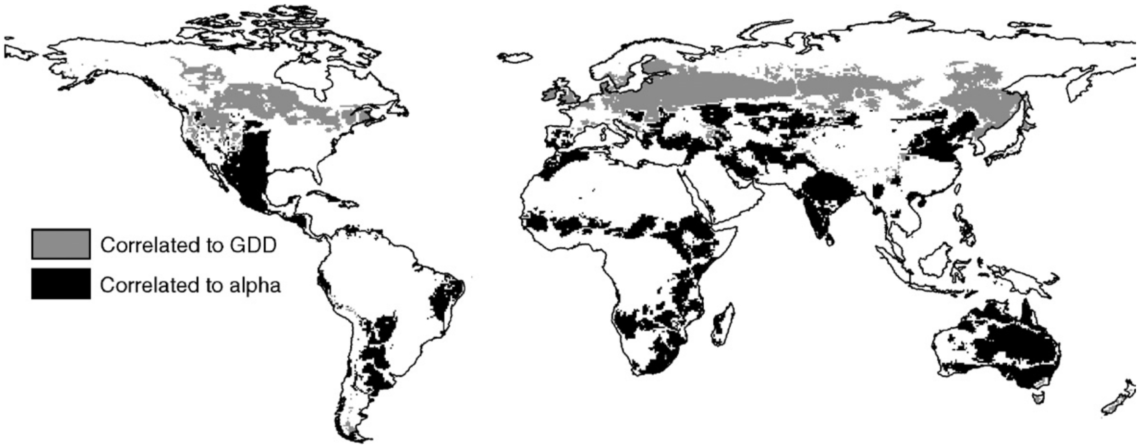

Fig. 6. Correlation analysis between changes in suitability and changes in α and GDD. This plot shows the regions of the world where the correlation between changes in suitability and changes in f_1 (GDD) over the 10 years of simulation are greater than 0.9 (shaded grey), or where the correlation between changes in suitability and changes in f_2 (α) are greater than 0.9 (shaded black). Regions of the world where suitability change is less than 0.01 in magnitude are masked out (as in Fig. 4).

Table 1
Suitability change in different regions of the world

Regions of the world with suitability change	Suitability change	GDD change	Alpha change	Origin of change
Canada	+ve	+ve		Local/non-local
Mountain-west USA	+ve	+ve		Non-local
U.S. Great Plains and Mexico	−ve		−ve	Non-local
Ireland and Eastern Europe	−ve	−ve		Local
Western Siberia	+ve	+ve		Non-local
Turkey	−ve		−ve	Non-local
Northern India	−ve		−ve	Local
Western India	+ve		+ve	Local/non-local
Iran/Afghanistan	+ve		+ve	Non-local
North China Plain	+ve		+ve	Local/non-local
Manchuria	−ve	−ve		Local
Sahel and East Africa	−ve		−ve	Local
Central and E. Australia	−ve		−ve	Non-local
Regions with land cover change, but no suitability change				
Midwestern U.S., Southeast U.S., Southeast Brazil, Southern China, Indochina Peninsula, Java				

cooling effect of increased albedo and causes a surface temperature increase. The temperature increase extends to the north, south and west of the deforested region (to Mountain-West USA); the mechanisms are yet unknown.

This result is contrary to that of Bonan, 1999, who found a regional cooling in summer and autumn associated with replacing temperate forests in the U.S. with croplands. His study showed increased albedo, decreased roughness length, leaf and stem area and increased stomatal conductance in the grid cells where crops replaced forests. As a result, net radiation decreased and was compensated for by a decrease in sensible heat flux, resulting in surface cooling. Therefore, while both studies found a decrease in net radiation due to cropland expansion, the major difference arises from whether the compensating effect is decreased latent cooling (our study) or decreased sensible heat flux (Bonan, 1999). It is possible that the decreased latent heat flux in our model is an artifact of the way we represent crops using grasslands as a proxy — our crops transpire less than savannas, while in reality crops may transpire more in the summer months (Twine et al., 2004). These contrasting outcomes show the need for caution in interpreting these model results.

The reduced suitability in Northern Mexico and the American Great Plains is due to reduced precipitation and decreased α in fall and increased temperatures year-round that seem to be due to non-local effects from vegetation changes elsewhere. Indeed, it appears as if the replacement of savanna by croplands in the Midwestern U.S. may be leading to temperature increase in the surrounding regions (leading to increased GDD in Canada and Mountain-West USA), and decreased rainfall to the west and south (leading to decreased α in Northern Mexico and the Great Plains) (supporting figures not shown). But we cannot rule out the possibility that the climatic changes observed in these regions are due to global teleconnections (changes in the general circulation of the atmosphere resulting from the land cover changes elsewhere).

3.2. Suitability changes in Europe and Former Soviet Union

In the British Isles and Europe, there is extensive cooling in spring and summer due to two different effects. The replacement of temperate forests that absorb solar radiation with crops that can be snow covered in the spring results in increased albedo, and therefore lower net radiation and reduced surface temperatures. Secondly, the lower roughness of crops also leads to decreased sensible heat transfer, which is consistent with lower surface temperatures. In essence, the reduced net radiation is compensated for through a reduction in sensible heat flux and reduced surface temperatures. Furthermore, the reduced surface temperature creates a shallower boundary layer, which increases cloudiness and further decreases net radiation and surface temperature (see Delire et al., 2002; Snyder et al., 2004a).

In addition to these local changes, we also find in our model that the local climate changes in Europe results in a general alteration of the dynamics of the atmosphere in the Northern Hemisphere high latitudes affecting climates in other regions. This shift in the tropospheric dynamics deepens the existing low pressure system over Europe in Northern Hemisphere spring and creates enhanced cyclonic flow over the region (Fig. 7), which also increases cloud cover. The enhanced cyclonic flow over Europe (centered on 60° N × 45° E) is responsible for the temperature increase over western Siberia, which is a result of warm air advection from the west and south of that region (Fig. 7)(Snyder et al., 2004a). We also see a decrease in suitability over Turkey due to reduced precipitation. In Northern Hemisphere winter, the prevailing winds over Turkey are off the Mediterranean, bringing moisture over the region. In our model simulation with croplands, we find a strong high pressure anomaly over

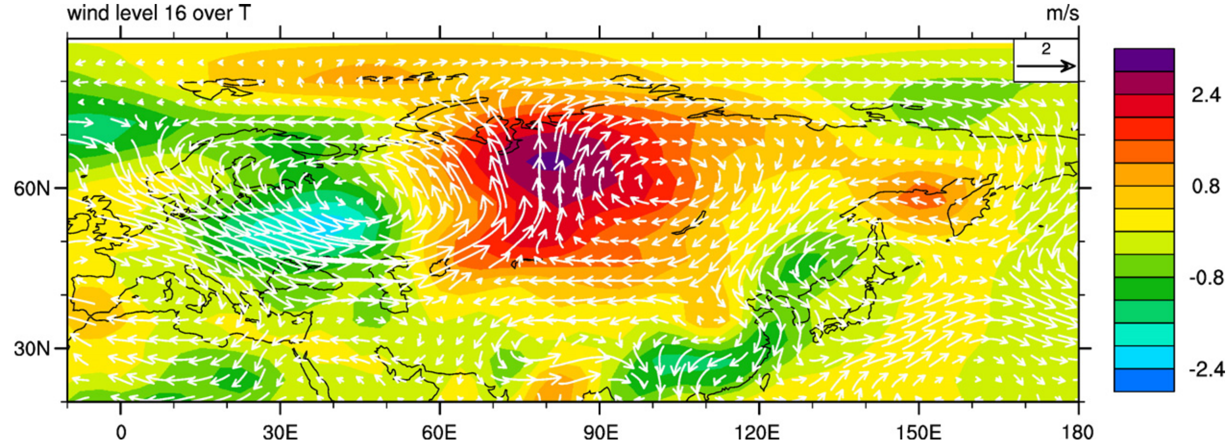

Fig. 7. Map showing wind speed anomalies plotted over temperature anomalies during March/April/May. The strong warm-air advection over Siberia from the south and west is clearly indicated by this plot.

the Atlantic, west of Spain. The anticyclonic flow anomaly associated with this high pressure anomaly weakens the winds off the Mediterranean over Turkey resulting in reduced moisture advection (supporting figure not shown), and reduced rainfall.

3.3. Suitability changes in Asia

The largest changes in α occur over India and the North China Plain. Deforestation in India results in reduced precipitation over the central and northeastern parts of the country. This is consistent with the results of deforestation studies in the tropics showing a decrease in convective activity following tropical deforestation due to increased albedo and reduced evapotranspiration (see extensive literature review in Bonan (2002)). The increase in precipitation in western India is a result of decreased roughness leading to increased moisture advection from the Arabian Sea (without increased advection, precipitation would have decreased as in northeastern India) (Snyder et al., 2004a). However, our model used climatologically prescribed sea surface temperatures (SSTs). If feedbacks from the ocean were included, the stronger winds would induce greater mixing of the thermocline bringing cooler water to the surface, resulting in cooler sea-surface temperatures. This would, through a negative feedback, limit evaporation over the Arabian Sea, and limit the convection and hence precipitation (Pickard and Emery, 1982; Delire et al., 2001). Thus our model simulation, due to the artifact of using fixed SSTs, may be over-estimating the moisture advection.

In the North China Plain, the replacement of mixed forest by crops results in increased precipitation in summer and fall, which increases α. When crops replace mixed forests in our model, the predominant effect is an increase in soil evaporation because more soil is now exposed. This increases the latent heat flux and therefore precipitation. In addition, we also find an additional effect of decreased surface roughness, and increased moisture convergence over the region (supporting figure not shown), which also increases the rainfall. Therefore, the essential result of replacing mixed forest with croplands is an enhancement of the hydrological cycle in the region. Over Manchuria, we see a cooling which is a result of the increased albedo and increased cloudiness — the same local mechanisms as over Europe. This cooling reduces GDD and hence the suitability.

Other regions with suitability changes are in Iran and Afghanistan, where suitability increases as a result of increased precipitation due to non-local vegetation changes, but the detailed mechanisms for this change are unclear.

3.4. Suitability changes in Africa and Australia

In the Sahel region and in East Africa, the removal of savanna for cultivation results in reduced convection, decreased rainfall in spring and summer, and slightly reduced α. This is consistent with studies of the role of land cover on the climate of the region (Charney, 1975; Zeng et al., 1999; Nicholson, 2000; Wang and Eltahir, 2000a,b). The decrease in suitability over Australia is also non-local — again the mechanisms are unclear, but we speculate that the land cover conversion in tropical Africa and Asia is disrupting the meridional Walker circulation. These results may also be a spurious result of the model variability, and inadequacy of our statistical tests.

3.5. Land cover change without suitability change

The regions of the world with significant land cover change, but no local suitability changes are southeastern U.S., Midwestern U.S. (changes here seem to influence climate non-locally, to the north, west, and south), southern China, the Indochina Peninsula and Java, and southeast Brazil. In the latter four regions, deforestation for agriculture did lead to increased precipitation according to our model. However, as these regions already experience high rainfall, the enhanced precipitation did not increase suitability; in other words, suitability for cultivation in these regions is not limited by rainfall.

4. Discussion and conclusions

This study illustrates some of the potential feedbacks that might have resulted from climate–vegetation interactions, due to human agricultural activities. When humans modified the landscape by clearing natural vegetation to grow crops, the resultant land cover change might have modified the climate in such a way that it altered the land suitability for cultivation. Although this study showed that the global changes in cropland suitability are quite small, it also indicated that large regional changes in suitability might have occurred. In particular, we found that Canada, Eastern Europe, the Former Soviet Union, northern India, and China are the regions where the largest changes in suitability occurred. Canada and western Siberia had the greatest increases in suitability, while Eastern Europe, Manchuria, northern India, and Mexico had the greatest decreases in suitability. Our study also showed some significant changes in climate that were not associated with local land cover changes. These changes may be the result of modifications to the general circulation of the atmosphere caused by vegetation changes elsewhere. Moreover, there were several regions with local land cover changes, but no local suitability change. Some of these regions are not temperature or water limited, and this might explain the lack of sensitivity of cropland suitability.

The magnitude and the sign of suitability change as well as the details of the spatial patterns shown in this study could be an artifact of the particular models we used and our particular experimental setup. We used the Pool-Permutation Procedure suggested by Preisendorfer and Barnett (1983), an improvement over standard *t*-tests, to test for the statistical significance of our results. Nevertheless, our specific results have to be treated with caution. Future work should include numerous ensemble simulations, with slightly different initial conditions, to test for the robustness of these results.

Our study focused on one specific component of the relationship between agriculture and climate — that of the influence of agricultural land cover (through changes in surface energy balance) on climate. However, there are numerous uncertainties that preclude these results from being generalized. An important omission from this study has been the representation of irrigation (e.g., de Rosnay et al., 2003), although an empirical study in the Great Plains suggested that the magnitude of this effect may be small (Moore and Rojstaczer, 2001). Future improvements on this study should include better representation of cultivated systems (e.g., Kucharik, 2003; Scholze et al., 2005), including various crop types and their productivity, the influence of grazing, reforestation, and other land use practices, nitrogen deposition, the effects on climate through changes in atmospheric chemistry resulting from land cover change, as well as the changes in suitability arising from changes in soil properties (assumed to not change in this study). These various modeling assumptions could also define a more complete uncertainty analysis to test for the robustness of the results.

Nevertheless, our study is illustrative and outlines an important issue for future research consideration. It demonstrates a methodology to assess the sensitivity of ecosystem services to land-use induced climate change at the global scale. It addresses an important question: *While deriving resources from the environment through our land use practices, are we inadvertently undermining the very ecosystem services that offered us those resources in the first place?*

This study also provides a different perspective for evaluating climate change. Traditionally, climate and climate change has been viewed from a purely biophysical perspective, i.e., variables such as temperature, precipitation, humidity, wind speeds, etc., and many derived diagnostic thereof (Houghton et al., 2001). However, evaluating climate and its change, as relevant to human societies, needs to be critically tied to the concept of the "ecosystem services" (Daily et al., 1997). In this study, we offer the concept of "land suitability for cultivation" as one such measure of climate, as it is relevant to the global food production system. We have used change in this suitability index, rather than climatic variables such as temperature and precipitation, to measure how human modifications of the landscape, mediated through climate–vegetation interactions, may potentially affect human food production capacities.

This study could be further extended to examine the influence of human activities on a whole suite of ecosystem services. With respect to provisioning services, the analysis is fairly straightforward — for example, when we derive timber from forests, we reduce the stock of timber in a directly quantifiable manner. The analysis is more difficult when we consider the supporting and regulating services such as climate regulation, water quality regulation, biodiversity, soil formation, nutrient cycling, etc. In the latter situation, most of the consequences of land use occur indirectly, through feedbacks, and can include non-linear effects. New methodologies, tools, and analysis techniques need to be developed to fully understand the consequences of human activities for the long-term sustainability of natural resources.

Acknowledgments

We would like to thank Drs. Steve Vavrus, Tracy Twine, and Jon Foley for their thoughtful suggestions regarding this work. Three anonymous referees and Dr. Thomas Stohlgren made very constructive comments that led to substantial revisions and improvement of this manuscript. This work was supported by the NASA's Office of Earth Science (through Interdisciplinary Science (IDS) Program grant NAG5-9452) and by a grant from the McDonnell foundation. We would like to thank the Land Use and Land Cover Change (LUCC) program for being supportive of such global-scale research on land use change.

References

Alexandratos, N., 1995. World Agriculture Towards 2010. Food and Agriculture Organization of the United Nations, Rome. 488 pp.

Baidya Roy, S., Hurtt, G.C., Weaver, C.P., Pacala, S.W., 2003. Impact of historical land-use/land-cover change on the July climate of the United States. Journal of Geophysical Research 108, 4793. doi:10.1029/2003JD003565.

Betts, R.A., 1999. The impact of land use on the climate of present day. In: Richie, H. (Ed.), Research Activities in Atmospheric and Oceanic Modelling, CAS/JSC WGNE Report. World Meteorological Organization, Geneva, pp. 7.11–7.12.

Bonan, G.B., 1997. Effects of land use on the climate of the United States. Climatic Change 37, 449–486.

Bonan, G.B., 1999. Frost followed the plow: impacts of deforestation on the climate of the United States. Ecological Applications 9 (4), 1305–1315.

Bonan, G., 2002. Ecological Climatology: Concepts and Applications. Cambridge University Press, Cambridge. 690 pp.

Bonan, G.B., Pollard, D., Thompson, S.L., 1992. Effects of boreal forest vegetation on global climate. Nature 359, 716–718.

Bounoua, L., DeFries, R., Collatz, G.J., Sellers, P., Khan, H., 2002. Effects of land cover conversion on surface climate. Climatic Change 52 (1–2), 29–64.

Box, E.O., 1981. Macroclimate and Plant Forms: An Introduction to Predictive Modeling in Phytogeography. Dr. W. Junk Publishers, Berlin.

Braconnot, P., 2000. Paleoclimate Modeling Intercomparison Project (PMIP). Proceedings of the Third PMIP Workshop. WCRP-111, WMO/TD-1007, Canada.

Brovkin, V., Claussen, M., Petoukhov, V., Ganopolski, A., 1998. On the stability of the atmosphere–vegetation system in the Sahara/Sahel region. Journal of Geophysical Research–Atmospheres 103 (D24), 31613–31624.

Brovkin, V., Ganopolski, A., Claussen, M., Kubatzki, C., Petoukhov, V., 1999. Modelling climate response to historical land cover change. Global Ecology and Biogeography 8 (6), 509–517.

Buringh, P., Dudal, R., 1987. Agricultural Land Use in Space and Time. In: Fournier, F.G.A. (Ed.), Land Transformation in Agriculture. John Wiley & Sons, Chichester, pp. 3–43.

Charney, J.G., 1975. Dynamics of deserts and drought in the Sahel. Quarterly Journal of the Royal Meteorological Society 101, 193–202.

Chase, T.N., Pielke Sr., R.A., Kittel, T.G.F., Baron, J.S., Stohlgren, T.J., 1999. Potential impacts on Colorado Rocky Mountain weather due to land use changes on the adjacent Great Plains. Journal of Geophysical Research 104 (D4), 16673–16690.

Chase, T.N., Pielke, R.A., Kittel, T.G.F., Nemani, R.R., Running, S.W., 2000. Simulated impacts of historical land cover changes on global climate in northern winter. Climate Dynamics 16, 93–105.

Chen, D., Cane, M.A., Zebiak, S.E., Canizares, R., Kaplan, A., 2000. Bias correction of an ocean–atmosphere coupled model. Geophysical Research Letters 27, 2585–2588.

Cooley, H.S., Riley, W.J., Torn, M.S., He, Y., 2005. Impact of agricultural practice on regional climate in a coupled land surface mesoscale model. Journal of Geophysical Research–Atmospheres 110 (D3).

Copeland, J.H., Pielke, R.A., Kittel, T.G.F., 1995. Potential climate impacts of vegetation change: a regional modeling study. Journal of Geophysical Research 101, 7409–7418.

Costa, M.H., Foley, J.A., 1999. Combined effects of deforestation and doubled atmospheric CO_2 concentrations on the climate of Amazonia. Journal of Climate 13 (1), 18–34.

Cramer, W.P., Solomon, A.M., 1993. Climatic classification and future global redistribution of agricultural land. Climate Research 3, 97–110.

Daily, G.C. (Ed.), 1997. Nature's Services: Societal Dependence on Natural Ecosystems. Island Press, Washington, D.C. 392 pp.

Daily, G., Alexander, S., Ehrlich, P., Goulder, L., Lubchenco, J., Matson, P., Mooney, H., Postel, S., Schneider, S., Tilman, D., Woodwell, G., 1997. Ecosystem services: benefits supplied to human societies by natural ecosystems. Issues in Ecology 2, 1–18.

de Rosnay, P., Polcher, J., Laval, K., Sabre, M., 2003. Integrated parameterization of irrigation in the land surface model ORCHIDEE. Validation over Indian Peninsula. Geophysical Research Letters 30 (19).

Delire, C., Behling, P., Coe, M.T., Foley, J.A., Jacob, R., Kuzbach, J., Liu, Z., Vavrus, S., 2001. Simulated response of the atmosphere–ocean system to deforestation in the Indonesian Archipelago. Geophysical Research Letters 28 (10), 2081–2084.

Delire, C., Levis, S.L., Bonan, G., Foley, J.A., Coe, M.T., Vavrus, S., 2002. Comparison of the climate simulated by the CCM3 coupled to two different land-surface models. Climate Dynamics 19 (8), 657–669. doi:10.1007/s00382-002-0255-7.

Delire, C., Foley, J.A., Thompson, S., 2003. Evaluating the carbon cycle of a coupled atmosphere–biosphere model. Global Biogeochemical Cycles 17 (1), 1012. doi:10.1029/2002GB001870.

Delire, C., Foley, J.A., Thompson, S., 2004. Long-term variability in a coupled atmosphere–biosphere model. Journal of Climate 17 (20), 3947–3959.

Fischer, G., H. van Velthuizen, Nachtergaele, F. Medow, S., 2000. Global Agro-Ecological Zones (Global– AEZ) [CD-ROM and web site http://www.fao.org/ag/AGL/agll/gaez/index.htm]. Food and Agricultural Organization/International Institute for Applied Systems Analysis (FAO/IIASA).

Foley, J.A., 1994. Net primary productivity in the terrestrial biosphere: the application of a global model. Journal of Geophysical Research 99 (D10), 20773–20783.

Foley, J.A., Prentice, C.I., Ramankutty, N., Levis, S., Pollard, D., Sitch, S., Haxeltine, A., 1996. An integrated biosphere model of land surface processes, terrestrial carbon balance, and vegetation dynamics. Global Biogeochemical Cycles 10 (4), 603–628.

Foley, J.A., Costa, M.H., Delire, C., Ramankutty, N., Snyder, P., 2003. Green surprise? How terrestrial ecosystems could affect earth's climate. Frontiers in Ecology and the Environment 1 (1), 38–44.

François, L.-M., Delire, C., Warnant, P., Munhoven, G., 1998. Modelling the glacial–interglacial changes in the continental biosphere. Global and Planetary Change 16–17, 37–52.

Fu, C., 2003. Potential impacts of human-induced land cover change on East Asia monsoon. Global and Planetary Change 37, 219–229.

Gedney, N., Valdes, P.J., 2000. The effect of Amazonian deforestation on the northern hemisphere circulation and climate. Geophysical Research Letters 27 (19), 3053–3056.

Geist, H.J., Lambin, E.F., 2001. What drives tropical deforestation? A meta-analysis of proximate and underlying causes of deforestation based on subnational case study evidence. LUCC Report Series #4 Ciaco Press, Louvain-la-Neuve. 116 pp.

Govindasamy, B., Duffy, P.B., Caldeira, K., 2001. Land use changes and northern hemisphere cooling. Geophysical Research Letters 28 (2), 291–294.

Haxeltine, A., Prentice, C.I., 1996. BIOME3: An equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability, and competition among plant functional types. Global Biogeochemical Cycles 10 (4), 693–709.

Henderson-Sellers, A., Dickinson, R.E., Durbridge, T.B., Kennedy, P.J., McGuffie, K., Pitman, A.J., 1993. Tropical deforestation: modeling local-to regional-scale climate change. Journal of Geophysical Research 98 (D4), 7289–7315.

Holdridge, L.R., 1947. Determination of world plant formations from simple climatic data. Science 105, 367–368.

Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., Linden, P.J.v.d., Dai, X., Maskell, K., Johnson, C.A. (Eds.), 2001. Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge. 944 pp.

IGBP-DIS, 1998. SoilData (V.0): A Program for Creating Global Soil-Property Databases. IGBP Global Soils Data Task, France.

Kabat, P., Claussen, M., Dirmeyer, P.A., Gash, J.H.C., Bravo de Guenni, L., Meybeck, M., Pielke Sr., R.A., Vörösmarty, C.J., Hutjes, R.W.A., Lütkemeier, S. (Eds.), 2004. Vegetation, Water, Humans and the Climate: A New Perspective on an Interactive System. Springer, Berlin. 246 pp.

Kalnay, E., Cai, M., 2003. Impact of urbanization and land-use change on climate. Nature 423 (6939), 528–531.

Kiehl, J.T., Hack, J.J., Bonan, G.B., Boville, B.A., Williamson, D.L., Rasch, P.J., 1998. The National Center for Atmospheric Research Community Climate Model: CCM3. Journal of Climate 11 (6), 1131–1149.

Klein Goldewijk, K., 2001. Estimating global land use change over the past 300 years: the HYDE Database. Global Biogeochemical Cycles 15 (2), 417–433.

Kucharik, C.J., 2003. Evaluation of a process-based agro-ecosystem model (Agro-IBIS) across the U.S. cornbelt: simulations of the inter-annual variability in maize yield. Earth Interactions 7, 1–33.

Kucharik, C.J., Foley, J.A., Delire, C., Fisher, V.A., Coe, M.T., Lenters, J.D., Young-Molling, C., Ramankutty, N., Norman, J.M., Gower, S.T., 2000. Testing the performance of a dynamic global ecosystem model: water balance, carbon balance, and vegetation structure. Global Biogoechemical Cycles 14 (3), 795–825.

Leemans, R., Solomon, A.M., 1993. Modeling the potential change in yield and distribution of the Earth's crops under a warmed climate. Climate Research 3, 79–96.

Marshall, C.H., Pielke, R.A., Steyaert, L.T., 2003. Wetlands: crop freezes and land-use change in Florida. Nature 426 (6962), 29–30.

Matthews, H.D., Weaver, A.J., Meissner, K.J., Gillett, N.P., Eby, M., 2004. Natural and anthropogenic climate change: incorporating historical land cover change, vegetation dynamics and the global carbon cycle. Climate Dynamics 22, 461–479.

McGuire, A.D., Sitch, S., Clein, J.S., Dargaville, R., Esser, G., Foley, J., Heimann, M., Joos, F., Kaplan, J., Kicklighter, D.W., Meier, R.A., Melillo, J.M., Moore, B., Prentice, I.C., Ramankutty, N., Reichenau, T., Schloss, A., Tian, H., Williams, L.J., Wittenberg, U., 2001. Carbon balance of the terrestrial biosphere in the twentieth century: analyses of CO_2, climate and land use effects with four process-based ecosystem models. Global Biogeochemical Cycles 15 (1), 183–206.

Millennium Ecosystem Assessment, 2003. Ecosystems and Human Well-Being: A Framework for Assessment. Island Press, Washington, D.C. 245 pp.

Monteith, J.L., 1995. Accommodation between transpiring vegetation and the convective boundary layer. Journal of Hydrology 166, 251–263.

Moore, N., Rojstaczer, S., 2001. Irrigation-induced rainfall and the great plains. Journal of Applied Meteorology 40, 1297–1309.

Narisma, G.T., Pitman, A.J., 2003. The impact of 200 years of land cover change on the Australian near-surface climate. Journal of Hydrometeorology 4 (2), 424–436.

New, M.G., Hulme, M., Jones, P.D., 1999. Representing twentieth-century space–time climate variability. Part I: development of a 1961–90 mean monthly terrestrial climatology. Journal of Climate 12 (3), 829–856.

New, M., Hulme, M., Jones, P.D., 2000. Representing twentieth century space–time climate variability. II. Development of 1901–1996 monthly grids of terrestrial surface climate. Journal of Climate 13 (13), 2217–2238.

Nicholson, S., 2000. Land surface processes and Sahel climate. Reviews of Geophysics 38 (1), 117–139.

Pickard, G.L., Emery, W.J., 1982. Descriptive Physical Oceanography. Pergamon Press, New York. 249 pp.

Pielke, R.A., Marland, G., Betts, R.A., Chase, T.N., Eastman, J.L., Niles, J.O., Niyogi, D.D.S., Running, S.W., 2002. The influence of land-use change and landscape dynamics on the climate system: relevance to climate-change policy beyond the radiative effect of greenhouse gases. Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character 360 (1797), 1705–1719.

Pitman, A.J., Narisma, G.T., Pielke Sr., R.A., Holbrook, N.J., 2004. Impact of land cover change on the climate of southwest Western Australia. Journal of Geophysical Research 109, D18109. doi:10.1029/2003JD004347.

Preisendorfer, R.W., Barnett, T.P., 1983. Numerical model—reality intercomparison tests using small-sample statistics. Journal of Atmospheric Sciences 40, 1884–1896.

Prentice, C., Cramer, W., Harrison, S.P., Leemans, R., Monserud, R.A., Solomon, A.M., 1992. A global biome model based on plant physiology and dominance, soil properties and climate. Journal of Biogeography 19, 117–134.

Prentice, I.C., Sykes, M.T., Cramer, W., 1993. A simulation model for the transient effects of climate change on forest landscapes. Ecological Modelling 65, 51–70.

Ramankutty, N., Foley, J.A., 1998. Characterizing patterns of global land use: an analysis of global croplands data. Global Biogeochemical Cycles 12, 667–685.

Ramankutty, N., Foley, J.A., 1999. Estimating historical changes in global land cover: croplands from 1700 to 1992. Global Biogeochemical Cycles 13, 997–1027.

Ramankutty, N., Foley, J.A., Norman, J., McSweeney, K., 2002. The global distribution of cultivable lands: current patterns and sensitivity to possible climate change. Global Ecology and Biogeography 11 (5), 377–392.

Scholze, M., Bondeau, A., Ewert, F., Kucharik, C., Priess, J., Smith, P., 2005. Advances in large-scale crop modeling. EOS, Transactions, American Geophysical Union 86 (26), 245–247.

Shukla, J., Nobre, C., Sellers, P., 1990. Amazon deforestation and climate change. Science 247, 1322–1325.

Snyder, P.K., Delire, C., Foley, J.A., 2004a. Evaluating the influence of different vegetation biomes on the global climate. Climate Dynamics 23, 279–302. doi:10.1007/s00382-004-0430-0.

Snyder, P.K., Foley, J.A., Hitchman, M.H., Delire, C., 2004b. Analyzing the effects of complete tropical forest removal on the regional climate using a detailed three-dimensional energy budget: an application to Africa. Journal of Geophysical Research, D: Atmospheres 109 (D21), D21102. doi:10.1029/2003JD004462.

Stohlgren, T.J., Chase, T.N., Pielke, R.A., Kittel, T.G.F., Baron, J.S., 1998. Evidence that local land use practices influence regional climate, vegetation, and stream flow patterns in adjacent natural areas. Global Change Biology 4 (5), 495–504.

Sud, Y.C., Lau, W.K.-M., Walker, G.K., Kim, J.-H., Liston, G.E., Sellers, P.J., 1996. Biogeophysical consequences of a tropical deforestation scenario: a GCM simulation study. Journal of Climate 9 (12), 3225–3247.

Thompson, S.L., Pollard, D., 1995a. A global climate model (GENESIS) with a land-surface transfer scheme (LSX). Part II: CO_2 sensitivity. Journal of Climate 8 (5), 1104–1121.

Thompson, S.L., Pollard, D., 1995b. A global climate model (GENESIS) with a land-surface-transfer scheme (LSX). Part 1: Present-day climate. Journal of Climate 8, 732–761.

Twine, T.E., Kucharik, C.J., Foley, J.A., 2004. Effects of land cover change on the energy and water balance of the Mississippi River basin. Journal of Hydrometeorology 5 (4), 640–655.

Wang, G., Eltahir, E.A.B., 2000a. Biosphere–atmosphere interactions over West Africa. I: development and validation of a coupled dynamic model. Quarterly Journal of the Royal Meteorological Society 126, 1239–1260.

Wang, G., Eltahir, E.A.B., 2000b. Ecosystem dynamics and the Sahel drought. Geophysical Research Letters 27, 795–798.

Werth, D., Avissar, R., 2002. The local and global effects of Amazon deforestation. Journal of Geophysical Research, D: Atmospheres 107 (D20).

Woodward, F.I., 1987. Climate and Plant Distribution. Cambridge University Press, New York.

Woodward, F.I., Smith, T.M., Emanuel, W.R., 1995. A global land primary productivity and phytogeography model. Global Biogeochemical Cycles 9 (4), 471–490.

Zeng, N., Neelin, J.D., Lau, K.M., Tucker, C.J., 1999. Enhancement of interdecadal climate variability in the Sahel by vegetation interaction. Science 286, 1537–1540.

Zhao, M., Pitman, A.J., Chase, T., 2001. The impact of land cover change on the atmospheric circulation. Climate Dynamics 17 (5–6), 467–477.