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Consequences of land use change for ecosystem services: A future unlike the past

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Abstract

This study investigates the implications of past and future land use change for two ecosystem services provided by terrestrial vegetation: net primary production, which is the basis of the food chain, and modulation of climate through exchanges of energy, water, and momentum between the land surface and atmosphere. At the global scale, the most extensive land use change over the past several centuries occurred in temperate areas with cropland expansion in fertile areas. This type of conversion has generally increased net primary production due to water and nutrient inputs to mechanized agriculture and cooled surface climate due to increased albedo. In contrast, future land use change is projected to occur predominantly in the humid tropics, with large reductions in net primary production and a warming effect due to decreased transpiration. In the past, the effects of land use change on NPP and surface climate are not substantially outside the range of decadal-scale interannual variability. Future land use change alters these ecosystem services outside this range. The consequences of land use change in the coming decades are likely to be fundamentally different than in the past.

Introduction

The earth's terrestrial ecosystems provide a range of services essential for sustaining life (Daily, 1997), including food and fiber, watershed protection, climate modulation, nutrient cycling, and habitats for plants and animals. A fundamental ecosystem service is primary production, which converts atmospheric carbon to plant growth and is the basis of the food chain for humans and all other animal species. Vitousek et al., (1986) estimate that approximately 40% of the earth's net primary production is currently appropriated for human use. Land use change potentially alters the total amount of net primary production available for appropriation, either positively or negatively. With conversion of temperate grasslands to cropland, for example, primary production generally increases with input of nutrients, water, and plant varieties. In the tropics, however, land use change generally decreases primary production through degradation and conversion to less productive agroecosystems (DeFries et al., 1999).

Another essential service provided by terrestrial vegetation is modulation of climate through both biogeochemical and biophysical mechanisms. Biogeochemically, vegetation stores carbon that would otherwise exist as a greenhouse gas in the atmosphere, approximately 466 Gt in above ground vegetation and 2011 Gt in soils to a depth of 1 m (Watson et al., 2000). Biophysically, the earth's vegetation strongly influences the amount of incoming solar radiation reflected back to space (albedo) and the balance between latent and sensible heat flux. Sensitivity studies with climate models suggest that these biogeochemical and biophysical mechanisms together counterbalance to cool the surface by a global average of 8°C relative to the temperature of an unvegetated earth (Kleidon et al., 2000; Claussen et al., 2001). Other studies indicate that human modification of land cover has local, regional, and possible global effects on climate (Chase et al., 1996, 2000; Bounoua et al., 2002).

Measures of the impacts of land use change on ecosystem services are only beginning to be developed (NRC, 2000). Clearly, any measure must take account of the natural background variability as a basis for assessing the anthropogenic impact. Net primary production, for example, varies from year to year in response to climate and other conditions. The anthropogenic effect of land use change must be evaluated against this backdrop.

In this paper, we examine the global and regional effects of past and future land use change on two aspects of ecosystem services: net primary production and modulation of surface climate through biophysical interactions with the atmosphere. We present the analysis to illustrate (1) the importance of considering land use change in the future provision of ecosystem services and (2) a methodology that could be applied at regional and local scales to assess the role of land use change.

Specifically, the analysis addresses the following questions:

– What are the consequences of anthropogenic land cover change at regional and global scales for two ecosystem services: net primary production and modulation of surface climate?

- How might consequences of future land cover change differ from the past?
- How do the consequences from anthropogenic land cover change compare with natural vegetation responses to decadal-scale interannual variability in climate?

To investigate these questions, the sensitivity of net primary production and surface climate to past and future land use change is investigated by applying land cover scenarios in a global terrestrial carbon model and a land surface model coupled to a general circulation model, respectively.

Methods

Models

We use a spatially explicit global terrestrial carbon model Carnegie-Ames-Stanford Approach (CASA) to examine the sensitivity of NPP to past and future land use change. CASA calculates NPP on a monthly time step as a product of intercepted photosynthetically active radiation (IPAR) and light use efficiency based on the approach of (Kumar and Monteith, 1981). Scalars for water and temperature stress adjust the maximum light use efficiency. IPAR is derived from photosynthetically active radiation intercepted by the canopy (FPAR) and surface solar irradiance. CASA uses monthly inputs of the Normalized Difference Vegetation Index (NDVI, the ratio of the difference of infrared and red reflectance normalized by the sum indicating the degree of photosynthetic activity) derived from NOAA's Advanced Very High Resolution Radiometer sensor (AVHRR) to calculate FPAR, monthly temperature and precipitation (Shea, 1986) to calculate stress scalars, and solar irradiance (Bishop and Rossow, 1991). NPP estimates from CASA correspond reasonably well with interannual variability in agricultural production (Malmstrom et al., 1997) and with the seasonal cycle of atmospheric carbon dioxide (Randerson et al., 1997), providing confidence in the model.

To examine the sensitivity of surface climate to land use change, we use the Simple Biosphere Model (SiB2) of Sellers et al. (1996a) coupled to the Colorado State University atmospheric General Circulation Model (Randall et al., 1996). SiB2 computes the exchanges of energy, water, momentum, and carbon between the biosphere and atmosphere, accounting explicitly for 12 vegetation classes. The model includes a realistic photosynthesis-conductance model to compute the simultaneous transfer of carbon and water vapor by vegetation (Collatz et al., 1991, 1992; Sellers et al., 1992). Details of the model and biophysical fields generated for use in the model can be found in Sellers et al., (1996a, b). Land cover conversion affects several properties of the model: albedo, surface roughness, monthly varying fields of leaf area index, and canopy assimilation of carbon.

The vegetation characteristics derived in SiB2 are coupled to the atmosphere in the GCM (Randall et al., 1996; Bounoua et al., 2002; DeFries et al., 2002). The GCM uses a 4 by 5 degree horizontal resolution and 17 layers in the vertical. Although the GCM contains a simple ocean and sea-ice model, we use a version with prescribed climatological sea surface temperature to isolate the sensitivity to changing vegetation parameters.

Data

Three global vegetation maps at one by one degree resolution were used in the model runs: existing vegetation, 'undisturbed' or past vegetation, and a scenario of future vegetation (Figure 1). The map for existing vegetation was derived from satellite data acquired in 1987 (DeFries and Townshend, 1994). An approximation of undisturbed vegetation is based on the natural vegetation map of Matthews (1983). The procedure for generating the map of undisturbed vegetation and eliminating artifacts, described in DeFries et al. (1999) and Bounoua et al. (2002), modifies the vegetation only in locations where best judgment suggests that humans have modified the vegetation. Because the study addresses the sensitivity of NPP and climate to land use change only, and not to climate change, the procedure aims to approximate a hypothetical 'undisturbed' vegetation for current climate conditions.

The future land cover scenario was derived from the IMAGE 2.1 model (Leemans et al., 1998) which provides gridded simulations from the years 1970 to 2100 for global land cover. IMAGE simulates land cover at 0.5 by 0.5 degree resolution based on modeled regional demands for land and local potential of land. The IMAGE model presents three alternative scenarios based on high, low, and intermediate trajectories for population growth, economic activity, and other driving forces (Alcamo et al., 1996). For this study, we use the projection based on the lowest estimate of driving forces to obtain a conservative estimate of future land cover changes for the year 2050. Similar to the procedure for obtaining the undisturbed vegetation map, artifactual differences between the existing and future maps, as well as difference in vegetation due to response to climate change and not human modification, were removed as described in DeFries et al. (2002). The procedure involves identifying locations where human activity modifies land cover between existing and 2050 conditions through agricultural expansion. Other differences in land cover due to climate changes are not included in the 2050 scenario used in this study.

In addition to vegetation maps, both CASA and the coupled SiB2-GCM require monthly fields of NDVI from which the vegetation characteristics are calculated. For the undisturbed and future scenarios, monthly NDVI fields were derived by locating the grid cell in closest geographic proximity with the corresponding land cover type in the existing vegetation map as described in DeFries et al. (1999).

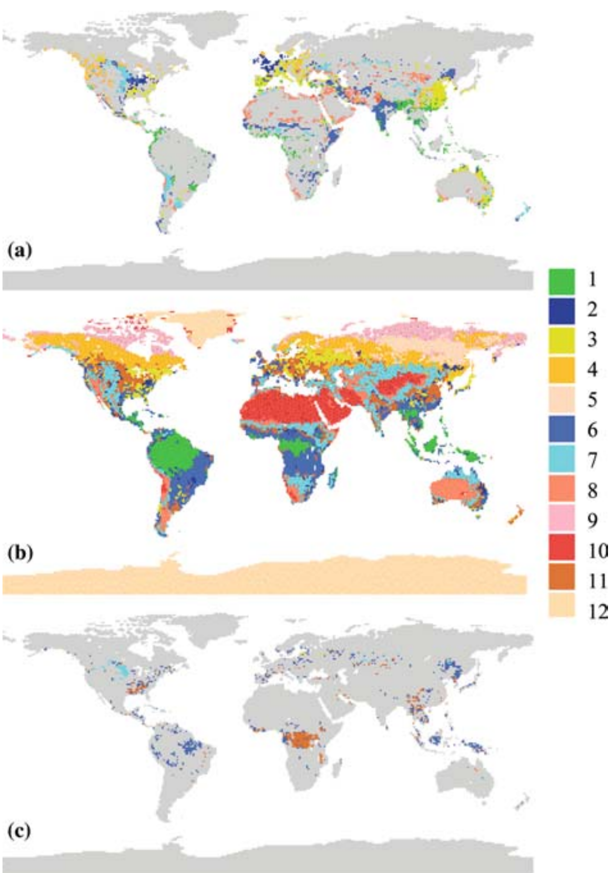

Figure 1. Land cover distributions for undisturbed vegetation (Figure 1a), existing vegetation (Figure 1b), and possible 2050 scenario (Figure 1c) at 1 by 1 degree resolution. Grey in Figure 1a and c indicates no difference in land cover type from the existing vegetation map. Land cover codes are: 1 = broadleaf evergreen forest and woodland, 2 = broadleaf deciduous forest and woodland, 3 = mixed forest and woodland, 4 = coniferous forest and woodland, 5 = high latitude deciduous forest, 6 = wooded grassland, 7 = grassland, 8 = shrubs and bare ground, 9 = tundra, 10 = bare ground, 11 = cropland, and 12 = ice.

To compare the sensitivity of NPP and surface climate to past and future land use change with decadal scale interannual variability, we use CASA and coupled SiB2-GCM simulations respectively based on the observed NDVI in the AVHRR record for the years 1982 through 1990 (Los et al., 2000). The AVHRR data have been adjusted for sensor degradation, volcanic aerosol effects, solar zenith angle variations, and missing data to obtain a realistic time series representing interannual variation. Comparison with century-scale variability in NDVI would provide yet a stronger basis to assess the significance of land use change, but such data are not available.

Model simulations

To examine the sensitivity of annual NPP to past and future land use change, we use CASA simulations for three conditions as described in DeFries (2002): existing vegetation condition; undisturbed condition; and future condition based on the IMAGE 2.1 land cover scenario for the middle of this century. Differences between NPP estimates for the undisturbed to existing condition and the existing to future condition at each grid cell indicate the sensitivity. To compare this sensitivity with decadal-scale interannual variability, we use CASA simulations run individually for each year in the 1982–1990 period, keeping constant the existing vegetation map in all years (Malmstrom et al., 1997). The interannual variability was calculated as the range for each grid cell over the 9-year period. Barring residual artifacts in the NDVI record, the interannual variability in NPP can be attributed to vegetation responses to variations in climate over the decade as well as responses to nutrient deposition, CO_2 fertilization, and land cover change that may have occurred. The interannual variability calculated with this approach may consequently overestimate the true natural variability from climate responses alone.

The sensitivity of surface climate to altered biophysical properties of the vegetation caused by past and future land use change was estimated by coupled SiB2-GCM simulations for the three conditions (Bounoua et al., 2002; DeFries et al., 2002). All coupled simulations were conducted at 4×5 degrees horizontal resolution, started from the same initial conditions and integrated for 15 years each. Differences between the simulations were calculated using monthly means generated from the last 13 years allowing for 2 years of model spinup. To assess the climate effects of decadal variability in the absence of land use change, two additional runs used average 1982–1983 NDVI values and 1989–1990 NDVI values, representing the lowest and highest global mean NDVI values in the 9 year period respectively. Because of computing limitations, these last two simulations were run for 10 years each and results averaged over the last 5 years.

Results

At the coarse resolution of this analysis, the most extensive changes in past land use have occurred in temperate areas. Large fertile areas of North America, Europe, and eastern China in the northern hemisphere and Argentina and Australia in the southern hemisphere have been converted to cropland. Extensive land use changes have also occurred in the Indian subcontinent and the Middle East associated with degradation of forests and shrublands to wooded grassland and bare ground respectively. The future scenario based on the IMAGE model suggests that large areas of the humid tropics in South America, Africa, and Southeast Asia will be modified in the first half of this century for cropland and pasture. Land use changes in temperate areas are far less extensive in the future scenario than in the past. While these maps cannot be viewed as realistic depictions of actual vegetation due to the coarse resolution and impossibility of predicting all the factors influencing future land use decisions, they do highlight a

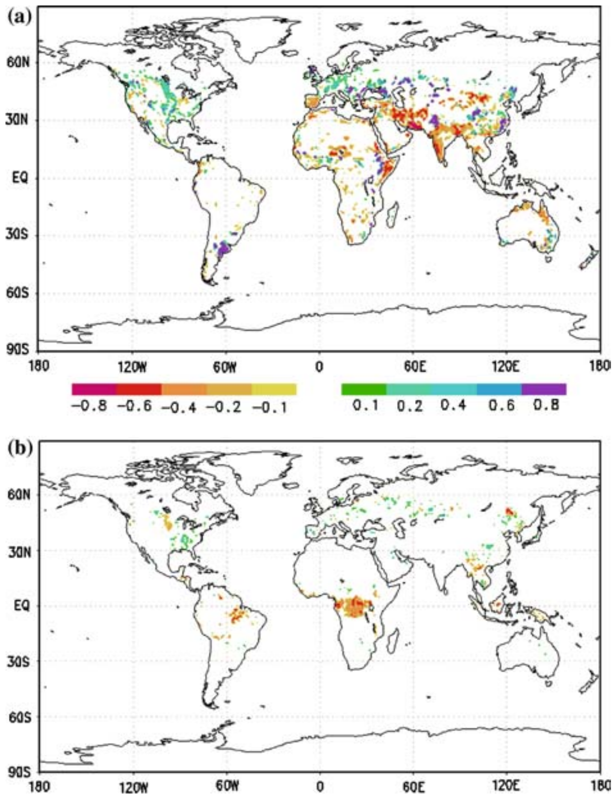

Figure 2. Percentage difference in annual NPP for current minus undisturbed vegetation (Figure 2a) and future minus current vegetation (Figure 2b). Percentaages are normalized to the annual NPP for undisturbed and current vegetation respectively.

general observation: in the past several hundred years, the dominant land use change was cropland expansion in temperate and subtropical locations; in the future, the dominant land use changes are likely to occur in the humid tropics.

Sensitivity of NPP to land use change

The sensitivity of NPP to the past and future land cover scenarios reflect this general observation (Figure 2). Current NPP in temperate areas of North America, Europe, and the former USSR is generally higher than the past vegetation, reflecting intensive agricultural practices, expensive water and nutrient supplements, and soil types suitable for sustained production. The increase is generally 20–40% but greater than 80% in other scattered locations in Argentina and northwestern India. In contrast, NPP losses greater than 80% occur in tropics and subtropics in areas with long histories of human habitation in Africa, the Indian subcontinent, and the Middle East. The large but spatially varying effects of land use change reduce NPP globally by 5% (DeFries et al., 1999), though the global average masks the regional disparities.

Modifications in NPP are most significant if they are larger than the interannual variability. Conversion types occurring over at least 10% of the modified grid cells (conversion types 1, 2, 6, 8, and 12, see caption to Figure 3 for definitions) are within the range of interannual variability or increase NPP beyond the interannual variability range relative to the past vegetation (Figure 3a and b). Other conversion types occurring in less than 10% of modified grid cells (conversion types 3, 4, 5, 7, 9, 10, and 11) lead to decreases in annual NPP outside of the interannual variability range. In sum, although past land use change has led to large local depletions in some areas of the tropics and subtropics, the major effect when viewed over latitude bands is to either increase NPP or to reduce NPP by an amount similar to the range of interannual variability (Figure 4a).

For the future, where the scenario based on the IMAGE model indicates extensive land use change in the

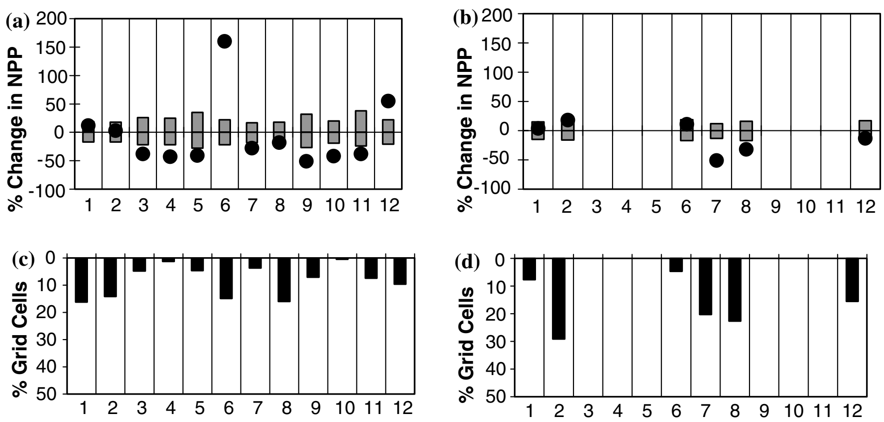

Figure 3. Percentage difference in annual NPP for conversion types for current minus undisturbed vegetation (Figure 3a) and future minus current vegetation (Figure 3c). Dots are averages over grid cells modified in the experiment for the conversion type (1 through 12). Bars represent the average range of interannual variability for 1982–1990 for the same grid cells (maximum minus mean for the positive difference and mean minus minimum for the negative difference). Proportion of total grid cells modified in the experiment are given for the current minus undisturbed case (Figure 3b) and future minus current vegetation (Figure 3d). Conversion types are coded as: 1 = temperate forest conversion to cropland, 2 = temperate forest conversion to other land uses than cropland, 3 = temperate degradation of woodland, 4 = temperate degradation of grassland, 5 = temperate degradation of shrubland, 6 = temperate nonforest conversion to cropland, 7 = tropical forest conversion to cropland, 8 = tropical forest conversion to other land uses than cropland, 9 = tropical degradation of woodland, 10 = tropical degradation of grassland, 11 = tropical degradation of shrubland, 12 = tropical nonforest conversion to cropland.

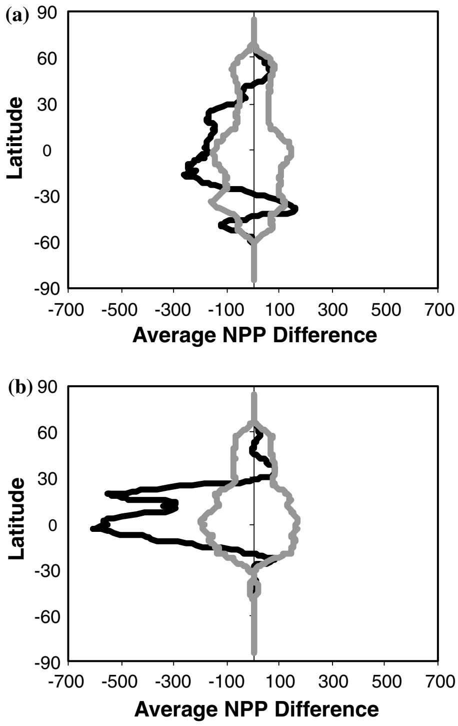

Figure 4. Differences in annual NPP for current minus undisturbed vegetation (Figure 4a) and future minus current vegetation (Figure 4b) averaged over latitude bands for all grid cells modified in the experiment. The black line indicates the difference from landscape modification and the gray line the interannual variability from 1982 to 1990. NPP differences are in g C/m^2/yr.

humid tropics, the effect on annual NPP is large reductions far in excess of the interannual variability (Figures 2 and 4b). Conversion types occurring over at least 10% of the modified grid cells (types 2, 7, 8, and 12) are either within the interannual variability or decrease NPP beyond the variability range (Figure 3c and d). Future conversions are likely to reduce NPP beyond the background variability in the tropics (Figure 4b), suggesting that future land use is likely to have a fundamentally different effect on NPP than in the past.

Sensitivity of surface temperature to land use change

The effect of land use change on surface temperature reflects a combination of several biophysical mechanisms. Removal of vegetation generally increases albedo from a higher reflectivity of background soil compared to darker vegetation, particularly in snow covered areas where forests no longer mask the snow. Previous results examining effects of past land use change on climate conclude that conversion to cropland generally led to cooling in temperate areas from the albedo effect (Hansen et al., 1995; Bonan 1999; Govindasamy et al., 2001; Bounoua et al., 2002). On the other hand, model studies of land use change in the humid tropics indicate a warming effect with deforestation due to reduced transpiration and increased sen-

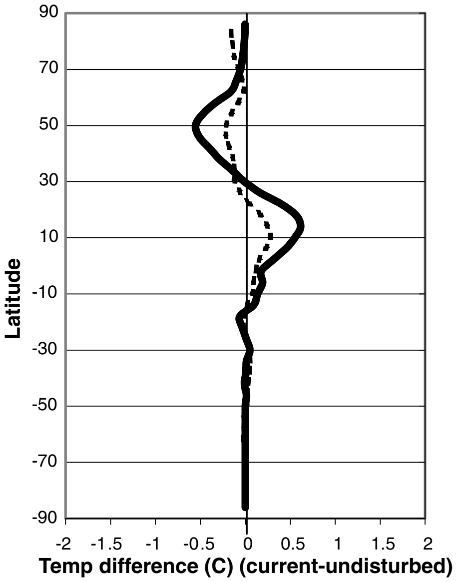

Figure 5. Difference in surface temperature for existing minus undisturbed vegetation averaged over latitude bands for summer (June, July, August). The solid line is the difference averaged only over grid cells where the vegetation type was altered in the experiment. The dotted line is averaged over all grid cells.

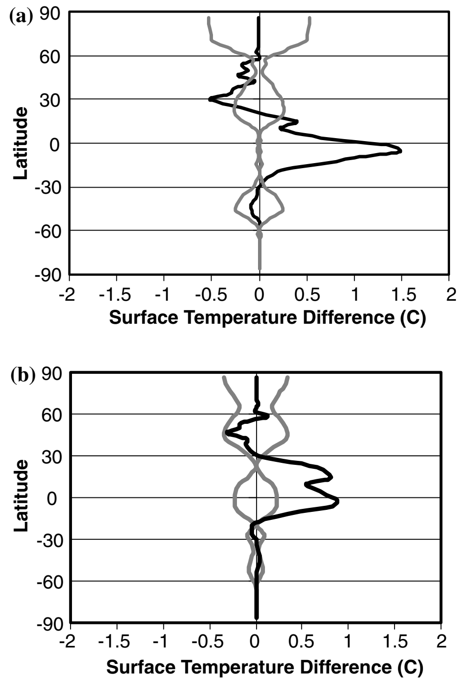

Figure 6. Difference in surface temperature for future minus existing vegetation averaged over latitude bands for (a) winter (average for December, January and februrary) and (b) summer (average for June, July, August). The black line indicates the difference from landscape modification and the gray line the interannual variability represented by the absolute difference between surface temperature estimated using NDVI from 1982–1983 to 1989–1990). Averages are for grid cells where vegetation type was altered in the experiment.

sible relative to latent heat flux (Shukla et al., 1990; Nobre et al., 1991; Costa and Foley, 2000).

The results from the simulations with the coupled SiB2-GCM for past land use change agree with these results (Figure 5). In temperate areas, the albedo effect, combined with similar or even slightly increased transpiration and hence latent relative to sensible heat flux (expected with the increase in NPP from the CASA results) has an overall cooling effect. In the tropics, on the other hand, where extensive land use change occurs in the future scenario, temperature increases up to 0.5°C.

Comparing the climate sensitivity to future land use change with the sensitivity to natural interannual variability in NDVI during the 1980s suggests that the land use response in temperate areas is generally the same order of magnitude or only slightly larger than the interannual variability response. In the tropics, the sensitivity to future land use change is much larger than the sensitivity to interannual variability, by approximately 1.5°C in winter and 0.8°C in summer (Figure 6). Similar to the effect of future land use change on NPP, the effect of future land use change on surface temperature is likely to be opposite in sign with an overall warming rather than cooling effect. The warming effect is far outside the sensitivity of temperature to interannual variability in NDVI, in contrast to the effect of past land use change.

Conclusion

In conclusion, the past does not provide guidance on the consequences of future land use change for ecosystem services. At the global scale, the predominant effect of past land use change was an increase in primary productivity and a cooling in surface temperature from cropland expansion in temperate parts of the world. These effects are not substantially different from the sensitivity of NPP and surface temperature to interannual variations in the vegetation's response to climate variability. In the future, land use change is likely to occur predominantly in the tropics, associated with decreases in net primary productivity and warming in surface temperature. These consequences are greater than the sensitivity to the vegetation response to interannual variability in climate.

The results presented here address the broad-scale patterns of land use change and the implications for ecosystem services at a global scale. The coarse-scale models do not capture important land use changes occurring at finer spatial resolutions, such as patchy tropical deforestation, forest plantations, and logging. Finer scale models are required to investigate the implications of land use change for ecosystem services at local and regional scales. Furthermore, the experiments address the sensitivity of net primary production and climate modification to land use change in the absence of other forcing factors. In reality, land use change is one of several factors that potentially feedback to ecosystem services, including climate change, climate variability, loss of biodiversity, and changing atmospheric composition. The consequences of these multiple, interacting factors on ecosystem services and human well-being are largely unknown.

The biophysical consequences of land use change are likely to have feedbacks to management decisions, which need to be factored into future projections of land use change. The results presented here are an illustration at the global scale, and consequently oversimplify the complex issues of land management decisions, the biophysical consequences on ecosystem services, and feedbacks to subsequent management decisions. Local and regional implications of land use change for ecosystem services need to be investigated and factored into land management decisions.

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