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The underpinnings of land-use history: three centuries of global gridded land-use transitions, wood-harvest activity, and resulting secondary lands

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Abstract

To accurately assess the impacts of human land use on the Earth system, information is needed on the current and historical patterns of land-use activities. Previous global studies have focused on developing reconstructions of the spatial patterns of agriculture. Here, we provide the first global gridded estimates of the underlying land conversions (land-use transitions), wood harvesting, and resulting secondary lands annually, for the period 1700–2000. Using data-based historical cases, our results suggest that 42–68% of the land surface was impacted by land-use activities (crop, pasture, wood harvest) during this period, some multiple times. Secondary land area increased 10–44 $\times$ 10^6 km^2; about half of this was forested. Wood harvest and shifting cultivation generated 70–90% of the secondary land by 2000; permanent abandonment and relocation of agricultural land accounted for the rest. This study provides important new estimates of globally gridded land-use activities for studies attempting to assess the consequences of anthropogenic changes to the Earth's surface over time.

Keywords: global change, land use, land-use history, logging, secondary forest age, secondary forest, secondary land, shifting cultivation, wood harvest

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Introduction

The conversion of land from its natural state has had profound effects on the Earth system (Turner *et al*., 1990; Vitousek *et al*., 1997). Land-use changes are estimated to have added a net 156 Pg C to the atmosphere during 1850–2000 (Houghton, 2003), and have altered the surface albedo, surface aerodynamic roughness, and rooting depth of vegetation (Defries *et al*., 2002; Pielke *et al*., 2002; Roy *et al*., 2003). Habitat loss and degradation associated with human use of the land are important causes of biodiversity decline (Birdlife International, 2000; Hilton-Taylor, 2000; UNEP, 2002). Although the role of humans in the Earth system is known to be large, significant challenges remain for quantifying the effects of centuries worth of spatially and temporally variable patterns of human land-use activities on terrestrial ecosystems and Earth system dynamics.

To begin to assess the impacts of land-use activities, information is first needed on the current and historical patterns of land-use activities. At the global scale, two major efforts have been undertaken (Ramankutty & Foley, 1999; Klein Goldewijk, 2001). These studies combined satellite-based information on the contemporary patterns of agriculture with historical data on agricultural and population to generate spatially gridded reconstructions of land use (e.g. crop, pasture, etc.) in discrete intervals over the past three centuries. To augment these data, historical information is also needed on land-use transitions. Land-use transitions describe the underlying changes to the use between two time intervals (e.g. which type of land was converted to what use). Explicit knowledge of these transitions is important

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because changes to the use of the land often directly alter land-surface properties (e.g. felling trees, etc.), the condition of land (e.g. soil quality, etc.), and the amount and age structure of secondary recovering lands.

At the global scale, land cover and land use are often specified as gridded products, with subgrid resolution information reported as fractional data. A data set may report the fractional area of each grid cell that is cropland, but not specify where within the grid cell the cropland is located. Knowing the state of land use at two consecutive time periods is, thus, not enough to uniquely determine the transitions that underpin the changes in state because an area of land that is fractionally covered by agriculture in two successive periods may have had any one of a large set of possible land-use transitions. For example, a grid cell that had equal fractional coverage of cropland at two time periods may have had no land-use change, or the abandonment of any area of cropland offset by the establishment of an equal area of new cropland during the interval. The many potential alternatives that underpin any sequence of land-use patterns can differ remarkably in terms of the effect on the land surface and ecosystems.

It is possible to estimate land-use transitions and the age structure of secondary lands directly by repeated observation. Several studies have overlain sequential (closely spaced in time) remote sensing products of land cover/land use to classify the transitions between these patterns (Alves & Skole, 1996; Steininger, 1996; Kimes *et al*., 1998; Nelson *et al*., 2000). These studies all point to the capability of estimating land-use transitions from satellite data over regional scales for the recent past (e.g. 1980s to present). However, significant challenges exist to extend these methods to global spatial scales and to accurately account for wood harvesting removals. Moreover, the data required to provide historical estimates (e.g. previous decades to centuries) are simply unavailable.

The primary objective of this study is to build on existing historical reconstructions of land-use and provide estimates of the underlying land-use transitions and wood harvest activities that have occurred. The core products we derive consist of globally gridded estimates of annual land-use transition rates including the effects of wood harvest and shifting cultivation 1700–2000. We also produce derived maps of the extent and age structure of secondary vegetation through time, and evaluate the sensitivity of key factors in the historical reconstructions. The results of this study are suited for applications in a large set of global gridded models (e.g. terrestrial ecosystem models, dynamic global vegetation models, and Earth system models) attempting to estimate the consequences of land-use activities over time.

Methods

To produce estimates of globally gridded land-use transition rates, we built an accounting model to track the state of the land surface at each $1^\circ \times 1^\circ$ terrestrial grid cell through time as a function of the previous state of the land surface and all possible transitions between tracked land-use categories. The state of the land surface through time can be represented by the matrix equation

$$\boldsymbol{l}(x, t+1) = \boldsymbol{A}(x,t)\,\boldsymbol{l}(x,t),$$

$$x = (1, \ldots, N), t = (t_0, \ldots, t_f), \tag{1}$$

where $\boldsymbol{l}(x,t)$ is a vector describing the proportion of land in each land-use category in grid cell x and year t, and $\boldsymbol{A}(x,t)$ is a matrix of time-dependent land-use transition rates. Each element $a_{ij}(x,t)$ of $\boldsymbol{A}(x,t)$ describes the rate at which land in use type j was converted to land in use type i from time t to $t + \Delta t$.

$$\boldsymbol{A}(x,t) = \begin{bmatrix} a_{11}(x,t) & \cdots & a_{1n}(x,t) \\ \vdots & a_{ij}(x,t) & \vdots \\ a_{n1}(x,t) & \cdots & a_{nn}(x,t) \end{bmatrix}. \tag{2}$$

The goal of our work is to solve for all a_{ij} for every terrestrial 1° grid cell on the globe annually over the period 1700–2000 (i.e. transitions from 1700 to 1999 that produce estimates of land in each land-use category from 1701 to 2000; the initial state was 1700). We also estimate the transitions associated with wood harvesting on secondary lands.

Generally, Eqn (1) is a large underdetermined problem; even with the patterns of land use specified at the beginning and end of a time step, there are many possible $\boldsymbol{A}$ matrices that will satisfy it. At $1^\circ \times 1^\circ$ resolution, for 300 years annually resolved, and four land-use categories (crop, pasture, primary, secondary), there are $\sim 10^8$ a_{ij}'s that must be specified. Our solution strategy was to first constrain the model with historical reconstructions of: (i) maps of land use, (ii) national wood harvest activity, and (iii) model estimates of the distribution of plant carbon density and its recovery. Because these do not fully constrain the problem, we added assumptions related to four additional factors: (iv) the residence time of agricultural land, (v) the inclusiveness of wood harvest statistics, (vi) the priority for land conversion and wood harvest (e.g. primary or secondary land), and (vii) the spatial pattern of wood harvest within a country. Because needed inputs (i–vii) are not uniquely known, a set of alternative solutions was derived using different assumptions in order to estimate uncertainty and characterize model sensitivity (Table 1, Fig. 1). Two 'focal cases' were identified as

Table 1 Model factors

Model factor	Case
H: Historical land-use reconstruction	H0. *No data*: linear interpolation in each grid cell from zero agricultural land use in 1700 to 2000 values
	H1. HYDE crop and pasture land-use history
	H2. SAGE crop land-use history + HYDE pasture land-use history
T: Residence time of agricultural land	T1. Minimum transitions
	T2. Minimum transitions plus fractional abandonment of crop and pasture (6.7% yr^{-1}), applied globally
	T3. Minimum transitions plus fractional abandonment of crop and pasture (6.7% yr^{-1}), applied to the tropics (23°S–23°N)
L: Wood harvest history reconstruction	L0. *No harvest*: wood harvest set to zero
	L1. Historical reconstruction from FAO and population data
	L2. No data: linear interpolation in each grid cell from zero wood harvest in 1700 to 2000 values
W: Land-conversion wood clearing tallied as harvest to satisfy annual wood harvesting	W1. 0%
	W2. 100%
P: Priority for land-use transitions	P1. Land needed for crop, pasture, or wood harvesting taken first from primary lands, then, as needed, from secondary lands
	P2. Land needed for crop, pasture, or wood harvesting taken first from secondary lands, then, as needed, from primary lands
Z: Spatial distribution of wood harvest	Z1: Priority to grid cells with land use, then to adjacent grid cells
	Z2: Uniform harvest across all forested grid cells in a country

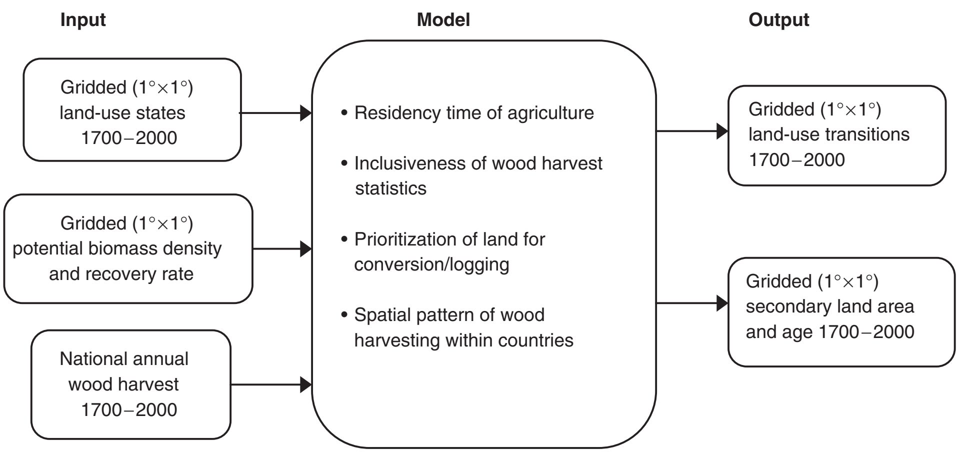

Fig. 1 Overview of modeling strategy.

reasonable case studies for potential use in subsequent applications.

Historical maps of land use

The fundamental input data sets used in our reconstructions were two global land-use history products: the History Database of the Global Environment (HYDE), a collection of global historical land-use and land cover maps at $0.5^\circ \times 0.5^\circ$ resolution (Klein Goldewijk, 2001); and the reconstruction of global cropland developed at the Center for Sustainability and the Global Environment (SAGE; Ramankutty & Foley, 1999). Antarctica and numerous small island nations (national areas $<30\,000\,km^2$) have been excluded from our analysis.

The HYDE database contains global maps of land use (crop and pasture) and land cover for 1700, 1750, 1800, 1850, 1900, 1950, 1970, and 1990 (Klein Goldewijk, 2001). These data were processed in the following manner.

First, a consistent global land mask (University of New Hampshire, 2001) was applied to delineate land area. Next, grid cells classified as one of the 13 nonagricultural land-cover classes were aggregated into one heterogeneous class termed 'Other'. Data were aggregated from $0.5^{\circ} \times 0.5^{\circ}$ to $1.0^{\circ} \times 1.0^{\circ}$ resolution and recorded as grid cell fractional coverage of each type (crop, pasture, other, water/ice); these fractional area values were then linearly interpolated to annual time steps between the HYDE values at the original published time steps. Each $1.0^{\circ} \times 1.0^{\circ}$ grid cell was then assigned to a single country by overlaying a political boundaries map from the Environmental Systems Research Institute's (ESRI)'s ArcWorld database (Environmental Systems Research Institute, 1992). Land-use data were extrapolated linearly from 1990 to 2000 at the grid cell level, using national statistics for the ratio of 2000–1990 areas of crop and pasture (FAOSTAT, 2004), and adjusting other to preserve grid cell area. Globally, cropland area increased by 2.2% and pastureland area by 1.2% from 1990 to 2000. Water/ice area was assumed to stay constant over 1700–2000.

The SAGE land-use history product (Ramankutty & Foley, 1999) consists of global estimates of cropland 1700–1992 at $5' \times 5'$ resolution. For our analyses, these data were aggregated to fractional coverage at $1^{\circ} \times 1^{\circ}$ resolution. To supplement the SAGE product with pasture information, we combined SAGE cropland estimates with HYDE estimates of pasture area at each of the eight time steps for which HYDE information was available. Grid-cell total land and water/ice areas from HYDE were preserved, and every effort was made to preserve SAGE crop area and HYDE pasture area. For grid cells where there was not enough land area to accommodate both SAGE crop estimates and HYDE pasture estimates, HYDE pasture estimates were reduced to the available land area, and other was set to zero. Otherwise, other was set to fraction of land not crop, pasture, or water/ice. We then applied the same methodologies described above to extrapolate 1990–2000, and to interpolate to an annual time step 1700–2000. Hereafter, this data set is referred to as SAGE/HYDE.

Both the HYDE and SAGE/HYDE land-use history data sets provide estimates of changes to the extent and spatial pattern of agriculture through time. These products differ substantially, and both include uncertainties associated with historical reconstruction. To help evaluate the sensitivity of our analyses to historical information on land use, we also developed a third land-use history reconstruction ('no-data' history) in which land area in crop and pasture for each grid cell linearly increased from zero in 1700 to the value of the HYDE reconstruction in 2000.

National statistics on wood harvest

Cutting forests for fuel and fiber has been a significant land-use activity over the past 300 years (e.g. Houghton, 2003). Houghton and Hackler have developed detailed reconstructions of annual national wood harvest histories for China 1700–2000 (Houghton & Hackler, 2003) and the US 1700–1990 (Houghton & Hackler, 2000), which we used as input data for our analyses. The US annual wood harvest time series was extended for 1991–2000 using annual FAO data (FAOSTAT, 2004), scaled by the 1990 US wood harvest ratio (1.013) of Houghton and Hackler to FAO. We disaggregated US wood harvest into Alaska (1% of US harvest for 1961–2000 and zero before then; Smith *et al.*, 2001) and non-Alaska. For all other countries, annual wood harvest for 1961–2000 was based on FAO national wood volume harvest data (total coniferous plus nonconiferous roundwood; FAOSTAT, 2004), and wood carbon density values of $0.225\,\mathrm{Mg\,C\,m^{-3}}$ for coniferous wood, and $0.325\,\mathrm{Mg\,C\,m^{-3}}$ for nonconiferous wood (Houghton & Hackler, 2000). We used a 1990 country list (e.g. USSR instead of Russia, Ukraine, Uzbekistan, etc.) and aggregated post-1990 FAO national totals to this country list.

Before 1961, we calculated national annual wood harvest based on national annual population and per capita harvest rates. National population values were obtained from the HYDE gridded population database (Klein Goldewijk, 2001), aggregated from $1^{\circ} \times 1^{\circ}$ to national values and linearly interpolated to annual values. Per capita wood harvest were linearly extrapolated from values reported for ca. 1920 in Zon & Sparhawk (1923) to 1961 values calculated from FAO wood harvest data and HYDE population data (Table 2). Before 1920, we assumed that national per capita wood harvest rates were constant and were equal to the Zon and Sparhawk values. Zon & Sparhawk (1923) reported ca. 1920 annual wood consumption (both total and per capita) for most countries, as well as volume of net export of wood. We added per capita consumption and per capita net export to estimate per capita harvest, and matched their 1920 country list to our 1990 country list using historical atlases (Ade Ajayi & Crowder, 1985; Schwartzberg, 1992; Parker, 1993). Per capita volume harvests were converted to per capita carbon harvests assuming the volume fraction of wood that was nonconiferous for each country was equal to value calculated from 1961 FAO data and using mean carbon densities noted above.

Zon & Sparhawk (1923) noted that the total cut of firewood could be at least 50% greater than indicated by their firewood harvest data, but that much of the additional firewood would have been cut from scattered trees and would not 'constitute a direct drain upon the

Table 2 Continental wood harvest statistics

Region	Fraction nonconiferous*, 1961	Harvest		
		1961[†] ($Mg\,C\,person^{-1}\,yr^{-1}$)	1920[‡] ($Mg\,C\,person^{-1}\,yr^{-1}$)	1700–2000[§] (Pg C)
Asia (excluding USSR)	0.71	0.15	0.15	40.0
Africa	0.97	0.29	0.20	4.7
Europe (including USSR)	0.25	0.87	0.68	13.0
North and Central America	0.29	0.92	1.71	23.0
South America	0.81	0.36	0.57	3.8
Oceania[¶]	0.50	0.82	0.34	0.5
Global	*0.46*	*0.61*	*1.07*	*86.0*

*Fraction by volume; calculated as FAO annual total nonconiferous roundwood harvest divided by FAO annual total roundwood harvest.

†Per capita annual harvest calculated as FAO annual total roundwood harvest (FAOSTAT, 2004) divided by 1961 population from HYDE database (Klein Goldewijk, 2001); conversion factors for wood density: $0.225\,Mg\,C\,m^{-3}$ (coniferous) and $0.325\,Mg\,C\,m^{-3}$ (nonconiferous).

‡Per capita annual harvest from Zon and Sparhawk (1923). Conversion factors for wood density: $0.225\,Mg\,C\,m^{-3}$ (coniferous) and $0.325\,Mg\,C\,m^{-3}$ (nonconiferous); we also assumed that for each country the fraction of total harvest that was nonconiferous wood was the same as the ratio calculated from 1961–2000 FAO data.

§Total annual harvest integrated from 1700 to 2000; does not include slash/residue.

¶Australia, New Zealand, and Papua New Guinea only.

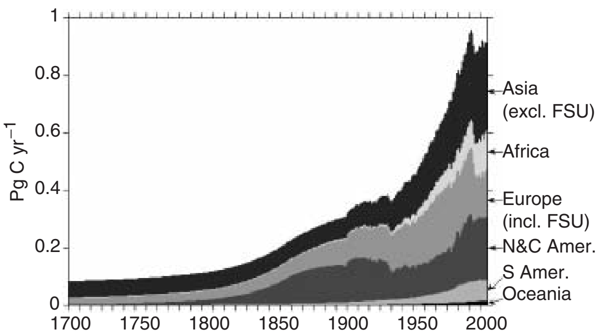

Fig. 2 Annual national wood harvest aggregated to continental values, for 1700–2000. Total global integrated wood harvest 1700–2000 is 86 Pg C. (FSU, Former Soviet Union.)

forests.' This was still the case at least into the 1980s in many regions (Mather, 1990). Because our interest is primarily in land-area conversion, we have not adjusted wood harvest estimates to account for these low intensity fuelwood harvest values. However, wood harvest was increased by a slash fraction to account for nonharvested losses. Houghton & Hackler (2000) estimated slash factors for the US of 33% in 1700, declining to 25% in 1990. Powell *et al*. (1993) reported wood harvest residues as about 20% of removals in the early 1990s in the US. Priasukmana (1986) estimated wood harvest waste in Indonesia as 30–40% of timber harvest. On the basis of these estimates, we used a constant global slash fraction of 30% of wood harvest.

We estimated that the accumulated global wood harvest 1700–2000 was 86 Pg C; 62% of this harvest was in Eurasia, 27% in North America, 6% in Africa, 4% in South America, and 1% in Oceania (Fig. 2; Table 2). Harvest impact on the landscape was larger due to the additional 30% slash loss associated with wood harvest. For comparison, we constructed two additional wood harvest cases: 'no harvest,' which had wood harvest set to zero for all countries for each year, and 'no data,' which had wood harvest for each country increasing linearly from zero in 1700 to the 2000 value used above. The 'no data' integrated global wood harvest, accumulated from 1700 to 2000, was 137 Pg C.

Biomass density

To convert quantities of harvested wood into areas of impacted land, and to discriminate forested land from nonforested land for wood harvest activities, information was needed on the historical distribution of aboveground carbon stocks and forest extent, and on their recovery following wood harvest and land-use abandonment. In general, these quantities may be considered to be highly uncertain over the relevant historical record because of lack of direct observation and must be estimated.

We applied a global terrestrial model to provide a consistent set of estimates of both global land cover and carbon stocks for our analyses. Estimates of ecosystem properties were based on a global extension of the

Miami-LU ecosystem model (Hurtt *et al*., 2002). Miami-LU is driven by the empirically based Miami Model of net primary production (Leith, 1975), and has associated simple submodels of natural plant mortality, disturbance from fire, and organic matter decomposition. The model tracks the subgrid-scale heterogeneity resulting from land-use changes in a manner similar to the more advanced ecosystem demography model (Hurtt *et al*., 1998; Moorcroft *et al*., 2001; Hurtt *et al*., 2002). To produce global estimates of potential carbon stocks, Miami-LU was run globally at $1^{\circ} \times 1^{\circ}$ resolution for a spin-up period of 1000 years using average climate data from the ISLSCP-I data set (Meeson *et al*., 1995; Sellers *et al*., 1995).

To constrain estimates of the historic spatial pattern of wood harvest activities, it was important that the model produce reasonable patterns of potential land cover, plant carbon stocks, and recovery rates. The Miami-LU estimated global stock of potential plant carbon was 695 Pg C (Fig. 3). For comparison, estimates of preindustrial carbon stocks, which should be somewhat lower due to pre-1850 land-use effects, are 610 Pg C (Siegenthaler & Sarmiento, 1993) and 620 Pg C (Houghton, 1999). Estimates of contemporary carbon stocks, which should be substantially lower due to land-use activities, are 466–654 Pg C (Prentice *et al*., 2001). To differentiate forest from nonforest areas, we used a definition based on the aboveground standing stock of natural cover of at least $2\,\mathrm{kg\,C\,m^{-2}}$ (Hurtt *et al*., 2002). Each grid cell was thus identified as potential forest or nonforest based on potential biomass. Using this definition, potential forests are estimated to have covered $56 \times 10^{6}\,\mathrm{km}^{2}$ (42%) of the land surface. This estimate compares favorably to the estimate of forest area in HYDE (based on the BIOME model) of $60 \times 10^{6}\,\mathrm{km}^{2}$ (Klein Goldewijk, 2001). Finally, Miami-LU was also used to estimate the recovery of carbon stocks on secondary lands. This was necessary in order to determine the amount of secondary forest carbon available for wood harvesting each year. The application used here tracked the mean age of secondary land, and did not account explicitly for the complete age distribution within secondary lands, or the potential effects of land degradation, climate variability, fertilization, fire management, or pollution that may have occurred.

Additional major factors

Residency time of agriculture. The residency time of land in agriculture affects both the conditions of land under management as well as that of surrounding lands. Globally, the amount of time land spends in agriculture (residency time) varies from centuries in cases of relatively permanent agriculture involving terracing and other significant investments in infrastructure, to years in cases of shifting cultivation. The former is characterized by consistent and relatively intensive use of land, whereas the latter is more dynamic and is typically associated with relatively large areas of nearby fallow or recovering secondary lands (Lanly, 1985; Buringh & Dudal, 1987).

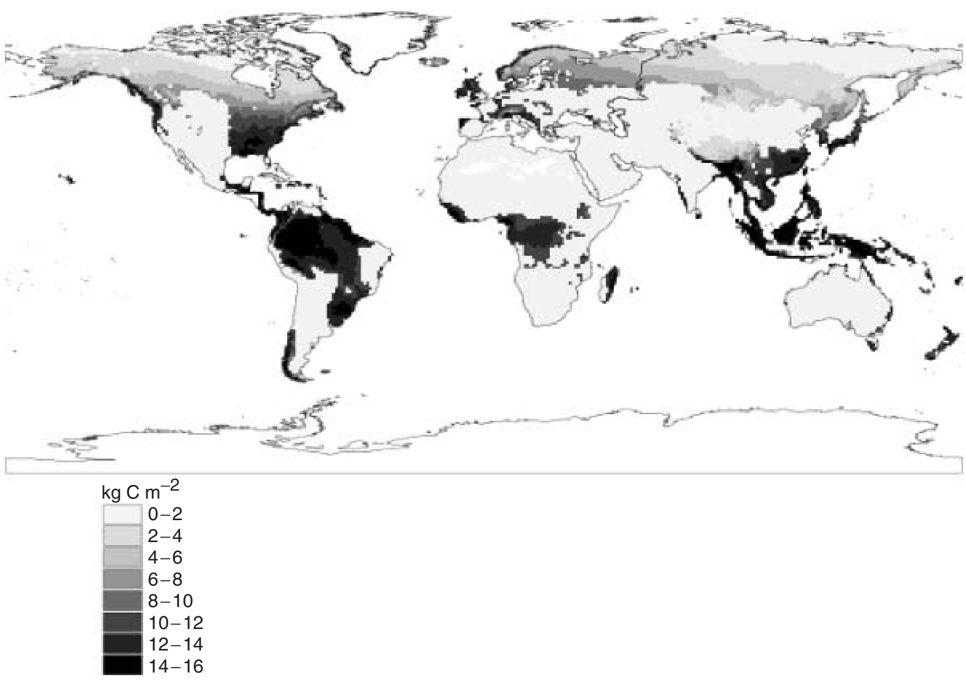

Fig. 3 Potential vegetation biomass density ($\mathrm{kg\,C\,m^{-2}}$) at $1^{\circ} \times 1^{\circ}$ from Miami-LU.

In general, neither the areas in shifting cultivation, nor the changes to those areas, are well known (Houghton & Goodale, 2004). Lacking detailed historical information on the spatial patterns of agricultural residency times, we evaluated three alternative cases. In the first case, we assumed that the smallest amount of land-use change occurred between all sequential patterns of land use. This case had minimal transitions and maximum residency times for agricultural land consistent with input data on the patterns of land use. In the remaining two cases, transitions were increased and residency times were shortened. In one case, shifting cultivation was assumed to occur in the tropics where it has been noted to be common (e.g. Butler, 1980; Lanly, 1985). Agricultural land in these areas was assumed to have a mean residency time of 15 years, implying a steady-state average abandonment rate of $6.7\%\,yr^{-1}$. This value was chosen as a compromise between the relatively short residence times of traditional long-fallow systems of cultivation, and the relatively long residence times of more permanent agricultural practices (Sunderlin & Resosudarmo, 1996). In the remaining case, agricultural land was assumed to be abandoned and replaced globally at the same rate as in the tropics.

Inclusiveness of wood harvest statistics

From national wood harvest statistics, it is not clear what fraction of harvested wood comes from wood harvest operations *per se*, and what fraction comes from land cleared for agriculture. Houghton (1999) did not count wood from agricultural clearing toward recorded wood harvest. However, this fraction is important because it will affect estimates of areas of land assumed to be logged. We developed two cases to evaluate the sensitivity of this factor. In one case, wood clearing generated by land conversion to agriculture was not counted toward fulfilling national wood harvest estimates. All wood harvesting estimates were assumed to be met only through explicit wood harvesting activities such as logging. In the second case, all wood cleared during land-use conversions counted toward meeting national wood harvest estimates; additional wood harvesting was only conducted when wood cleared to create agricultural land was less than national wood harvest estimates.

Prioritization of land for conversion and wood harvesting

Both primary and secondary land can be used for wood harvesting and for conversion to agriculture. Alternative assumptions about the use of primary or secondary land for agriculture and wood harvesting affect underlying land-use transitions and resulting estimates of secondary land area and age. In practice, decisions about land conversion depend on many complex factors such as the suitability for intended crops, climate, technology, economics, land-use policies, and other factors (Bolin *et al*., 2000). While these are generally beyond the scope of this study, we evaluated two cases for land priority. In one case, primary land was used first and secondary was cleared only if it there was not enough primary land/wood available. In the second case, the reverse was assumed. In both cases, secondary was logged preferentially only if it had accumulated sufficient biomass.

Spatial pattern of wood harvesting

The spatial pattern of wood harvesting directly affects the spatial pattern of this disturbance and the resulting patterns and structure of secondary forests. However, the spatial patterns of wood harvesting within countries are more detailed and generally less well known than aggregated national harvests estimated above. Some subnational temporal reconstructions or spatial snapshots exist (e.g. Zon & Sparhawk, 1923; Haden-Guest *et al*., 1956; Richards & Tucker, 1988), but no global gridded historical database has been published. One factor that clearly constrains the potential patterns for wood harvesting is the presence of forests. This factor was used in all of our analyses, and was a necessary but not sufficient condition to uniquely specify patterns of wood harvesting. We evaluated two additional conditions. In one case, wood harvesting occurred close to other ongoing agricultural activities, presumably due to proximity to transportation infrastructure (accessibility) or local markets (FAO, 2001). In this case, wood harvest activities occurred first in those grid cells that contained other land-use activities (e.g. crop, pasture, secondary), and radiated outward from these grid cells until wood harvest demand was met. For comparison, we also constructed an alternative case which assumed wood harvesting activities were distributed evenly across all forested grid cells on a country specific basis, independent of proximity to other land-use activity.

Methodology for calculating land-use transitions

Determining agricultural land-use transitions. We used a book-keeping approach to calculate land-use transition rates given the data inputs and additional factors discussed above. We first determined annual transitions for each grid cell between four possible land-use types (crop, pasture, primary, and secondary). To determine these, we first calculated minimum transition rates between just three types (crop, pasture, and other; other was defined as the sum of primary and secondary), based on the gridded annual input data on land-use patterns. With only three types, unique minimum transitions (i.e. solutions to Eqn (1) were easily determined. Non-minimum transitions associated with shifting cultivation and wood harvest were then calculated. In cases of shifting cultivation, land-use transitions from crop to other, other to crop, pasture to other, and other to pasture were all increased by the abandonment rate of agricultural land. Transitions from other were then partitioned into transitions from primary and secondary based on the prioritization chosen and availability. All transitions from crop or pasture to other were defined as transitions to secondary. The amount of wood cut in converting land to agriculture was determined by overlaying these transitions with estimates of biomass density.

Determining area cleared by wood harvest

For each country, the amount of annual wood harvest that was met by land conversion to agriculture depended on the assumed inclusiveness of wood harvest and other factors described above. Any remaining unmet wood harvest following land conversions was met through additional explicit wood harvesting. Wood harvesting of primary land was represented by the transition primary to secondary. Harvesting of secondary land was represented by the age- (and biomass-) resetting transition secondary to secondary. To calculate these transitions in area units, wood harvest was converted to area units using the carbon density of land affected.

The selection of specific grid cells to be logged within a country depended on the presence of forest, the priority of land for conversion/wood harvesting (primary or secondary), and the assumed spatial pattern of wood harvesting. In cases where primary land was prioritized, transitions from primary to secondary were calculated proportionally for each grid cell that met the spatial pattern of wood harvesting criteria described above. If primary forest in a country could not meet the demand, or if secondary forests were prioritized, secondary forests were logged based on maturity. Logging of secondary forests was implemented assuming an average probability of harvest vs. biomass function parameterized from detailed age-specific harvesting algorithms previously developed and applied in the US (Hurtt *et al*., 2002). If mature secondary forests could not satisfy the wood harvest demand for a country, primary forests were cut to meet the remaining demand. In cases when both primary forest and mature secondary forest could not meet national wood harvest demand, remaining (nonmature) secondary forests were cut proportionally from grid cells. Finally, in rare cases when the combination of available primary and secondary forest within a country could not meet national wood harvest demand, non-forest grid cells were harvested proportionally to meet remaining demand. (Note that a nonforested $1^\circ \times 1^\circ$ grid cell with mean aboveground biomass density $<2\,\mathrm{kg\,C\,m^{-2}}$ could have scattered woody vegetation.)

Results

In total, 216 land-use history reconstructions were generated using all combinations of input data and factors described above (Table 1). The results from these reconstructions are summarized in aggregated statistics on transitions, and in estimates of resulting secondary land area and age. To evaluate sensitivity, we paired simulations where only a single factor was changed, and calculated the difference for each pair of simulations for four output metrics: total gross transitions for 1700–2000, total net transitions for 1700–2000, global area of secondary in 2000, and global mean age of secondary in 2000. Generally, the sensitivity of each factor varied by output metric, and depended strongly on other model assumptions (Fig. 5). These results are followed by a more detailed description of the results for two focal cases that are based on the best information available.

Aggregate results and model sensitivity

Gross transitions. Gross transitions are a measure of all land-use change activity; specifically, they are the sum of the absolute value of all land-use transitions. In most cases, total gross transitions (the sum of gross transitions across the domain) increased through time, from 0.1 to $1 \times 10^6\,\mathrm{km^2\,yr^{-1}}$ in the early 1700s to 0.5–$4 \times 10^6\,\mathrm{km^2\,yr^{-1}}$ by the end of the 1900s (Fig. 4a). High values were generated in cases with non-minimum residency times for agriculture and maximum wood harvest. Low values were generated by minimum transitions and no wood harvest.

In paired comparisons, two factors had a large impact on total gross land-use transitions: the residency time of agricultural land, and the land-use history product used (Fig. 5a). The dominant factor was the residency time of agriculture. Applied globally, cases with shifting cultivation generated 400–$800 \times 10^6\,\mathrm{km^2}$ more gross transitions than the minimum transition assumption. Applied only in the tropics, these differences were about half as large. Land-use history was also a sensitive factor. SAGE/HYDE generated more activity than the HYDE land-use history alone. This result was primarily driven by the fact SAGE/HYDE had more widespread low-density agricultural land use which in

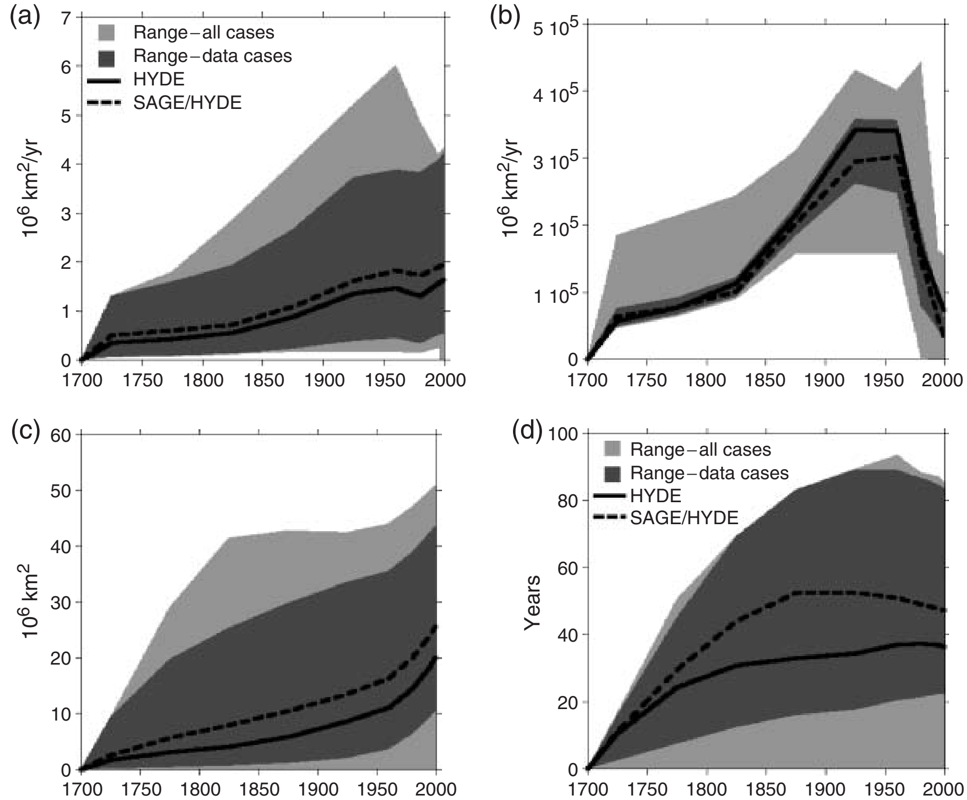

Fig. 4 Simulated range in (a) total gross transitions, (b) total net transitions into use, (c) total secondary land area 1700–2000, and (d) global mean age of secondary land 1700–2000, for all runs (light gray region; $n = 216$) and data-based runs (dark gray region; $n = 48$), and 'focal case' simulations with HYDE (heavy solid line) and SAGE/HYDE (heavy dashed line) input data on land-use history. All runs include cases with and without historical data and wood harvest used as inputs. Data-based runs use reconstructed wood harvest, HYDE or SAGE/HYDE land-use history.

turn provided increased access and opportunities for shifting agriculture in reconstructions that included it.

Net transitions. Net transitions measure only net changes in land use (i.e., net transitions exclude wood harvest on secondary forests, and land abandonment that is offset by gains). Net land-use transitions were smaller than gross. Total net land-use transitions generally peaked in the early- to mid-1900s at 0.15–$0.4 \times 10^6\,\mathrm{km}^2\,\mathrm{yr}^{-1}$ (Fig. 4b). Estimates for the 1700s and late 1900s were in the range 0.05–0.25 and 0.01–$0.15 \times 10^6\,\mathrm{km}^2\,\mathrm{yr}^{-1}$, respectively. High values were due to cases with high wood harvest, primary land priority, and that excluded wood clearing from agricultural land conversion in wood harvest; low values occurred with opposite settings for these factors.

In paired comparisons, total net land-use transitions depended most strongly on wood harvest history, and secondarily on the inclusiveness of wood harvest (Fig. 5b). High values resulted from cases that require more wood harvesting on primary land and thus generate more net land-use transitions. Total net transitions were also sensitive to the land-use history. HYDE and SAGE/HYDE had different distributions of cropland area, and different degrees of permanent cropland abandonment (e.g. the relocation of cropland from the eastern to the midwestern US). With land-clearing included toward wood harvest, this influenced how much additional land had to be cut to meet wood-harvest demand. The case using neither HYDE nor SAGE/HYDE had no abandonment of agricultural land and, thus, generally small total net transitions.

Secondary area. Patterns of gross and net transitions have implications for estimates of secondary land. For secondary land area, the results from all simulations ranged from no increase to an increase of $51 \times 10^6\,\mathrm{km}^2$ from 1700 to 2000 (Fig. 4c). The full range was bounded on the bottom by cases in which crop and pasture land area increased monotonically, and on the top by cases that maximized wood harvest, prioritized primary land for land-use changes, and assumed nonminimum

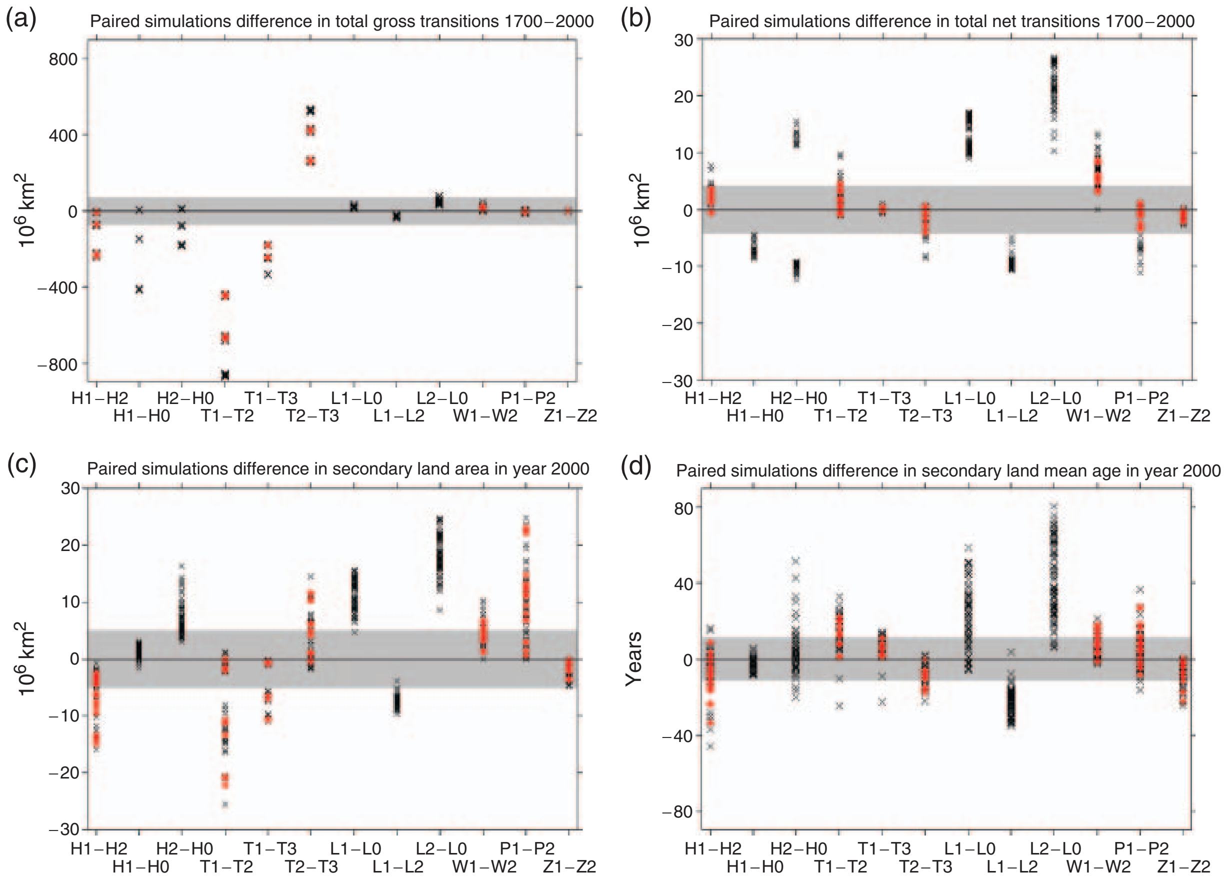

Fig. 5 Model sensitivity to factors (Table 1) for (a) total gross transitions integrated from 1700–2000, and (b) total net land-use transitions integrated from 1700–2000, (c) total secondary land area in 2000, and (d) global mean age of secondary land in 2000. Each symbol represents the difference in the simulated value for a pair of simulations that differ in only in the factor identified on the horizontal axis. For example, the first set of points represents the difference between 72 pairs of simulations with HYDE (H1) and SAGE/HYDE input data on land-use history (H2), with each pair having all other parameters equal. Red diamonds are for paired simulations that are both 'data based' (i.e. H1 or H2, and L1), whereas X's are for paired simulations that are not 'data-based' (i.e. H0 or L0 or L2 for one or both of the pair). The thickness of the shaded horizontal band in each panel is twice the difference between results for the HYDE and SAGE/HYDE focal-case runs.

residency times for agriculture. Data-based reconstructions produced an intermediate range of secondary land of 10–44 $\times 10^6$ km^2.

Secondary area in 2000 was most sensitive to the priority of land for land use, and the residency time of agricultural land (Fig. 5c). This sensitivity varied strongly as a function of the values for the other factors. For example, land priority had a relatively large impact on secondary land in cases with non-minimum residence time for agriculture because of the large amount of secondary present in these cases. Similarly, the abandonment of agricultural land generated more secondary land when primary land was a priority for land-use change. Secondary area was also sensitive to land-use history, with SAGE/HYDE having more secondary than HYDE due to more diffuse agriculture (as noted above). Wood harvesting was most important when wood from clearing for agriculture was excluded from harvest.

Secondary age. The mean age of secondary was calculated each year for each grid cell and aggregated to a global mean age. The global mean age was defined as zero in 1700. By 2000, the range across all simulations was 0–86 years (Fig. 4d). For data-based simulations, the range was 22–84 years. Low mean age values resulted from cases with secondary land priority and in which wood from agricultural clearing counted toward harvest. High values resulted from cases with minimum transitions, primary land priority, explicit wood harvesting only, and either the SAGE/HYDE or 'no land-use history' driver.

The mean age of secondary in 2000 was most sensitive to land-use history and wood harvesting

(Fig. 5d). SAGE/HYDE generated a younger secondary mean age in 2000 than HYDE when primary land was prioritized, due to more extensive shifting cultivation. Almost all simulations with wood harvesting had older secondary than the corresponding simulations without it. Wood harvesting generally added more secondary land, and this land typically had longer periods of recovery before reharvest than fallow agricultural land.

Two focal cases

Two reconstructions were chosen for detailed analyses based on three criteria: quantity of data inputs, the reasonableness of model assumptions, and comparisons of estimates of secondary land area and age to independent estimates. One case was based the detailed land-use history reconstruction of HYDE, and the other on SAGE/HYDE. Both were driven with the FAO-based wood harvest reconstruction. Wood harvesting activities were concentrated in forested grid cells with prior land-use activities; a recent FAO study on forest accessibility that found that about half the world's forest was with 10 km of major transportation infrastructure (roads, railways, rivers), and about three-quarters within 40 km (FAO, 2001). Both cases applied minimum transitions outside the tropics and nonminimum transitions (e.g. shifting cultivation) in the tropics, roughly corresponding to the distribution of shifting cultivation in the mid-late 1900s (Butler, 1980; Lanly, 1985). Estimates of secondary land were compared with estimates from FAO (FAO, 1998) for selection of remaining factors (Table 3). Based on these considerations, primary land was used as a priority for land conversion and wood harvest on all continents, except Eurasia, where secondary land was prioritized. In addition, wood harvesting from land conversion was not counted towards fulfilling national wood harvest demand, except in Eurasia for the SAGE/HYDE case.

Integrated transitions, secondary area, and secondary age

The results from the two focal cases tended to be well within the range of all simulations in terms of integrated transitions, secondary land area, and secondary land age (Fig. 4). Total gross transitions rose fairly steadily from 1700 to 2000 (Fig. 4a). In contrast, total net transitions peaked at a much lower rate in the early 1990s (Fig. 4b), and declined thereafter as agricultural expansion slowed and abandonment of agricultural land increased. Estimates of secondary land area generated 1700–2000 were $20–25 \times 10^6\,km^2$ for HYDE and SAGE/HYDE cases, respectively (Fig. 4c); in each case about half of this was forested. The mean age of secondary land rose in both cases to between 37 and 55 years, and declined thereafter (Fig. 4d).

Land clearing for agricultural in the HYDE case rose from the early −1700s to a peak of $\sim 0.8 \times 10^6\,km^2\,yr^{-1}$ in the mid-1900s, then dropped to $\sim 0.6 \times 10^6\,km^2\,yr^{-1}$ by the late-1900s (Fig. 6a). Until the mid-1900s, about two-thirds of this annual clearing was associated with shifting cultivation. The abandonment of more permanent agricultural land (i.e. not shifting cultivation) was less, and rose from near zero before 1950 to $\sim 0.1 \times 10^6\,km^2\,yr^{-1}$ in 2000. Land clearing for wood harvest rose to $\sim 0.3 \times 10^6\,km^2\,yr^{-1}$ in 2000. Until 1900, almost all wood harvesting occurred on primary land, but wood harvesting on secondary land rose to about 40% of the total by 2000. These patterns were similar for reconstructions with the SAGE/HYDE land-use history, but with 20–40% higher rates of clearing for agriculture and shifting cultivation, and a larger fraction of wood harvest from secondary land (Fig. 6b). Cumulatively, $12–15 \times 10^6\,km^2$ of primary forest and $4–6 \times 10^6\,km^2$ of secondary forest were cleared to meet wood harvest demand. Cumulative estimates of biomass cut in land conversion to agriculture globally 1700–2000 (including shifting cultivation in the tropics) were 163 Pg C (HYDE) and 244 Pg C (SAGE/HYDE), and exceeded

Table 3 Estimates of continental secondary and total forest areas ($10^6\,km^2$) in 1990

	Secondary forest area		Total forest area	
Region	FAO (1998)*	Range†	FAO (1998)*	Range†
North and Central America	4.6	0.6–3.7	6.2	9.8–10.0
South America	3.2	0.1–2.3	8.7	8.4–8.4
Africa	2.5	0.2–1.6	4.0	4.1–4.3
Eurasia	4.2	0.8–14.0	12.0	17.5–18.7
Oceania	0.5	0.0–0.3	0.9	*0.7–0.8*
Global	*15.0*	*2.1–21.9*	*32.0*	*40.5–42.2*

*FAO (1998) total values do not include all countries, but are estimated to be within 10% of FAO total global forest area.
†Ranges from data-based runs (excluding H2, L0, and L4; see Table 1).

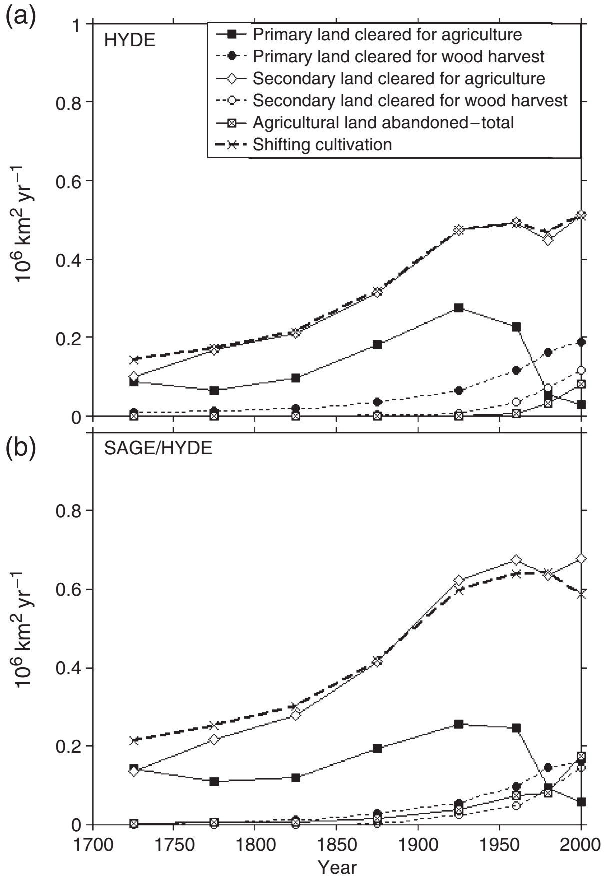

Fig. 6 Mean land-use transition rates for (a) HYDE and (b) SAGE/HYDE. Agriculture includes both crop and pasture. 'Agricultural land abandonment' refers land transitions out of agriculture (crop + pasture) that are not the result of shifting cultivation. 'Agricultural shifting cultivation' refers to land transitions out of agriculture that are the result of shifting cultivation.

global wood harvest every year until the 1960s, when agricultural expansion slowed while wood harvest continued to increase.

Spatio-temporal patterns of transitions, secondary area, and secondary age

The spatio-temporal pattern of transitions, secondary land area, and secondary mean age were computed annually. Gross transitions were largest in the tropics in the focal cases, due to shifting cultivation. Africa had 38–47% of total gross transitions in both focal cases in all three centuries, though the range in values for all other cases was always larger for Eurasia (Table 4). Low-intensity gross transitions were much less widespread with the HYDE input data (Fig. 7a–c) than with the SAGE/HYDE input data (Fig. 8a–c). Cropland in the SAGE database was more widely distributed than in the HYDE database, and these additional grid cells, with low fractional crop area values, experienced low intensity gross land-use transitions due to both shifting cultivation and wood harvesting. By the 1900s, land-use activities had spread to cover most of the world except northern Canada, northern Siberia, and small parts of the Tibetan Plateau, Australia, and central Africa when the SAGE/HYDE land-use history was used. With the HYDE land-use history, these areas expanded and also included large areas of tropical America, tropical Africa, and the western US.

Eurasia had the largest area of total net land-use transitions in both focal cases in all three centuries, and also the largest range in values (Table 4). Total net land-use transitions were highest in eastern China in the 1700s, in the central US, central China, and north-eastern Australia in the 1800s, and in northeast and western China, central Australia, the Sahel, eastern and southern Africa, central Asia around the Aral Sea, and southern Brazil and northern Argentina in the 1900s (Figs 7d–f, 8d–f). Large areas of low intensity gross and net land-use transitions are generated by wood harvest activity across northern Africa and the Middle East. Spatial patterns of gross and net land-use transitions were similar for both HYDE and SAGE/HYDE input data.

Africa had the largest area of secondary land in both focal cases in 1800 and 1900, but by 2000 secondary land area in Eurasia was larger (Table 5). For the focal case based on HYDE land-use history, secondary occupied a small fraction of the area in most of northern and southern Africa and the Middle East in 1800 (Fig. 9a). By 1900, secondary occupied small fractions of eastern North America, Europe, India, and Southern Brazil (Fig. 9b). In 2000, secondary occupied much of eastern North America, Fenno-Scandia and parts of western Europe, and the southern forests of Russia, while low density secondary land is common in Australia, Argentina, central North America, and the rest of Europe (Fig. 9c). For the SAGE/HYDE case, the pattern of secondary land are similar, though low-density secondary land is much more widespread in 1800, 1900, and 2000 (Fig. 10a–c).

The mean age of secondary in the HYDE case nearly doubled between 1800 and 2000 for North and Central America, but had much less net change for the other continents; in the SAGE/HYDE case, mean ages were somewhat less variable between continents than the HYDE case (Table 5). The mean age of secondary became more spatially variable through time in both cases (Figs 9d–f, 10d–f). By 2000, the oldest mean secondary land was in the eastern US, southern Sweden, eastern Europe, and Namibia (HYDE case; Fig. 9d–f), and throughout sub-Saharan Africa

Table 4 Mean gross and net land-use transitions by century

	Mean gross land-use transitions (10^3 km^2 yr^{-1})				Mean net land-use transitions (10^3 km^2 yr^{-1})			
	HYDE	SAGE/HYDE	Range (data)*	Range (all)†	HYDE	SAGE/HYDE	Range (data)*	Range (all)†
1700–1800 mean								
North and Central America	31	39	3–78	3–151	3	6	3–6	3–24
South America	66	65	6–99	6–145	5	6	5–6	5–20
Africa	177	259	11–309	10–318	11	12	11–12	10–45
Eurasia	110	185	42–919	38–924	42	42	33–56	31–95
Oceania‡	6	6	6–46	6–130	6	5	5–6	5–17
Global	*390*	*554*	*68–1451*	*62–1667*	*67*	*71*	*57–86*	*54–201*
1800–1900 mean								
North and Central America	77	90	30–256	19–412	36	36	27–37	19–71
South America	110	114	13–181	13–395	12	12	12–12	12–22
Africa	302	395	29–464	27–748	29	27	27–29	25–63
Eurasia	185	264	80–1291	66–1661	71	62	57–82	52–134
Oceania‡	45	45	18–119	17–353	17	16	16–17	16–17
Global	*720*	*908*	*170–2311*	*142–3570*	*165*	*152*	*138–176*	*123–308*
1900–2000 mean								
North and Central America	122	144	57–550	20–633	40	31	17–42	15–48
South America	249	293	40–419	19–562	31	32	28–32	16–44
Africa	580	657	84–759	35–1081	68	57	54–69	28–79
Eurasia	334	509	176–1847	73–2305	116	103	76–129	47–159
Oceania‡	103	107	33–256	18–494	21	19	19–21	12–23
Global	*1389*	*1711*	*391–3830*	*164–5076*	*275*	*242*	*194–293*	*118–353*

*Range of all simulations using data-based input (H1 or H2 and L1; see Table 1).
†Range of all simulations.
‡Australia, New Zealand, and Papua New Guinea only.

(SAGE/HYDE case; Fig. 10d–f). Wood harvesting generated the majority of the secondary land in eastern North America, northern Africa and the Middle East, and the boreal zone of Eurasia in both cases (Fig. 11a and c), while abandonment of crop and pasture land (and shifting cultivation in the tropics) generated most of the secondary land in the Great Plains of North America, temperate Europe and central Asia, sub-Saharan Africa, and Australia (Fig. 11b and d).

Discussion

Our analyses introduce several new factors into global gridded land-use history reconstructions. We estimated global gridded land-use transitions for the period 1700–2000. Information on these transitions is necessary in order to specify the pattern, amount, and type of land that changes use over time. The transitions themselves imply direct alterations to the land surface (e.g. land clearing, land abandonment), and have lasting implications for affected land (e.g. secondary area, secondary age). Moreover, the transitions are not directly inferable from information on land-use types alone, unless that information has extremely fine spatial and temporal resolution.

Previous global gridded land-use history products have focused on patterns of land use, and have not included estimates of land-use transitions or activities such as shifting cultivation, or wood harvesting (Ramankutty & Foley, 1999; Klein Goldewijk, 2001). Related modeling studies using land-use history information have either been at very coarse spatial resolution (e.g. continental scale; Houghton, 1999, 2003), noncomprehensive, or nonexplicit about the details of these factors. For example, the analyses of McGuire *et al.* (2001) on the carbon balance of the terrestrial biosphere did not include pasture or wood harvesting. In addition, historical cropland data were reclassified in that study into homogeneous $0.5^\circ \times 0.5^\circ$ pixels and subsequently temporally filtered to prevent shifting in and out of cropland, implying that the analyses of shifting cultivation were crude or nonexistent. More recently, Brovkin *et al.* (2004) evaluated the role of land-cover change over the last 150 years for atmospheric CO_2 increase and climate change using a coupled carbon and climate model. The study used input from the two land-use history data sets also used in this study

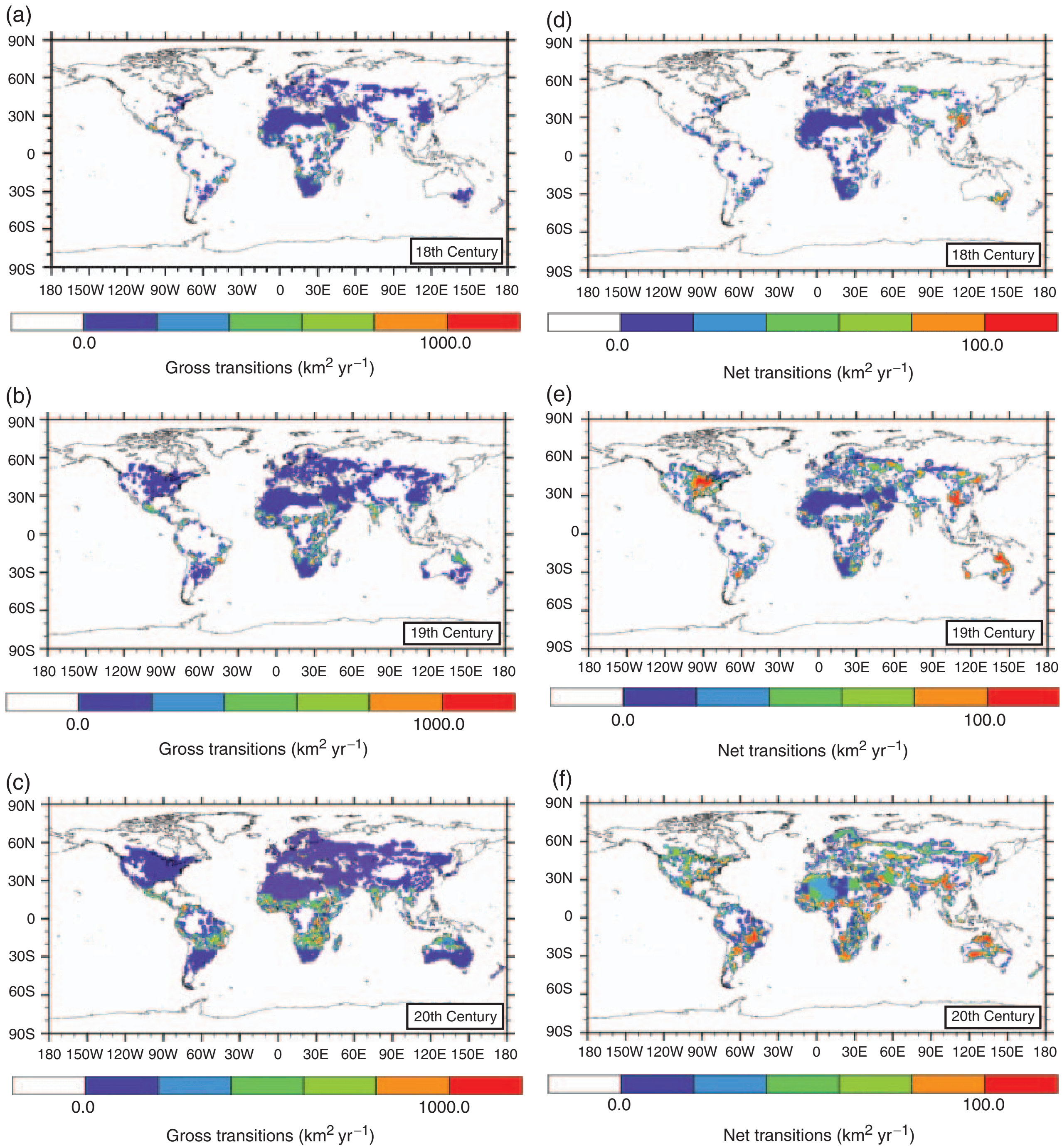

Fig. 7 For simulations with HYDE land-use history, mean annual gross land-use transitions in each $1^{\circ} \times 1^{\circ}$ grid cell during (a) 18th century, (b) 19th century, and (c) 20th century, and total integrated net land-use transitions in each $1^{\circ} \times 1^{\circ}$ grid cell during (d) 18th century, (e) 19th century, and (f) 20th century. Note that the scale for gross transitions is 10 times the scale for net transitions.

(Ramankutty & Foley, 1999; Klein Goldewijk, 2001), but did not address wood harvesting or details of land-use transitions. The phenomena we have emphasized in our study (e.g. wood harvest, and shifting cultivation) would amplify the uncertainty in and potentially alter the conclusions of these and other similar studies. In addition to the omitted direct effects of wood harvesting, our analyses indicate that omitting shifting cultivation and wood harvesting would lead to underestimates of secondary land area created by land use globally of 70–90% by 2000. In regional studies, wood harvesting and the distribution and characteristics of secondary

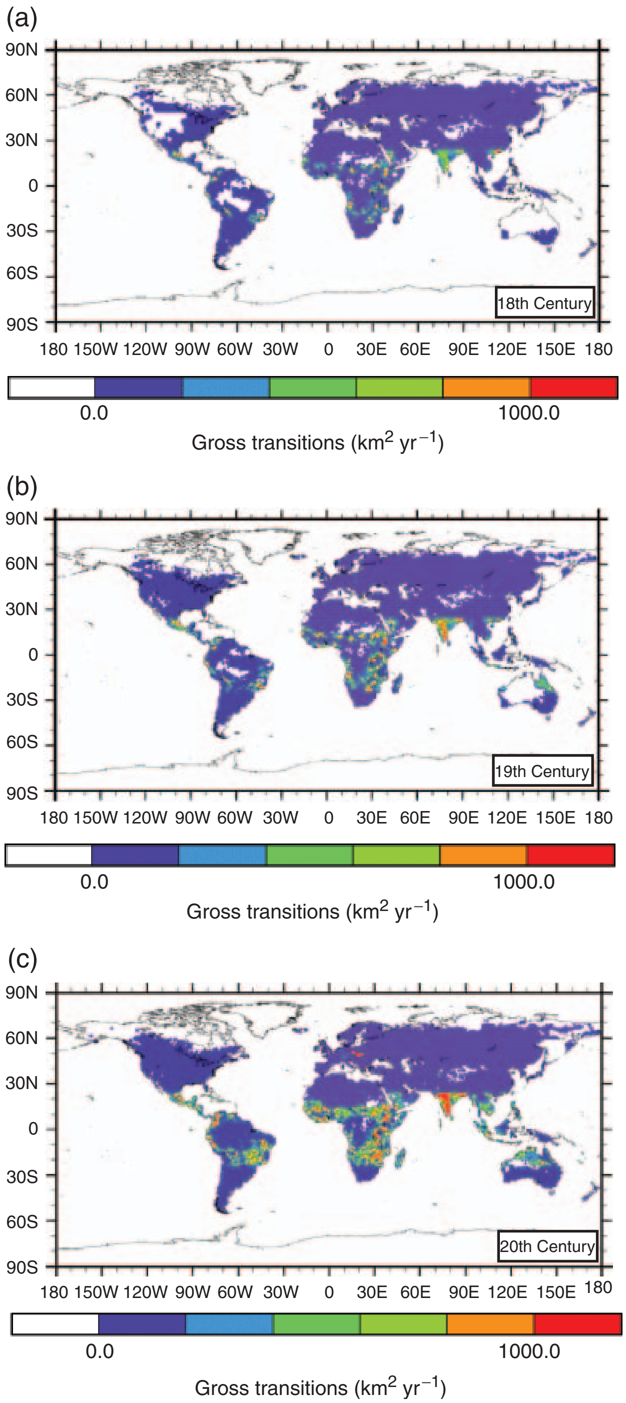

Fig. 8 Same as Fig. 7, but for simulations with SAGE/HYDE land-use history.

lands have been implicated in strongly affecting carbon balance, atmospheric conditions, and even climate (Turner *et al.*, 1995; Houghton, 1999, 2003; Pacala *et al.*, 2001; Goodale *et al.*, 2002; Hurtt *et al.*, 2002; Roy *et al.*, 2003; Purves *et al.*, 2004).

For global analyses, direct spatial data on historical land-use transitions are not available. Historical estimates of relevant phenomena are uncertain and often rely on extrapolating patterns back in time with per-capita ratios, and/or assuming invariant spatial patterns of land use over time when information is limiting (e.g. Houghton, 1999; Ramankutty & Foley, 1999; Klein Goldewijk, 2001). Generally, little or no attention has been given to the uncertainty associated with these

Table 5 Secondary land area and mean age of secondary land

	Secondary land area (10^6 km^2)				Mean age of secondary land (y)			
	HYDE	SAGE/ HYDE	Range (data)*	Range (all)†	HYDE	SAGE/ HYDE	Range (data)*	Range (all)†
1700–1800 mean								
North and Central America	0.40	0.66	0.00–1.92	0.00–4.85	27.8	34.5	1.3–41.1	0.0–41.1
South America	0.63	0.75	0.00–1.13	0.00–4.53	24.5	28.2	1.3–59.4	0.0–72.4
Africa	1.85	4.62	0.07–5.19	0.00–9.05	26.3	39.7	9.6–45.9	0.0–54.6
Eurasia	0.63	0.76	0.40–14.28	0.00–17.36	38.4	37.6	11.9–52.4	0.0–57.7
Oceania‡	0.00	0.03	0.00–0.30	0.00–3.75	18.9	37.8	1.0–37.8	0.0–37.8
Global	*3.50*	*6.83*	*0.47–22.81*	*0.00–39.53*	*28.3*	*37.7*	*10.5–58.7*	*0.0–58.7*
1800–1900 mean								
North and Central America	1.04	1.76	0.02–4.07	0.00–5.68	33.6	48.7	1.9–66.8	0.0–73.5
South America	1.01	1.45	0.01–2.07	0.00–4.42	24.6	38.3	1.6–55.2	0.0–67.1
Africa	2.79	6.04	0.23–6.57	0.00–9.97	28.0	63.7	23.1–71.3	0.0–73.0
Eurasia	1.61	1.98	1.13–17.66	0.00–21.03	56.7	54.0	20.2–79.1	0.0–109.4
Oceania‡	0.14	0.26	0.01–0.68	0.00–2.87	15.3	38.5	3.3–61.3	0.0–73.2
Global	*6.59*	*11.50*	*1.40–31.05*	*0.00–43.98*	*35.1*	*56.0*	*18.6–88.2*	*0.0–88.2*
1900–2000 mean								
North and Central America	3.29	4.01	1.58–5.90	0.00–7.19	51.7	54.7	14.1–61.4	0.0–87.9
South America	2.03	3.75	0.23–4.60	0.00–5.16	23.8	38.6	3.4–48.3	0.0–87.7
Africa	6.21	8.19	2.56–8.58	0.00–11.02	28.6	52.7	24.1–54.0	0.0–99.2
Eurasia	7.32	8.24	6.12–23.30	0.00–26.14	42.2	43.6	23.0–72.2	0.0–95.3
Oceania‡	0.92	1.23	0.46–2.05	0.00–2.15	16.8	35.6	7.2–42.9	0.0–53.9
Global	*19.78*	*25.42*	*10.95–44.44*	*0.00–51.66*	*36.4*	*47.2*	*22.2–83.5*	*0.0–85.5*

*Range of all simulations using data-based input (H1 or H2 and L1; see Table 1).
†Range of all simulations.
‡Australia, New Zealand, and Papua New Guinea only.

reconstructions, and the sensitivity of alternative assumptions. To evaluate this, we developed and analyzed a large set of reconstructions using different assumptions. Alternative assumptions about the details of land-use history substantially affected all four aggregate model diagnostics: total gross transitions, total net transitions, area of secondary land, and age of secondary land. Shifting cultivation substantially affected gross transitions, and the area and age of secondary lands. The prioritization of primary or secondary land for use in land conversion and wood harvesting, and the accuracy and inclusiveness of wood harvest statistics all substantially affected estimates of net transitions, area and age of secondary land. The spatial distribution of wood harvesting did not substantially affect these aggregate statistics, but did substantially affect spatial patterning of secondary lands.

We also evaluated two cases in detail. Comparisons between these cases suggests differences in terms of gross transitions, secondary land area, and land-use activity in 'remote' but nonarctic areas. These differences were largely attributable to the fact that the spatial pattern of cropland is more diffuse in SAGE/HYDE product, probably because it was derived from a finer resolution analysis. There was less of a difference between HYDE and the 'no land-use history data' case than between the two focal cases, because the 'no data' case was based on a linear progression to the final state of the HYDE product, and there was less relocation of cropland land in the HYDE product than the SAGE product.

Rigorous validation of these products is difficult because the size and highly underdetermined nature of the problem necessitates the use of as much information as possible for input, and because many of our model outputs are new and lack independent data sets for comparison. We compared our results to several additional lines of information as a means of partial validation. Global wood harvest 1700–2000, including slash, was estimated to be 112 Pg C. Total biomass cut in land conversion to agriculture during the period was 163 Pg C (HYDE) and 244 Pg C (SAGE/HYDE). Houghton (1999) estimated for the period 1850–1990 near-global wood harvest of 106 Pg C, and slash production (from land conversion and wood harvesting) of 149 Pg C, for a total of 255 Pg C. For comparison, wood harvest from our reconstruction for the same period (1850–1990) was 100 Pg C, including slash. Wood clear-

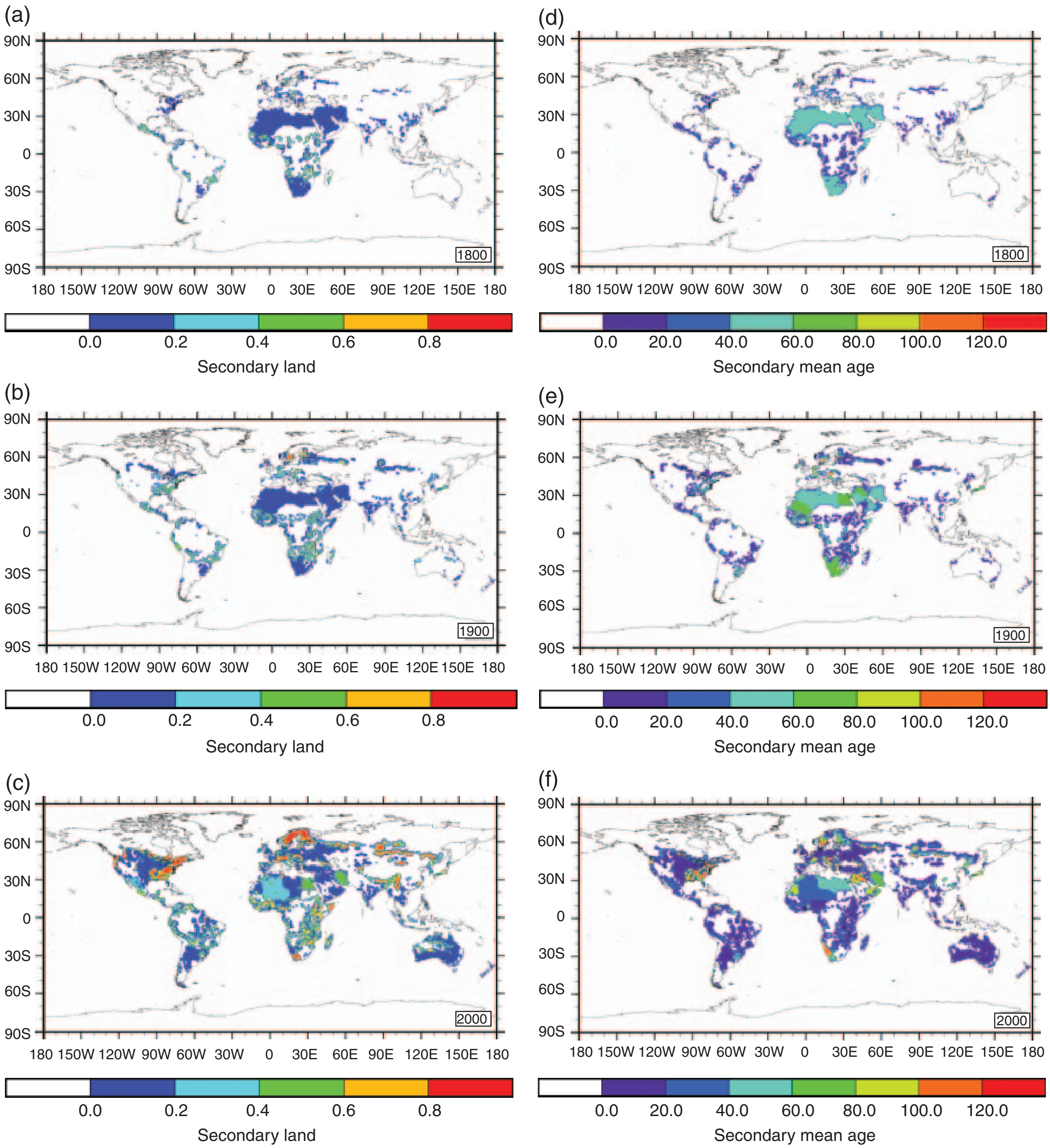

Fig. 9 For simulations with HYDE land-use history, secondary land area fraction of each $1° \times 1°$ grid cell in (a) 1800, (b) 1900, and (c) 2000, and mean age of grid cell's secondary land in (d) 1800, (e) 1900, and (f) 2000. Secondary land is generated by abandonment of cropland or pasture and by wood harvesting.

ing for land conversion to agriculture 1850–1990 was an additional 105 Pg C (HYDE) or 153 Pg C (SAGE/HYDE), implying the total wood biomass cut 1850–1990 was 205 Pg C (HYDE) or 258 Pg C (SAGE/HYDE), or 85 –101% of the Houghton (1999) estimate.

From 1700 to 2000, about 18×10^6 km^2 were cut to produce 112 Pg C of wood. Cutting of primary forest accounted for 66% and 75% of the total wood harvest clearing in the HYDE and SAGE/HYDE simulations, respectively. For the conterminous US, 94% of

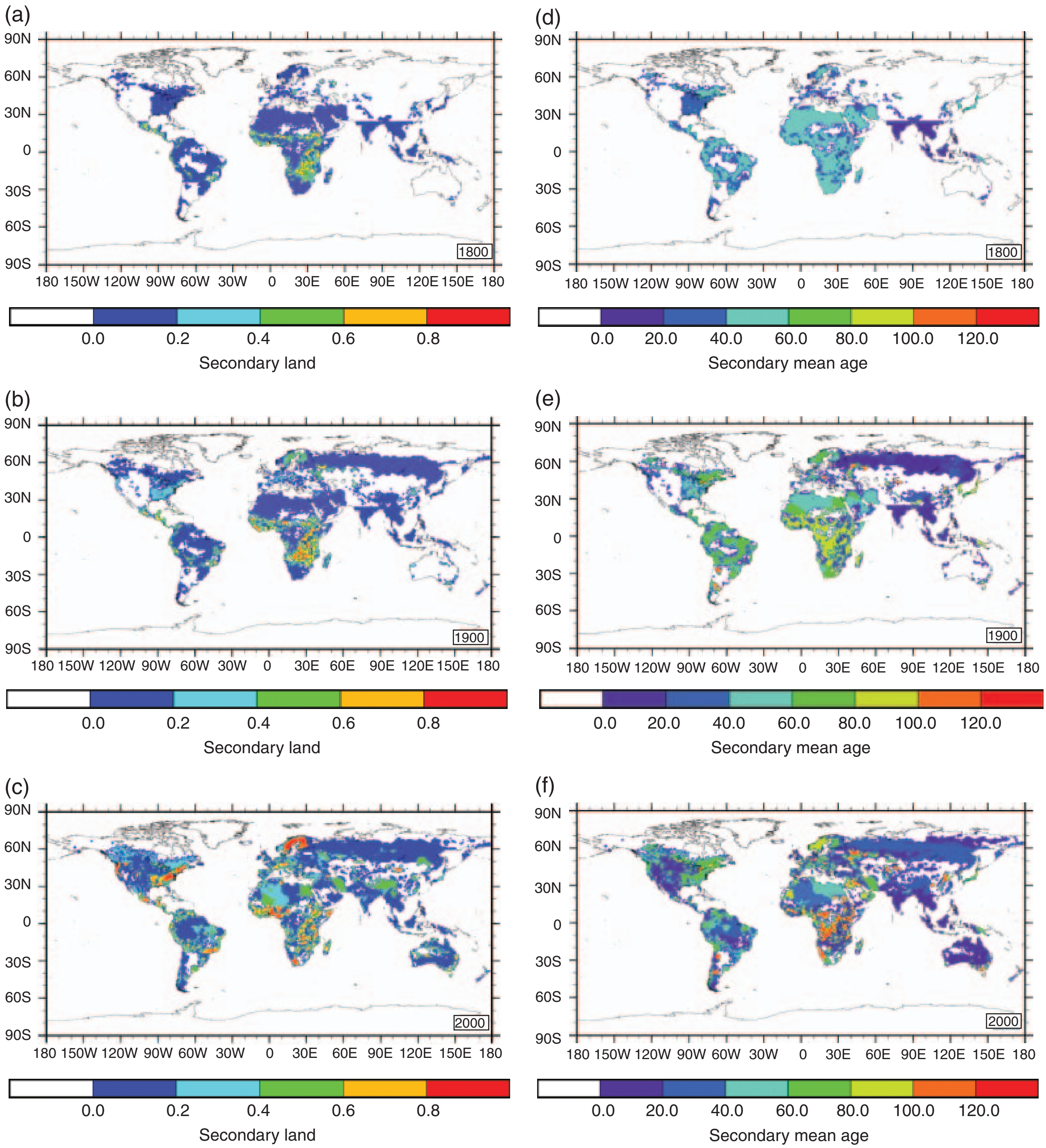

Fig. 10 Same as Fig. 9, but for simulations with SAGE/HYDE land-use history.

remaining forest in 2000 was secondary in the HYDE focal case, and >99% was secondary in the SAGE/HYDE focal case. These estimates are broadly consistent with previous studies that suggest the vast majority of coterminous US forests are in recovery (e.g. Birdsey & Heath, 1995; Turner *et al*., 1995; Turner *et al*., 1995b; Pacala *et al*., 2001; Hurtt *et al*., 2002; Goodale *et al*., 2002).

They can also be compared with forest age data in the region. A synthesis of US Forest Inventory (FIA) data aggregated to $1^\circ \times 1^\circ$ (P. Moorcroft, personal communication) suggests a mean age of forested land east of the Mississippi of approximately 42–48 years. Corresponding estimates from the HYDE and SAGE/HYDE focal cases were 33 and 42 years, respectively.

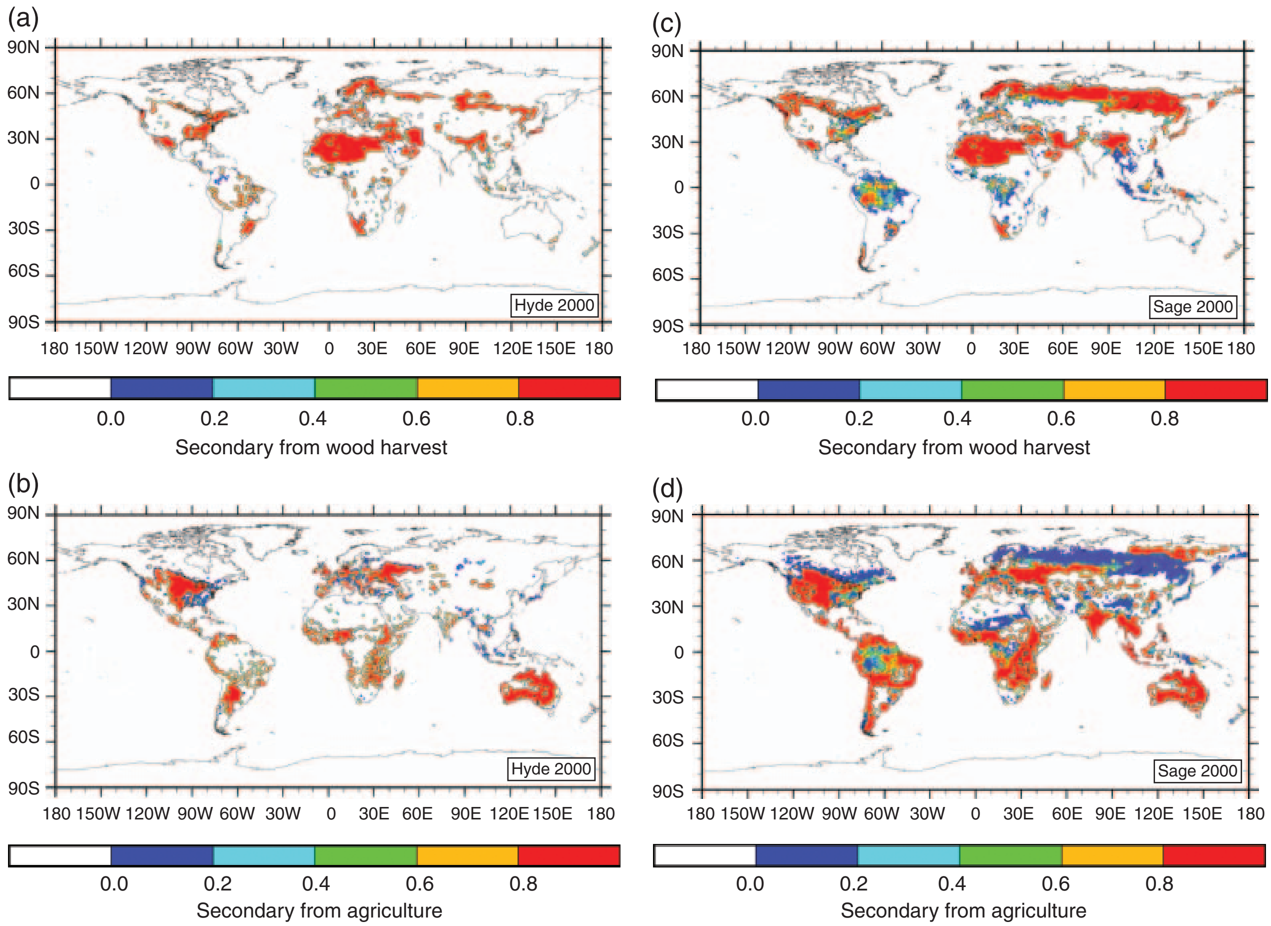

Fig. 11 Fraction of secondary land in a grid cell in year 2000 that was created in the HYDE case by (a) wood harvesting, and (b) agriculture, and in the SAGE/HYDE case by (c) wood harvesting, and (d) agriculture. Agriculture generates secondary land primarily through shifting cultivation, but also through abandonment of more permanent crop or pasture land. Grid cell values in panel (a) plus values in panel (b) (or panel (c) plus panel (d) add to 1.0 if the grid cell contains secondary land, and to 0.0 otherwise. The fraction of each grid cell actually occupied by secondary land in 2000 is shown in Figs 9c and 10c.

In both focal cases, shifting cultivation was the largest contributor to gross land-use transitions throughout the 1700–2000 period, with its impact increasing from $0.2 \times 10^6\,km^2\,yr^{-1}$ in the 1700s to $0.5–0.6 \times 10^6\,km^2\,yr^{-1}$ in 2000. Rojstaczer *et al*. (2001) synthesized available data to estimate a contemporary mean per capita shifting agriculture clearing rate of 0.17 ($\pm$16%) ha yr^{-1}, and that 0.45 ($\pm$ 16%) billion people currently engaged in shifting agriculture, suggesting a clearing rate of $0.5–1.0 \times 10^6\,km^2\,yr^{-1}$. Shifting cultivation also cleared (including reclearing) more than ten times more land than wood harvesting during the 1700s and 1800s, with this declining to about twice as much land as wood harvesting by 2000 (Fig. 11). About $6–10 \times 10^6\,km^2$ of tropical land (forest and nonforest) were estimated to be in shifting cultivation and this area increased by $0.4–0.7 \times 10^6\,km^2$ from 1980 to 2000. For comparison, Lanly (1985) estimated that about $4 \times 10^6\,km^2$ of tropical forest were in shifting cultivation fallow in 1980. Global forest resource assessments by the FAO (FAO, 1996, 2001) report about $2 \times 10^6\,km^2$ in short and long fallow forests and another $2 \times 10^6\,km^2$ in fragmented forest; these areas increased by 0.3×10^6 and $0.5 \times 10^6\,km^2$, respectively, from 1980 to 2000. Rojstaczer *et al*. (2001) reported that slightly less than half of all shifting cultivation occurs in savannah and slightly more than half in tropical forest (most of this in tropical secondary forest). Applying the Rojstaczer *et al*. (2001) estimate of the fraction of fallow in forests to the Langley and FAO estimates of fallow forest area gives an estimate of total shifting cultivation fallow of $4–8 \times 10^6\,km^2$, approximately consistent with estimates of this study.

While the history of land-use transitions and wood harvest can never be known with certainty for every grid cell, estimates can be constrained with available information. Despite the progress reported here, our results depend on uncertain inputs, and rely on several simplifying assumptions that warrant future attention.

Our analysis included a simple representation of shifting cultivation and found it to be an extremely important factor. The spatial pattern of wood harvesting within countries, though a relatively insensitive factor in national or global budgets, was very important regionally and locally. Our analyses did not include urban lands. Urban areas, while globally a relatively small area (Loveland *et al*., 2000), represent an intense alteration to the land surface and should be included in future analyses. Our analyses also did not include forest plantations. Forest plantations are about 5% of total global forest area, but 25% in northern Africa and the Middle East (FAO, 2001). Many of the countries in northern Africa and the Middle East also have small natural forest areas where precipitation is sufficient (e.g. coastal Algeria and Tunisia, northern Iran) (FAO, 2001), but these are not captured in our coarse resolution biomass product (Fig. 3). This may have led to overestimates of secondary land generated by wood harvesting in these regions (Figs 9, 10 and 12).

To improve estimates, research on land-use history should be continued and expanded with emphasis on the most sensitive and uncertain factors. In addition, field- and remote-sensing based estimates of vegetation structure could potentially be used to provide critical information on the contemporary spatial patterns of secondary forest area and age structure to help constrain the spatio-temporal patterns of land-use history (Frayer & Furnival, 1999; Lefsky *et al*., 1999; Dubayah & Drake, 2000; Harding *et al*., 2001; Goodale *et al*., 2002; Drake *et al*., 2002; Lefsky *et al*., 2002; Hurtt *et al*., 2004). To be most useful, these estimates need to be obtained globally. Future studies are also needed to specify land-management practices on agricultural lands, and to detail the changes to ecosystems that occur during land-use transition events. Differences in management, including crop type, harvesting schedule, tillage, irrigation and nutrient inputs, and the use of machinery, affect the structure and biogeochemical dynamics of these systems, and can have lasting impacts on the dynamics of recovering secondary lands (Dobson *et al*., 1997; Matson *et al*., 1997). Reconstructions of these activities should be developed and combined with the products developed here for more complete descriptions of anthropogenic changes to the land surface. These products, in turn, will require enhanced global models to account for these changes and improve our understanding of the affects of human activity on the Earth system.

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