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Comprehensive data set of global land cover change for land surface model applications

Shannon Sterling^{1,2} and Agnès Ducharne¹

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[1] To increase our understanding of how humans have altered the Earth's surface and to facilitate land surface modeling experiments aimed to elucidate the direct impact of land cover change on the Earth system, we create and analyze a database of global land use/cover change (LUCC). From a combination of sources including satellite imagery and other remote sensing, ecological modeling, and country surveys, we adapt and synthesize existing maps of potential land cover and layers of the major anthropogenic land covers, including a layer of wetland loss, that are then tailored for land surface modeling studies. Our map database shows that anthropogenic land cover totals to approximately 40% of the Earth's surface, consistent with literature estimates. Almost all (92%) of the natural grassland on the Earth has been converted to human use, mostly grazing land, and the natural temperate savanna with mixed C₃/C₄ is almost completely lost (~90%), due mostly to conversion to cropland. Yet the resultant change in functioning, in terms of plant functional types, of the Earth system from land cover change is dominated by a loss of tree cover. Finally, we identify need for standardization of percent bare soil for global land covers and for a global map of tree plantations. Estimates of land cover change are inherently uncertain, and these uncertainties propagate into modeling studies of the impact of land cover change on the Earth system; to begin to address this problem, modelers need to document fully areas of land cover change used in their studies.

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1. Introduction

[2] As a result of continuing population and economic growth, humans are altering huge swaths of the Earth's land surface through conversion of natural landscapes to cropland, built-up land, grazing land, inundated land, reservoirs, and tree plantations. It has been estimated that humans alter 39–50% of the Earth's land surface [Vitousek *et al.*, 1997]. Land cover is dominated by grazing, which takes place on roughly one fourth of the terrestrial Earth.

[3] Changes to the land surface impact major biogeochemical cycles [Holmes *et al.*, 2005], and directly alter climate through alterations to land-atmosphere fluxes of the water, energy, and carbon cycles [Bosch and Hewlett, 1982; Bounoua *et al.*, 2002; Foley *et al.*, 2005; Sterling, 2005]; therefore, a key research direction is to improve our knowledge on how global anthropogenic land use/cover change (LUCC) impacts our planet [GWSP, 2005]. To reach this goal, we must understand the nature of global LUCC; most basically, the actual areas altered, spatial distribution

of these areas, and the types of LUCC. The most common tool used in global-scale studies on the impact of LUCC on the Earth system are land surface models (LSMs), a set of equations which simulate global-scale land surface water and energy fluxes that may be coupled to an atmospheric general circulation model, or driven by an atmospheric forcing data set.

[4] A key limitation to the state of knowledge is that the majority of LSM studies do not discuss the area of land cover subjected to change [Betts, 2001; Betts *et al.*, 2007; Bounoua *et al.*, 2002; Brovkin *et al.*, 1999; DeFries, 2002; DeFries *et al.*, 2002; Diffenbaugh and Sloan, 2002; Feddema *et al.*, 2005a, 2005b; Govindasamy *et al.*, 2001; Matthews *et al.*, 2003, 2004; Myhre and Myhre, 2003; Zhao *et al.*, 2001], or, if they do, the area altered is considerably less than the estimated 39–50% of LUCC (for example, 15% [Chase *et al.*, 2000]; 11% [Gordon *et al.*, 2005]; and 7.9% [Pitman and Zhao, 2000]). Akin to the concentration of CO₂ in climate change experiments, the area of land surface altered is a critical parameter in studies of impacts of land cover change and is needed to interpret the results and compare them among studies. Given the range of land cover change areas used in modeling studies, it is not surprising that there are differences in predictions on how the Earth is being impacted from LUCC.

[5] One cause of the areas of altered land being too low in LSM experiments is that the suite of major land cover

¹Laboratoire Sisyphé, CNRS, Université Pierre et Marie Curie, Paris, France.

²Now at Department of Geography, University of Toronto, Toronto, Ontario, Canada.

changes generally is not considered in modeling efforts. For example, many studies only consider one or two types of anthropogenic land cover (ALC), here defined as land use/land covers of anthropogenic origin, including cropland, irrigated cropland, grazing land, and reservoirs. Cropland is often only considered without separate consideration of grazing or built-up land [Betts, 2001; Brovkin *et al.*, 1999; Chase *et al.*, 2000; DeFries, 2002; DeFries *et al.*, 2002; Govindasamy *et al.*, 2001; Matthews *et al.*, 2003]. In addition to the estimation of appropriate areas of LUCC, it is important to include the range of major ALCs, since different types of LUCC alter different ecosystem and land surface processes and even the direction of change of surface fluxes. For example, conversion of savanna to grazing land should decrease evapotranspiration, while conversion of savanna to inundated land in reservoirs would increase evapotranspiration [Sterling, 2005]. Similarly, deforestation to irrigated cropland would invoke different climatological and ecological changes than would deforestation to built-up areas.

[6] While hydrologic modifications to the land surface are of potentially large importance to the energy and water cycles, they are only recently beginning to be considered in LSM studies, for example, irrigation and reservoir creation [Haddeland *et al.*, 2006; Hanasaki *et al.*, 2006]. And while there have been some studies on wetland loss since the last glacial maximum [de Noblet-Ducoudré *et al.*, 2002], to our knowledge, studies on the impact of wetland loss driven by the current extent of land cover change have not yet been conducted.

[7] Another issue in mapping LUCC for LSMs is that the land cover classes in maps need to be coherent with ecological functioning categories used by LSMs. Plant functional types (PFTs), plant species or land covers sharing similar properties as regards their structure, photosynthesis pathway, response to disturbances and interactions with the land surface [Crucifix *et al.*, 2005], are used as ecological functioning categories by many third generation land surface models [Bonan *et al.*, 2002; Ducoudré *et al.*, 1993a; Foley *et al.*, 1996; Haxeltine and Prentice, 1996; Kucharik *et al.*, 2000; Neilson, 1995; Running and Coughlan, 1988; Running and Gower, 1991; Running and Hunt, 1993; Schimel and Braswell, 1997; VEMAP Members, 1995] which translate land cover classes provided in maps to combinations of PFTs, in order to predict the composition and function of ecosystems. Land cover data sets do not come with rules to translate to PFTs, and such translation can add uncertainty and bias as the coherence between land cover types and PFTs is often unclear. For example, with the widely used data sets of Global Ecosystems Legend [Loveland *et al.*, 2000; Wilson and Henderson-Sellers, 1985], many land cover classes are composed of mixed life-form classes (for example, “cool fields and woods,” “evergreen broadleaf cropland,” “pasture + tree”), making it difficult to choose percentage composition for the PFTs. This lack of coherence in PFTs and land covers results in ad hoc correlations and instances where each modeler creates his/her own rules, adding to the difficulty in comparing the results from different studies. Recent work has been done to document the translation among land

cover classes to PFTs for the Canadian Terrestrial Ecosystem (CTEM) land surface model for time series of land cover maps from 1850 and 2100 [Wang *et al.*, 2006], which advances the transparency of this important modeling step.

[8] In addition, PFTs represent important ecological distinctions that are often not presented in LUCC maps, in particular C₃/C₄ photosynthetic pathways, which are important to hydrologic and carbon cycle studies. The difference in stomatal conductance in C₃ and C₄ plants produces large differences in transpiration and water use efficiency, and a C₄ plant canopy will typically partition more net radiation to sensible heat than latent heat compared to a C₃ canopy operating under identical conditions [Still *et al.*, 2003].

[9] The recent development of continuous fields of vegetation [DeFries *et al.*, 1999; Hansen *et al.*, 2003] overcomes the above problems of translation between land cover types and PFT classifications, in that parameters required for PFT classes (e.g., growth form, leaf type, leaf duration) are measured directly from satellites, depicted by their percent presence by pixel. Data sets generated by this method are of high quality, and some modelers such as Bonan *et al.* [2002] have adapted their models to use these percent fields, providing, for example, improvements in LSM modeling of the surface climate [Lawrence and Chase, 2007]. While our method has higher information loss in increased error because of the translation of land cover maps to PFTs, the advantage of our approach is that it enables us to examine anthropogenic impact directly.

[10] The problems with the state of knowledge identified above are in part due to the lack of availability of suitable maps. With the aim to address these problems, we present an assembly of LUCC maps (here, a raster covering the Earth that has a data attribution for all of the land cells) and layers (here, a raster covering the Earth that has “no data” for some of the land cells), tailored to LSM studies, which represent global-scale change from potential land cover (PLC), the vegetation cover that is expected in present-day climate had no human intervention occurred, to current land cover (CLC), the land cover expected to exist at present. The maps have a resolution suitable for state-of-the-art LSMs and Earth system models. This land cover change data set consists of PLC and CLC maps, the difference being described by ALC layers. It is designed for experiments that enable elucidation of direct effects of land cover change, in contrast with experiments that combine temporally varying drivers of climate and land cover change. It is important to note that the land cover changes in the data set are an idealized picture of the differences between climax vegetation communities under current climatic conditions and an interpretation of a range of current land cover maps. Given the idealized nature of the land cover change, it is expected that there will be local areas of unrealistic land cover change.

[11] The data set has the following key characteristics: (1) has areas of transformed land that is within the 2 standard deviation range of current literature estimates (areas are conserved in all raster manipulations), (2) represents major ALC changes, including hydrologic alterations, (3) has land classes that have an improved and clear correspondence with PFT classes, and (4) has a relatively high spatial

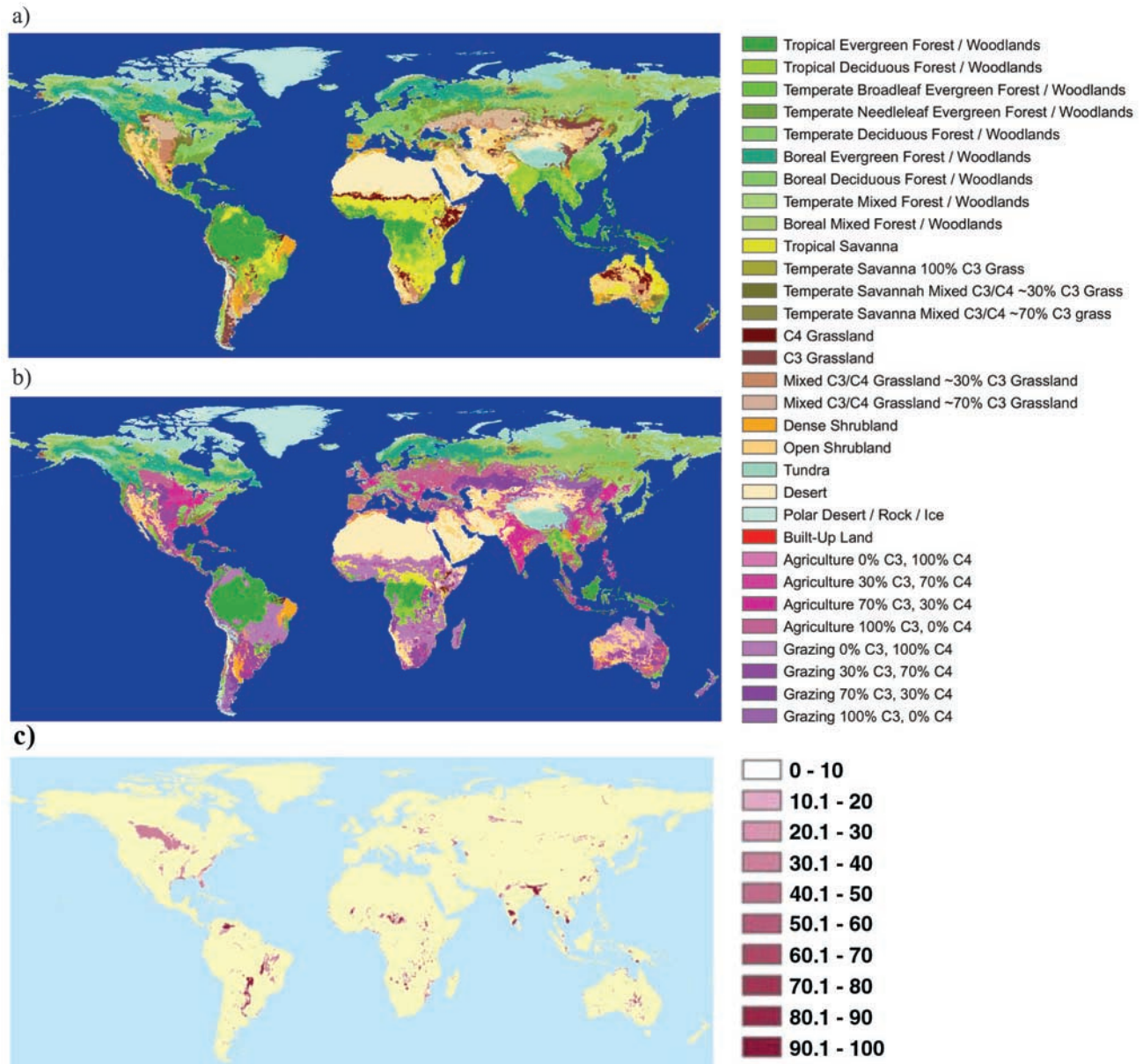


Figure 1. Potential land cover (PLC). Five-minute resolution, modified from *Ramankutty and Foley* [1999], as explained in the text. C_3/C_4 divisions are based upon the work of *Winslow et al.* [2003]. Antarctica, Greenland, and Spitzbergen added from 5-min USGS GLCC. (b) Current land cover (CLC), where grazing has been censored. Dominant cover at a 5-min resolution. (c) Estimated wetland loss, defined at the 1-min resolution as wetland cells (as estimated by WELAREM [*Lehner and Döll*, 2004]) that coincide with anthropogenic land cells (as estimated from Figure 1b and scaled to 1-min resolution). The number of cells of wetland loss at the 1-min resolution has been aggregated to percentage of 1-min wetland loss cells in each 30-min cell for the purposes of Figure 1c only, to improve visibility of individual wetlands.

resolution in order that the grids can define detailed features, such as small urban areas, reservoirs, or wetlands, and that upscaling to the most state-of-the-art resolution in land surface modeling is possible. The base resolution of the maps is 5 min, with dominant cover classifications in the CLC and PLC maps, and percent cover for the ALC layers. We show how the database can be adapted to PFTs in an LSM, using the case of ORCHIDEE [*de Rosnay et al.*,

2003; *Ducoudré et al.*, 1993a], but it can be used for all the LSMs that have similar or simpler PFT categories. In order to be able to evaluate anthropogenic impact on PFTs, our method links PFTs to land cover so that PFT distribution associated with ALCs and PLCs may be distinguished; a limitation to this method is that it negates the major motivation of using PFTs in describing biome composition:

Table 1a. Land Cover Classes in Original *Ramankutty and Foley* [1999] Potential Vegetation Map and Plant Functional Types Used in ORCHIDEE Model [Ducoudré et al., 1993a]

Original <i>Ramankutty and Foley</i> [1999] Potential Vegetation Land Cover Classes	PFT Classes From ORCHIDEE ^a
Tropical evergreen forest and woodland	Bare soil
Tropical deciduous forest and woodland	Tropical broadleaf evergreen forest
Temperate broadleaf evergreen forest and woodland	Tropical broadleaf raingreen forest
Temperate needleleaf evergreen forest and woodland	Temperate needleleaf evergreen forest
Temperate deciduous forest and woodland	Temperate broadleaf evergreen forest
Boreal evergreen forest and woodland	Temperate broadleaf summergreen forest
Boreal deciduous forest and woodland	Boreal needleleaf evergreen forest
Mixed Forest	Boreal broadleaf summergreen forest
Savanna	Boreal needleleaf summergreen forest
Grassland/steppe	C ₃ grass
Dense shrubland	C ₄ grass
Open shrubland	C ₃ crop
Tundra	C ₄ crop
Desert	
Polar desert/rock/ice	

^aPFT: plant functional type.

to describe landscape heterogeneity continuously without the constraint of arbitrary defined land cover classes.

2. Assembly of Land Cover Data and Layer/Map Creation

2.1. PLC Mapping

[12] For the PLC map (Figure 1a), we adapt a widely used map from the University of Wisconsin [Ramankutty and Foley, 1999], generated from the IGBP Discover Seasonal Land Cover Regional data set (SLCR 1.2) which provides detailed classifications of land cover in 1992 for each of five continental regions. Grid cells with more than 50% crop cover or less than 20% dominant potential vegetation were replaced by simulated natural vegetation data as a function of climate and that the vegetation cover is in equilibrium with the present climate for the mid-1990s using the BIOME3 model [Haxeltine and Prentice, 1996], producing a map of dominant potential land cover at a 5-min resolution. The map has 15 land classes (Table 1a), which we have modified to 22 potential land classes corresponding more closely with typical PFT types (Table 1b). The resulting areas for the 22 PLC are given in Table 1b. These modifications were conducted in a Geographic Information System (GIS) and are as follows:

[13] 1. Division of savanna into temperate and tropical savanna. In the original map, savanna is a single land cover class that encompasses two types of tree PFTs: tropical broad-leaved raingreen in tropical savannas [Hoffmann and Jackson, 2000], and temperate broad-leaved summergreen in temperate savannas (Wisconsin Botanical Information System, 2006, Habitat Descriptions, University of Wisconsin, Madison, available at <http://www.botany.wisc.edu/wisflora/curtis.asp>). We thus divided the savanna class into temperate and tropical savannas, using 30 degrees latitude as a limit between the two classes.

[14] 2. Division of mixed forest into temperate mixed forest and boreal mixed forest. The “mixed forest” biome in the original PLC map encompasses two PFT forest categories:

temperate and boreal mixed forest. We separate the mixed forests into temperate and boreal mixed forests, using the boundary of “boreal evergreen forest” from other maps [FAO, 2005; Olson and Dinerstein, 1998; Ramankutty and Foley, 1999].

[15] 3. Division of savannas and grasslands based on C₃ and C₄ composition. As C₄ plants are largely confined to the herbaceous growth form [Still et al., 2003], we subdivide the land covers with dominant herbaceous composition, grasslands, tropical savanna, and temperate savanna into C₃/C₄ classes, using existing maps on the distribution of C₃ and C₄ grasses for the current climate throughout the globe, as predicted from the SAW algorithm which predicts C₃/C₄ distribution on the basis of the seasonal timing of water availability with respect to the different C₃ and C₄ growing seasons [Winslow et al., 2003].

[16] 4. Greenland, Spitzbergen, and Antarctica have been added to the PLC map from the GLCC EDC USGS Olson Classification Map [Loveland et al., 2000] so that the major landmasses are included. These areas contain polar desert/rock/ice and tundra land classes.

2.2. Current Extent of ALC

[17] We assemble and modify four anthropogenic land cover data sets to produce a layer of the current extent of each ALC. We define major ALC types as those that cover over 1% of the Earth’s land surface, as estimated from the literature, and that represent a relatively permanent state of land cover change. These are cropland (both irrigated and nonirrigated), built-up areas, and grazing lands (Table 1b). Anthropogenically burned areas (such as fuelwood burning) were not included because the land cover change in these cases is transient, involving trajectories of successional stages [Batistella and Moran, 2005], or these areas are replaced by croplands or grazing, and then there would be double counting anthropogenic land covers. A layer of tree plantations, industrial forestry, and selective logging [Asner et al., 2005] was not included because a global database of these land use/cover areas was not yet available. Also, the

Table 1b. Land Cover Classes and Their Area in Potential and Current Vegetation Map and Sources of Mapping Information^a

Land Cover Class	Area in Potential Vegetation Map (10 ¹² m ²)	Area in Actual Vegetation Map (10 ¹² m ²)	Change, Expressed as a Percentage of Potential Vegetation (%)	Source of Original Map ^b
<i>Potential Land Cover</i>				
Tropical evergreen forest/woodlands	13	10	-23.0	1
Tropical deciduous forest/woodlands	4.8	1.5	-68.0	1
Temperate broadleaf evergreen forest/woodlands	1.0	0.35	-66.0	1
Temperate needleleaf evergreen forest/woodlands	4.1	2.2	-46.0	1
Temperate deciduous forest/woodlands	5.2	2.6	-50.0	1
Boreal evergreen forest/woodlands	8.9	8.6	-3.5	1
Boreal deciduous forest/woodlands	3.3	3.2	-3.1	1
Temperate mixed forest/woodlands	5.3	3.2	-39.0	1, 2, 3
Boreal mixed forest/woodlands	16	16	-2.8	1, 2, 3
Tropical savanna	12	2.7	-77.0	1
Temperate savanna 100% C ₃ grass	1.7	1.0	-44.0	1, 4
Temperate savanna mixed C ₃ /C ₄ ~30% C ₃ grass	0.82	0.042	-95.0	1, 4
Temperate savanna mixed C ₃ /C ₄ ~70% C ₃ grass	2.3	0.31	-86.0	1, 4
C ₄ grassland	2.9	0.32	-89.0	1, 4
C ₃ grassland	4.3	0.81	-81.0	1, 4
Mixed C ₃ /C ₄ grassland ~30% C ₃ grassland	3.2	0.11	-97.0	1, 4
Mixed C ₃ /C ₄ grassland ~70% C ₃ grassland	5.8	0.17	-97.0	1, 4
Dense shrubland	3.4	2.3	-33.0	1
Open shrubland	11	11	-3.1	1
Tundra	12	12	0.0	1
Desert	13	13	-0.9	1
<i>Anthropogenic Land Cover</i>				
Cropland 0% C ₃ , 100% C ₄	n/a	0.010	n/a	5, 6
Cropland 30% C ₃ , 70% C ₄	n/a	1.2	n/a	5, 6
Cropland 70% C ₃ , 30% C ₄	n/a	7.3	n/a	5, 6
Cropland 100% C ₃ , 0% C ₄	n/a	9.4	n/a	5, 6
Grazing (censored) 0% C ₃ , 100% C ₄	n/a	12	n/a	7, 4
Grazing (censored) 30% C ₃ , 70% C ₄	n/a	4.6	n/a	7, 4
Grazing (censored) 70% C ₃ , 30% C ₄	n/a	4.4	n/a	7, 4
Grazing (censored) 100% C ₃ , 0% C ₄	n/a	4.5	n/a	7, 4
Built-up land	n/a	0.50	n/a	8
Total land	1.3E + 02	1.3E+02		
Inundated land	n/a	0.14	n/a	7
Difference between censored and noncensored grazing land	n/a	11	n/a	4
Wetland loss layer	n/a	2.2	28	this study; 9
Irrigated areas layer	n/a	2.6	n/a	10

^a[FAO, 2005; Leff et al., 2004; Lehner and Döll, 2004; Olson and Dinerstein, 1998; Ramankutty and Foley, 1999, 1998; Siebert et al., 2005b; Winslow et al., 2003; N. Ramankutty, 2004; B. Miteva, 2004; A. Strahler, personal communication, 2002]. Grazing land is censored to not occur in barren land, desert, tundra, or shrubland. The classes of C₃/C₄ composition were chosen on the basis of the distribution of histogram, which had two peaks at 0 and 100%, and a remaining even distribution between 10 and 90%. The classes of 0% covers the peak in the 0–10%, the 30% category covers the 10–50% range (mean of 30%), the 70% category covers the 50–90% range (mean of 70%), and the 100% category covers the second peak in the 90–100% range.

^b(1) Ramankutty and Foley [1999]. (2) Olson and Dinerstein [1998]. (3) FAO [2005]. (4) Winslow et al. [2003]. (5) Ramankutty and Foley [1998]. (6) Leff et al. [2004]. (7) N. Ramankutty (2004). (8) B. Miteva (2004). (9) Lehner and Döll [2004]. (10) Siebert et al. [2005a, 2005b].

mapped land changes here do not include anthropogenic land cover changes thought to occur from anthropogenically caused climate change, for example, increase in shrubs in the Arctic [Chapin et al., 2005]. A synthesis of areal estimates and mapping products available for ALCs are provided in Appendix A.

[18] The data sets of ALC were chosen for our study on the basis of the following criteria: that they were produced

no earlier than 1990, with preference given to layers with land cover classifications compatible with the PFTs, and to those with a minimum 5-min (~10-km) grid resolution (Table 1b), where available. The data set is representative of approximately the middle to late 1990s.

[19] The map of the present-day distribution of global croplands was obtained from the University of Wisconsin [Ramankutty and Foley, 1998], and represents the cropland

Table 2. Comparison of Anthropogenic Land Cover Areas in This Database and Other Widely Used Land Cover Maps^a

Anthropogenic Land Cover	This Study (Grazing Censored)	This Study (Grazing Not Censored)	Hyde [1996]	Olson [Loveland et al., 2000] ^{b,c}	Mathews [1983]	Richards [1990] After Houghton et al. [1983]
Built-up land	0.5	0.5	n/a	0.26	n/a	n/a
Cropland	18	18	14.7	6.8	17.6	15.0
Grazing	25	36	34	5.6	n/a	n/a
Total anthropogenic land	43.5	54.5	48.7	15	17.6	15.0
Percent land surface altered ^d	32%	41%	36%	11%	13%	11%

^aUnits: 10¹² m². Adapted from Klein Goldewijk [2001].

^bWhere a land cover category was a mix of two types, a 50% distribution of the two types was assumed (e.g., crops and towns, crops and forest).

^cThe land cover category “fields” was considered to be grazing land.

^dLand area is set to 1.34E + 14 m², to represent land areas not covered with permanent ice.

cover of the world on a continuous scale, depicting the percentage of land in cultivation during the early 1990s for each 5-min grid cell. This data set was developed to understand the consequences of historical changes in land use and land cover for ecosystem goods and services, and was created by synthesizing remotely sensed land cover data with contemporary land inventory data. Another reason that we chose the Ramankutty and Foley [1998] data set to represent croplands was because it contains a new layer of global crop types (e.g., beans, rice, and corn) [Leff et al., 2004] having a distinct C₃/C₄ composition, and thus which we used to separate cropland into C₃/C₄ classes, classifying “others” crops as C₃, because they consist of mainly C₃ plants in the description of the category [Leff et al., 2004].

[20] The map of the present-day distribution of global built-up land was obtained from the University of Wisconsin (B. Miteva, 2004, Map of Built-Up Areas of the World, SAGE, Madison, Wisconsin, available at <http://www.sage.wisc.edu/atlas/maps.php?datasetid=18&includerelatedlinks=1&dataset=18>). This map combines the two main sources of the extent of urban and built-up areas: the DMS/OLS Nighttime Lights [Imhoff et al., 1997] and the IGBP land cover characterization data sets (A. Strahler, Consistent Year Product, Boston University, personal communication, 2002) gridded to percent cover at a 5-min resolution.

[21] For the map of the present-day distribution of global grazing lands we used a map from the University of Wisconsin (N. Ramankutty, Map of Grazing Lands of the World, 2004). The data set is a 30-min grid that has been converted to a 5-min grid, with percent cell occupied by grazing land. This data set was selected also because it is complementary in extent to the map of croplands, with few overlapping cells. We modified the grazing layer so that it is divided into C₃/C₄ categories, using the same method as used for natural grassland in the potential vegetation map.

[22] In addition to its typical grassland setting, grazing occurs also in harsher environments such as tundra, shrubland, and desert. At present, many models parameterize grazing land as a form of grassland. Therefore, if areas such as open shrubland were included as grazing land in such model studies, the model would simulate grazing of open shrubland as a conversion to grassland, and spurious ecological responses might result, such as an erroneous increase

of evapotranspiration. To address this problem, we have created a “censored” version of grazing land that does not allow grazing in areas with lower productivity or frozen soils. Thus, we have two grazing scenarios: censored, where grazing on shrubland, desert, and tundra is removed, for use in most LSMs, and noncensored, where grazing on shrubland, desert, and tundra is included, which we include when we want a global survey of anthropogenic impact. It is known that grazing indeed does occur in these less productive regions; for example, since 1978 in the Tibetan Plateau that contains tundra, sheep and cattle production have increased by 106 and 249%, respectively [Cui et al., 2006; Du et al., 2004].

2.3. Current Land Cover Map

2.3.1. Map of Dominant Current Land Cover

[23] We created a map of CLC (Figure 1b) through the combination of ALC layers and the PLC map. In order to make a single CLC map, as required by many LSMs, in lieu of having a separate layer for each ALC, we integrated three different ALC layers into one layer (cropland, censored grazing land, and built-up land). We did not include the inundated land layer because this CLC map is designed for LSMs like ORCHIDEE which do not contain an open water PFT. ALC layers needed to be converted from the continuous percent cover to dominant land cover at the 5-min resolution in order to create a single CLC map. A threshold percentage is used to convert percent cover to presence/absence, chosen so that the original area of the ALC is globally conserved (39, 19, and 29% for cropland, built-up land, and censored grazing land, respectively). In creating the dominant land cover map, if more than one of built-up, censored grazing, or cropland occupy the same cell, priority of cell occupation is given first to built-up land, then to cropland, then finally to censored grazing land, chosen to represent increasing total area. Finally, to create the CLC map, we replaced 5-min cells in the PLC map with 5-min dominant cover ALC cells. The ALC cells form 33% of the CLC land surface (Table 2).

2.3.2. Layer of Wetland Loss

[24] Because of its potential importance to the Earth system, we have generated a layer of wetland loss (Figure 1c). To do so, we modified a map of global wetland

distribution from University of Kassel (CESR) Global Lakes and Wetlands Database (WELAREM1) [Lehner and Döll, 2004]. WELAREM1 is a global 1-min (~1.8-km) map in dominant cover of wetlands, lakes, and reservoirs and was derived by combining various digital maps (Environmental Systems Research Institute (ESRI), 1993 (Digital Chart of the World 1:1 Mio., Redlands, California, data obtained on four CDs, also available at <http://www.maproom.psu.edu/dcw/>): wetlands, lakes, and reservoirs; ESRI, 1992 (ArcWorld 1:3 Mio. Continental Coverage, Redlands, California, data obtained on CD): wetlands, lakes, reservoirs, and rivers; World Conservation Monitoring Centre, 1999 (Digital Wetlands Data Set, Cambridge, United Kingdom; see http://www.geo.uni-frankfurt.de/ipg/ag/dl/forschung/Global_Water_Modeling/WELAREM1/index.html): lakes and wetlands; *Vörösmarty et al.* [1997]: reservoirs; and attribute data (International Commission on Large Dams (ICOLD) [1998] and *Birkett and Mason* [1995]: lakes and reservoirs)). To obtain the map of wetland loss, we removed the dominant cover 1-min wetlands that exist in the same 5-min cell with the ALCs (cropland, censored grazing land, and built-up land). The cells that were removed (wetland loss) are expressed as a percentage cover for a 5-min cell (Figure 1c). We used the censored grazing land so that wetlands would not be removed by grazing in shrubland, deserts, and tundra, because in these dry areas it is unlikely that wetlands in these areas will be drained for grazing purposes; instead the wetlands may be used as oases. The bulk of such areas is located in central Australia, the Tibetan Plateau, and in the Arabian Peninsula. We treat the wetland loss as separate from the PLC/CLC map because wetlands coexist with other land covers; for example, wetlands may occur in grasslands, forests, or tundra.

[25] While there is very little information on the loss of wetlands [Finlayson and Rea, 2004], there are some estimates from which we can compare our results. Our resulting area of wetland loss (28.7%) (Table 1b) is very close with other estimates of global wetland loss (26%) [Moser *et al.*, 1996; *Organization for Economic and Cooperative Development/World Conservation Union (OECD/IUCN)*, 1996]. Geographically, the layer of wetland loss corresponds with major known areas of wetland loss (Figure 1c). For example, the layer captures the widespread wetland loss in South Australia [Moser *et al.*, 1996], the Orinoco basin, the Hong floodplain, and in the Canadian prairies where wetlands have been drained for cropland.

2.3.3. Irrigated Layer and Inundated Land Layer

[26] For the map of present-day distribution of anthropogenic inundated land/reservoirs, we used a map from University of Kassel (CESR) Global Lakes and Wetlands Database (WELAREM1), as described in section 2.3.2 [Lehner and Döll, 2004]. Inundated land in reservoirs is treated as a separate hydrologic layer because some LSMs, like ORCHIDEE, do not have parameterizations for this land cover type.

[27] Finally, in our analysis we include a layer of irrigation, based on an existing map produced by *Siebert et al.* [2005a]. The layer documents amount of area equipped for irrigation in the 1990s as a percentage of the total area on a raster with a resolution of 5 min. Percent cover was

converted to dominant land cover, using a threshold of 5.0%, chosen to preserve the estimated area of irrigation at approximately 17% of all cropland [Wood *et al.*, 2000].

3. Analysis and Validation of Land Cover Transformations

3.1. Analysis of Land Cover Transformations

[28] First, by comparing PLC (Figure 1a) with CLC (Figure 1b), we obtain an estimate of the spatial distribution of anthropogenic alteration of the Earth's surface. We see that most of the productive temperate and tropical areas have been converted to human use, except for mountainous or very dry terrain and large tropical forest areas around the Zaire and Amazon watersheds, and parts of Southeast Asia and the Northern Hemisphere evergreen forests. The amount of forest lost is likely underestimated in these areas because, as described above, we do not include industrial forestry or conversion to tree plantations. For example, in Myanmar it is known that large parts of the forest have been lost to deforestation and shifting cultivation [Brunner *et al.*, 1998], and in western Canada it is known that extensive areas have been deforested for industrial forestry.

[29] Next, by employing a GIS analysis of the LUC data set (PLC and CLC maps and ALC layers), we develop a perspective of the nature of the current extent of global LUC. This reveals that some natural biomes have been almost completely converted to anthropogenic use (Table 1b). Grassland biomes are the most impacted in terms of percent loss: almost all (92%) of the original natural grassland area has been converted. Approximately 75% of natural savanna has been transformed to anthropogenic uses; temperate savanna with mixed C₃/C₄ grasses (30% C₃ grass) is almost completely lost. Forests also have also undergone a large percent loss, ranging up to 68.3% for tropical deciduous forest and woodlands. In terms of total area of change, anthropogenic activities have caused the greatest losses of the natural states of tropical savannas and C₃ grasslands (Figure 2a). In contrast, the land covers with the biggest areal increase are C₄ grazing land, followed by C₃ cropland (Figure 2a).

[30] Also, the mapping database provides insight into which potential biomes each ALC has replaced (Figure 2b) Over half of cropland occurs in previously forested areas (predominantly in Europe, China, and India), and a large proportion of cropland occurs in previous mixed C₃/C₄ grassland (North America and Russia). As consistent with most built-up land occurring in developed countries, we find that the majority of built-up land occurs in the (potential) temperate forest biomes. Grazing land predominantly occurs in the (potential) temperate grasslands, open shrublands (when considering grazing in less productive areas), tropical savannas, and tropical grasslands. For wetland loss, the data indicate that almost a quarter has occurred in the tropical savanna biome, in South America and in sub-Saharan Africa, and another quarter in the grasslands of the Northern Hemisphere (in particular in the North American prairies). Irrigation occurs most often in lands that were converted from tropical deciduous forest (India), temperate

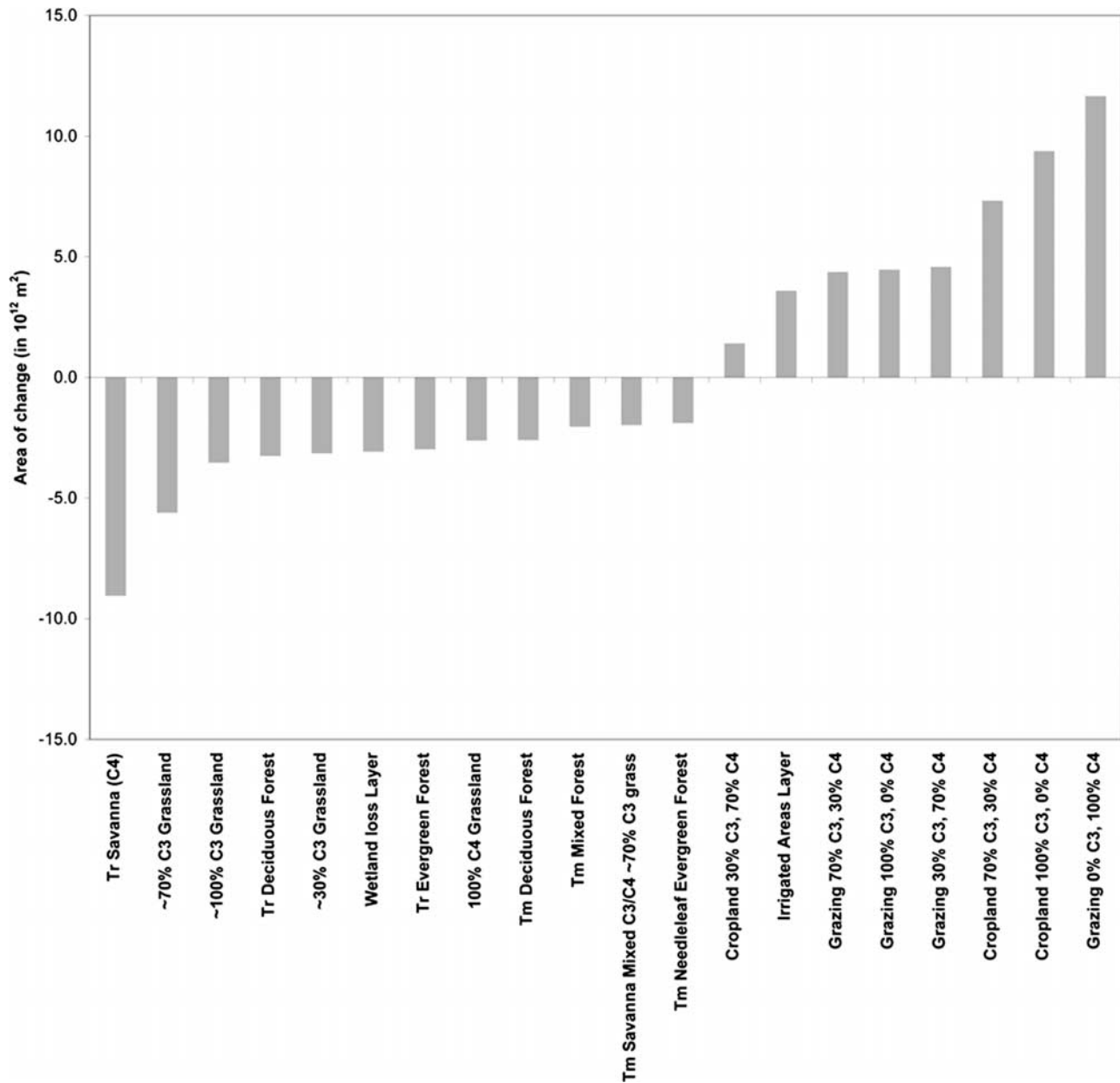


Figure 2a. Areal changes in land cover types (potential and anthropogenic) between CLC and PLC maps (included if greater than 10^{12} m^2). Grazing is censored.

mixed forest (China), and shrublands (central/western Asia, west/central North America). Most of the reservoirs occur in the boreal evergreen forest region in Russia and Canada, associated with major hydropower projects in the northern rivers.

[31] Finally, the assembled maps indicate the associated anthropogenic causes for the losses in each PLC (Figure 2c), with the caveat that forest converted to abandoned land or tree plantations is not considered here. We see that savannas and tropical forests have very similar patterns of ALC replacement. Conversion to grazing land is the principal driver for loss of natural grasslands (82% from grazing) and for tropical savanna (92% from grazing); however, conver-

sion to cropland is the major cause of loss of natural temperate savanna (64% from cropland). Loss of temperate and boreal forests is due mostly to cropland conversion (~80% of converted land), where deforestation of tropical forests tend to result almost equally from conversion to cropland and grazing land. Boreal forest is the only natural biome that has a notable fraction lost to inundated lands. The total loss of potential forest cover for all biomes is estimated to be $1.4 \text{ E} + 13 \text{ m}^2$, or ~23% of the original forest cover, slightly less than the FAO estimate of original forest cover loss of $3.95 \text{ E} + 13 \text{ m}^2$ [FAO, 2005]; the difference may be explained because our estimate does not take into account forest loss from tree plantations. However,

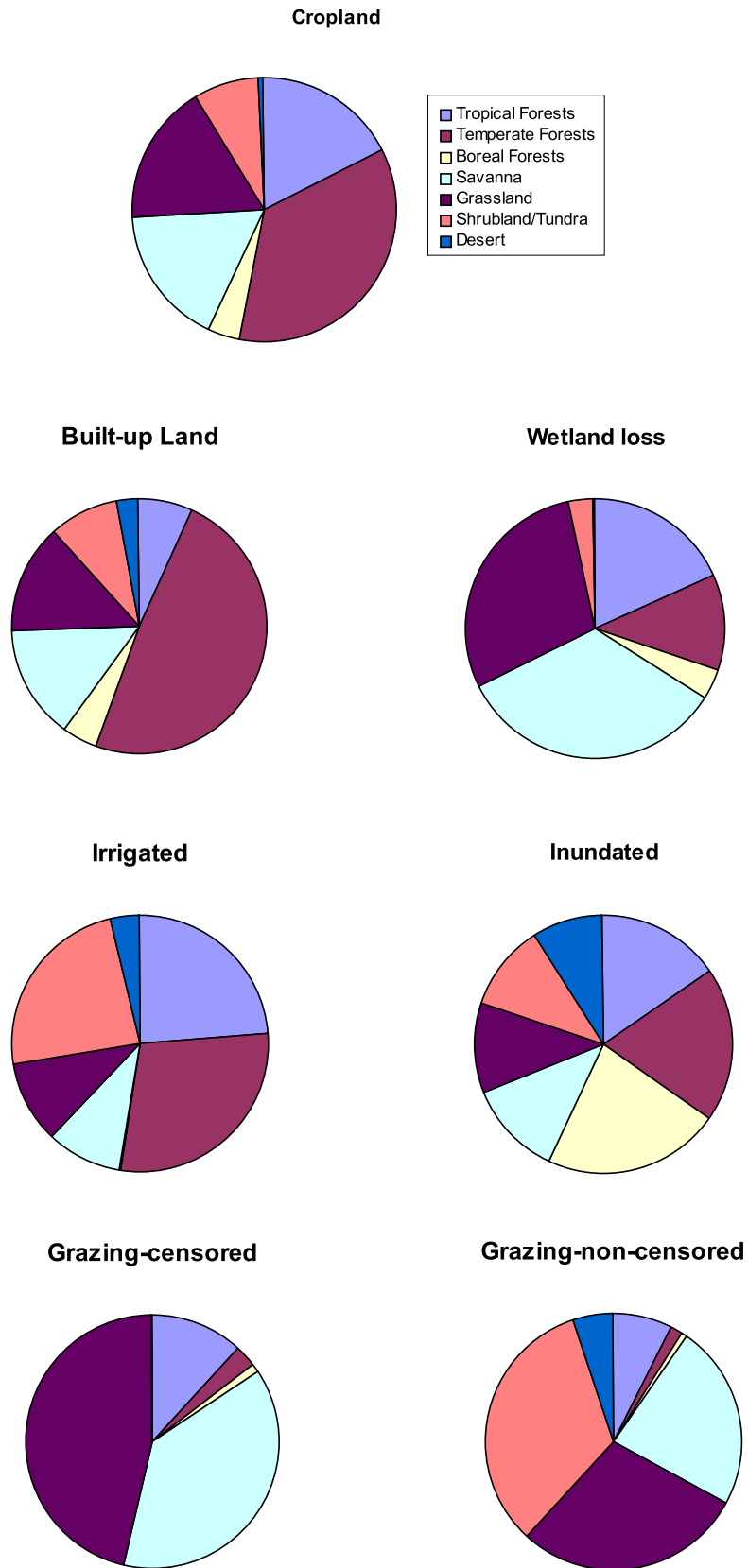


Figure 2b. PLC composition of lands that were converted to individual anthropogenic land covers (ALCs). Both censored and noncensored grazing are included.

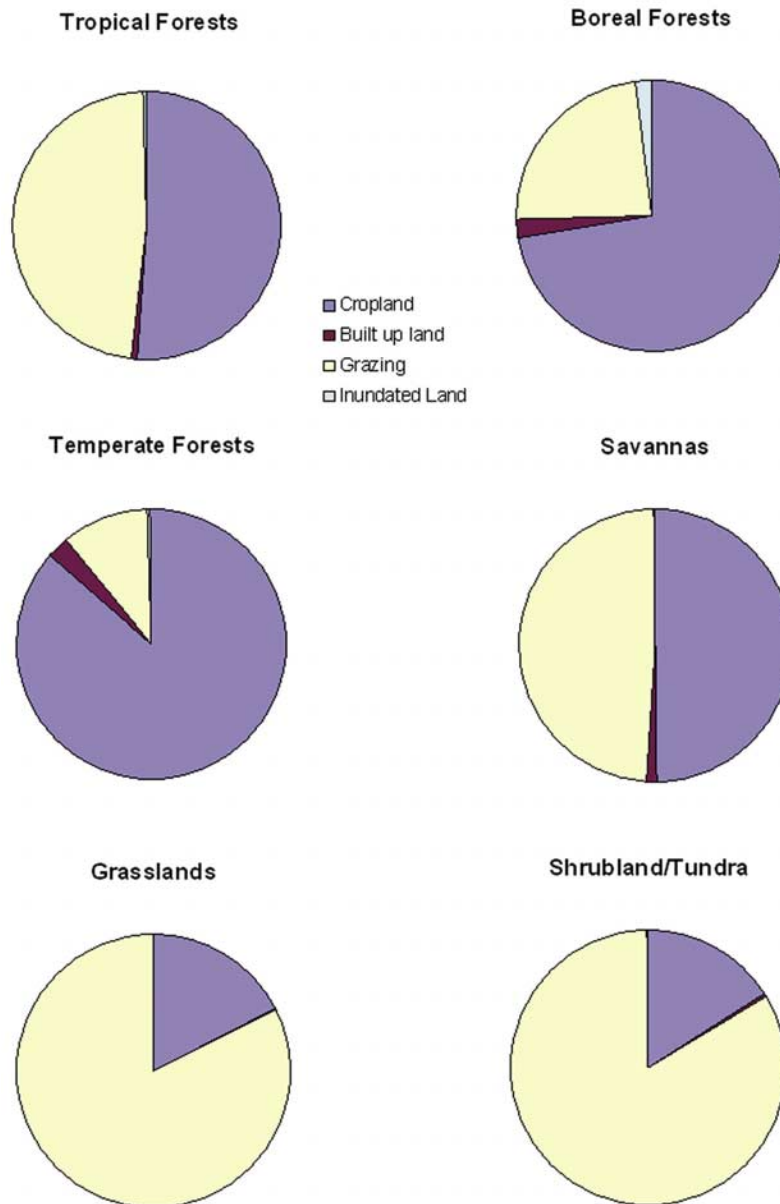


Figure 2c. Breakdown of ALCs that replaced each type of PLCs, by percent of total area of reduction in PLC. Grazing land is noncensored.

our estimate of total forest loss $1.43 \text{ E} + 13$ is slightly larger than estimates of total forest loss in the past 300 years (~ 0.7 to $1.1 \text{ E} + 13 \text{ m}^2$) [Foley *et al.*, 2005].

[32] Natural shrubland has been estimated to be largely replaced by anthropogenic land cover, estimated to currently be 10.5% of original (i.e., potential) shrubland area [Asner *et al.*, 2004]; if the “noncensored” grazing was included in our estimate of shrubland loss, shrubland we find that, like Asner *et al.*, most of the open shrubland has been converted to grazing land (97%). Our observation that grazing land predominantly occurs in the temperate grasslands, open shrublands (when considering grazing in less productive areas), tropical savannas, and tropical grasslands is consistent with previous estimates [Asner *et al.*, 2004].

3.2. Validation of Land Cover Maps and Layers

[33] As a validation we compare the areas of land cover and of land cover change presented in this database with estimates from the literature. First we estimate the mean and variance global area of ALC as a percent of the Earth’s land surface, abbreviated here as %ALC (not including permanent ice areas). By summing the mean areas of cropland, grazing land, built-up land, burned land, tree plantations, and inundated land as gathered from the literature (Figure 3 and Appendix A), we estimate mean %ALC to be 44%. This value falls within the 39–50% range previously estimated [Vitousek *et al.*, 1997], and it is consistent with an estimate that wilderness covers 44% of the globe [Mittermeier *et al.*,

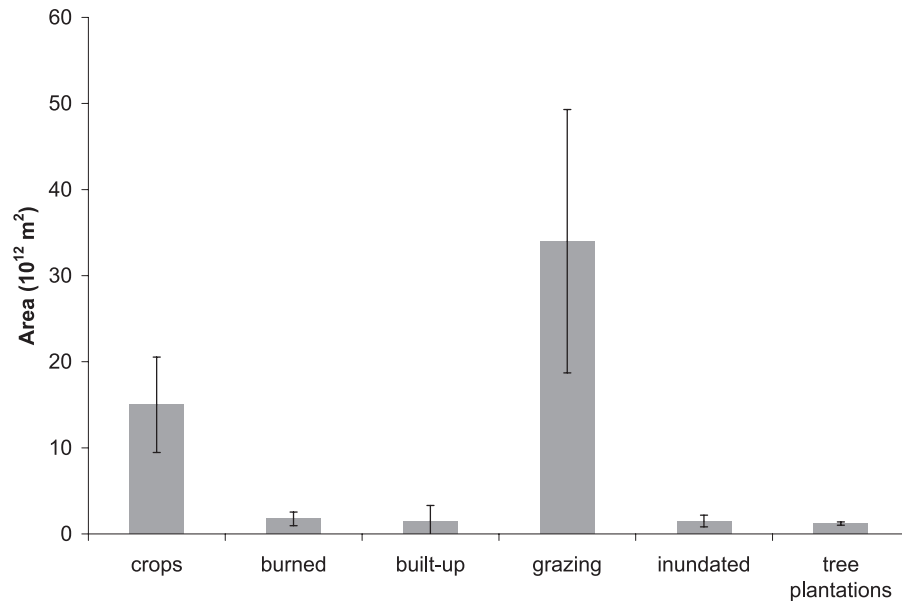


Figure 3. Estimated areas of the major suite of anthropogenic land uses/land covers that individually cover more than 1% of the land surface and together comprise 44% of total land surface, presented in m^2 with their uncertainties estimated from variation in literature estimates (Appendix A). For grazing land, there were three literature estimates that had approximately the same value, bringing into question their independence among each other; so to calculate standard deviation for grazing land we assumed a 45% standard error. The same standard error was used for the estimation of inundated land, with one observation.

2003], in that the remaining $\sim 12\%$ of land may be accounted by fragmented land or land near roads that was not included in either occupied or wilderness classification. The uncertainty in the global estimate of %ALC is large, $\pm 17\%$ at a 95% confidence interval, reflecting the high degree of uncertainty in all area parameters except those related to tree plantations (a parameter whose low uncertainty likely reflects an absence of independent data sources). The confidence interval was estimated using stochastic Monte Carlo simulations in which each parameter was allowed to vary randomly constrained by its mean and estimated variance (Appendix A). The estimate of variability in our knowledge of %ALC was estimated by repeating these calculations 1 million times.

[34] As compared to literature means, the %ALC in the CLC map is 41% (Table 2) (uncensored grazing), very close to the literature mean of 44%. Our CLC map value is slightly less than the literature mean, which is explained by the absence of inundated land, burned areas, and tree plantations in the CLC map (the total of literature means of cropland, built-up land, and grazing land is 39% of the Earth's land surface). Note that the areal estimates for each ALC in this database are included in the calculation of the literature averages (Appendix A).

[35] In this study, total cropland area is $1.8 \text{ E} + 13 \text{ m}^2$, close to the literature average of $1.7 \text{ E} + 13 \text{ m}^2$. The area of uncensored grazing land in this study is $3.6 \text{ E} + 13 \text{ m}^2$, slightly more than the literature average. There is a wide range of estimates of built-up land in the literature; the area of built-up land in this study ($5.0 \text{ E} + 11 \text{ m}^2$) lies in the middle of the literature estimates. The area of inundated

land is less than the one estimate found in the literature (Appendix A).

[36] There is a wide variation in %ALC in other commonly used land cover databases (Table 2). We find the HYDE database [Klein Goldewijk, 2001] has a total anthropogenic area (36%, Table 2) that is similar, if just slightly less, to the literature estimate of %ALC, and thus to our study. Our estimate of %ALC is slightly larger than the HYDE database, mostly deriving from the cropland being larger in extent. Other commonly used land cover databases, however [Houghton *et al.*, 1983; Loveland *et al.*, 2000; Matthews, 1983; Richards, 1990], have estimations of anthropogenic extent below the 2 standard deviation of the literature mean (Table 2). Two of the data sets are at least a decade older, which may explain why the cropland extent is slightly lower than the literature mean; yet it is the absence of accounting for grazing land in these data sets that explains why they are much lower than the literature average of total anthropogenic land cover.

4. Conversion of Land Covers to PFTs

[37] As they were designed, the PLC and CLC map land cover classes are easily converted into PFT categories. And the description of land cover change in terms of change in PFTs provides insight into the nature of change in ecological functioning caused by LUCC. As an example of PFT conversion from this LUCC data set (Table 3), we use a typical PFT scheme from the IPSL ORCHIDEE LSM [de Rosnay and Polcher, 1998; Ducoudré *et al.*, 1993b;

Table 3. Conversion of Vegetation Land Cover Classes to Plant Functional Types Used in the LMD Land Surface Model ORCHIDEE, With Reference to the Literature^a

	Bare Soil	TR	BL	EG	TR	BL	RG	TM	NL	EG	TM	BL	EG	TM	BL	SG	BO	NL	EG	BO	BL	SG	BO	NL	SG	C ₃ gs	C ₄ gs	C ₃ cr	C ₄ cr					
Tropical evergreen forest/woodlands ^b	-	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-					
Tropical deciduous forest/woodlands ^b	-	-	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-				
Temperate broadleaf evergreen forest/woodlands ^b	-	-	-	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-				
Temperate needleleaf evergreen forest/woodlands ^b	-	-	-	-	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-				
Temperate deciduous forest/woodlands ^b	-	-	-	0	-	-	-	-	-	-	-	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-				
Boreal evergreen forest/woodlands ^b	-	-	-	0	-	-	-	-	-	-	-	-	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-				
Boreal deciduous forest/woodlands ^c	-	-	-	0	-	-	-	-	-	-	-	-	0.05	-	-	-	0.05	-	-	-	-	-	-	-	-	-	-	-	-	-				
Temperate mixed forest/woodlands ^d	-	-	-	0.50	-	-	-	-	-	-	-	-	-	0.50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-				
Boreal mixed forest/woodlands ^d	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-				
Tropical savanna ^e	0.05	-	-	-	-	-	0.35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.05	0.55	-	-	-				
Temperate savanna 100% C ₃ grass ^f	0.05	-	-	-	-	-	-	-	-	-	-	0.27	-	-	-	-	-	-	-	-	-	-	-	-	-	0.68	-	-	-	-				
Temperate savanna mixed C ₃ /C ₄ ~30% C ₃ grass ^f	0.05	-	-	-	-	-	-	-	-	-	-	0.27	-	-	-	-	-	-	-	-	-	-	-	-	-	0.20	0.48	-	-	-				
Temperate savanna mixed C ₃ /C ₄ ~70% C ₃ grass ^f	0.05	-	-	-	-	-	-	-	-	-	-	0.27	-	-	-	-	-	-	-	-	-	-	-	-	-	0.48	0.20	-	-	-				
C ₄ grassland ^g	0.10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.90	-	-	-			
C ₃ grassland ^g	0.10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.90	-	-	-	-	-			
Mixed C ₃ /C ₄ grassland ~30% C ₃ grassland ^g	0.10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.27	0.63	-	-	-	-			
Mixed C ₃ /C ₄ grassland ~70% C ₃ grassland ^g	0.10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.63	0.27	-	-	-	-			
Dense shrubland ^h	0.10	-	-	-	-	-	-	-	-	-	0.10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.80	-	-	-	-	-	-		
Open shrubland ⁱ	0.50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.30	-	-	-	-	-	-		
Tundra ^j	0.50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.50	-	-	-	-	-	-		
Desert ^k	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
Polar desert/rock/ice ^b	100% - no bio	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Built-up land ^l	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Cropland 0% C ₃ , 100% C ₄ ^m	0.15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.85	
Cropland 30% C ₃ , 70% C ₄ ^m	0.15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.60	
Cropland 70% C ₃ , 30% C ₄ ^m	0.15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.60	
Cropland 100% C ₃ , 0% C ₄ ^m	0.15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.85	
Grazing 0% C ₃ , 100% C ₄ ⁿ	0.20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.80	
Grazing 30% C ₃ , 70% C ₄ ⁿ	0.20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.24
Grazing 70% C ₃ , 30% C ₄ ⁿ	0.20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.56
Grazing 100% C ₃ , 0% C ₄ ⁿ	0.20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.80

Table 4. Changes in Global PFT Distribution From Potential to Current Land Cover Scenarios^a

	PFT	Potential		Current	
		Area (10 ¹² m ²)	Percent of Total	Area (10 ¹² m ²)	Percent of Total
1	Bare soil	30	22	35	26
2	Tropical broadleaf evergreen forest	13	10	10	7.6
3	Tropical broadleaf raingreen forest	8.9	6.6	2.4	1.8
4	Temperate needleleaf evergreen forest	6.7	5.0	3.8	2.9
5	Temperate broadleaf evergreen forest	1.4	1.0	0.57	0.43
6	Temperate broadleaf summergreen forest	9.1	6.8	4.5	3.4
7	Boreal needleleaf evergreen forest	17	13	17	12
8	Boreal broadleaf summergreen forest	8.3	6.2	8.0	6.0
9	Boreal needleleaf summergreen forest	3.0	2.2	2.9	2.2
10	C ₃ grass	23	17	20	15
11	C ₄ grass	14	10	15	11
12	C ₃ crop	0	0	13	9.4
13	C ₄ crop	0	0	2.6	1.9

^aAn example using ORCHIDEE PFTs. Grazing land is censored.

Verant *et al.*, 2004]. Even though the translation of land cover classes to PFT classes is relatively smooth, there are still assumptions that need to be made in the conversion, in particular, the assignment of percent bare soil to each land

cover type (Table 3). Note that parameterizations of built-up land are still very crude in LSMs, and are usually parameterized as bare soil, as is the case here. Since grazing land was censored for the LSM simulation, the PFT areas reflect

Notes to Table 3.

^a*Crucifix et al.* [2005], *FAO* [2005], *Hoffmann and Jackson* [2000], *McMaster and Davis* [2001], *Ngo-Duc et al.* [2005], *Oleson and Bonan* [2000], *Weltzin and McPherson* [1999], *Winslow et al.* [2003], University of Maine (2006, Pasture Management Home Study, online course in N. R. C. Centre, available at http://www.umaine.edu/umext/pasture/Lessons/L5/stock_den.htm), and J. Gerrish (2005, *Grazier's Arithmetic*, University of Minnesota, available at <http://www.extension.umn.edu/Beef/components/homestudy/plesson5.pdf>). Abbreviations are as follows for the PFT classes: TR_BL_EG, tropical broadleaf evergreen forest; TR_BL_RG, tropical broadleaf raingreen forest; TM_NL_EG, temperate needleleaf evergreen forest; TM_BL_SG, temperate broadleaf summergreen forest; BO_NL_EG, boreal needleleaf evergreen forest; BO_BL_SG, boreal broadleaf summergreen forest; BO_NL_SG, boreal needleleaf summergreen forest; C₃ gs, C₃ grassland; C₄ gs, C₄ grassland; C₃ cr, C₃ cropland; C₄ cr, C₄ cropland.

^bPFT and land cover classes are the same. The PFT fraction falls within the limits for these land covers given by *Crucifix et al.* [2005].

^cThe PFT forest composition was estimated from the Atlas of Russia's Intact Forest Landscapes (available at <http://www.forest.ru/eng/publications/intact>). The boreal deciduous forest class is mainly in eastern Siberia, in the larch forests.

^dAssume 50% coniferous and 50% deciduous, on the basis of previous ORCHIDEE classification. The PFT fraction falls within the limits for these land covers given by *Crucifix et al.* [2005].

^eBare soil percent, tree type, and tree density taken from *Hoffmann and Jackson* [2000]. C₄ grass percentage is taken from C₃/C₄ grass maps [*Winslow et al.*, 2003]. Tree percentage is slightly higher than the upper limit set by *Crucifix et al.* [2005] (30%).

^fTree density taken from *Weltzin and McPherson* [1999]. Bare soil is taken to be the same as tropical savanna. Tree density for temperate savannas (29%) is derived from the average of six temperate savanna sites in Arizona from *Weltzin and McPherson* [1999]. A biome-scale average tree density for temperate savannas could not be found. By definition, tree canopies in savannas do not exceed 50% coverage (Wisconsin Botanical Information System, available at <http://www.botany.wisc.edu/wisflora/curtis.asp>). Assume the most common species in temperate savannas is oak (<http://www.botany.wisc.edu/wisflora/curtis.asp>).

^gPFT and land cover classes are the same, percent bare soil taken from original ORCHIDEE scheme, as it is within the range of grasslands given by F. B. Fisher *et al.* (1998, Montana Land Cover Atlas, unpublished report, viii + 50 pp., Montana Cooperative Wildlife Research Unit, University of Montana, Missoula). The PFT fraction falls within the limits for these land covers given by *Crucifix et al.* [2005].

^hThe shrubland biome is dominated by shrubs with small but thick evergreen leaves; therefore we choose broadleaf evergreen as the tree species. Since shrublands occur in parts of South America, Western Australia, central Chile, and around the Mediterranean Sea, we chose the type of tree to be "temperate." We choose broadleaf evergreen for the "tree" (Community and Ecosystem Dynamics, available at <http://www.estrellamountain.edu/faculty/farabee/biobk/BioBookcommecosys.html>). ORCHIDEE does not have a shrub PFT. Grass must be added so that shrubland does not behave like a forest, even though there is very little grass in the actual biome. The percentage grassland is based upon *Ngo-Duc et al.* [2005]. C₃ grass is chosen, because shrubs they are intended to simulate are C₃.

ⁱWe used percentage of bare soil from *Ngo-Duc et al.* [2005]. C₃ grasses used because shrubs are C₃.

^jWe reduced bare land to 50% because not all tundra is barren tundra, as was given by *Ngo-Duc et al.* [2005].

^kPFT and land cover classes are the same. The PFT fraction falls within the limits for these land covers given by *Crucifix et al.* [2005].

^lEquivalent to 100% bare soil with no vegetation permitted.

^mPFT and land cover classes are the same. Percentage of bare soil from *Ngo-Duc et al.* [2005]. Perhaps too low; as in Canada, bare soil in cropland has been estimated to be 75% [*McMaster and Davis*, 2001]. Same percent of bare soil as used by *Oleson and Bonan* [2000].

ⁿWe assigned 20% bare soil for grazing land. This corresponds with a "good" condition pasture, as defined by the *FAO* [2005], University of Maine (2006), and J. Gerrish (2005). Also see <http://cesantabarbara.ucdavis.edu/lr600.htm>. There are a wide range of estimates of percentage bare soil in grazing land, from 86% in arid areas (R. O. Knuteson *et al.*, Progress Toward a Characterization of the Infrared Emissivity of the Land Surface in the Vicinity of the ARM SGP Central Facility: Surface (S-AERI) and Airborne Sensors (NAST-I/S-HIS, available at http://www.arm.gov/publications/proceedings/conf11/extended_abs/knuteson_ro.pdf), to 55% in areas of severe drought (Trend Study 13B-5-05, available at <http://wildlife.utah.gov/range/pdf/wmu13b/13B-05.pdf>). See also UMCE Pasture Management Home Study: An online course, available at http://www.umaine.edu/umext/pasture/Lessons/L5/stock_den.htm. See also University of Minnesota Extension Service, Lesson 5, *Grazier's Arithmetic*, available at <http://www.extension.umn.edu/beef/components/homestudy/plesson5.pdf>. Another study notes that grassland with introduced grazers can have bare ground coverages in the 10 to 50 percent range (Fisher *et al.*, 1998) (Vegetation Appendix, available at <http://bogc.dnrc.state.mt.us/PDF/FinalEIS/10%20Vegetation%20App.pdf>). In Canada, pasture was measured to have 24% bare soil [*McMaster and Davis*, 2001].

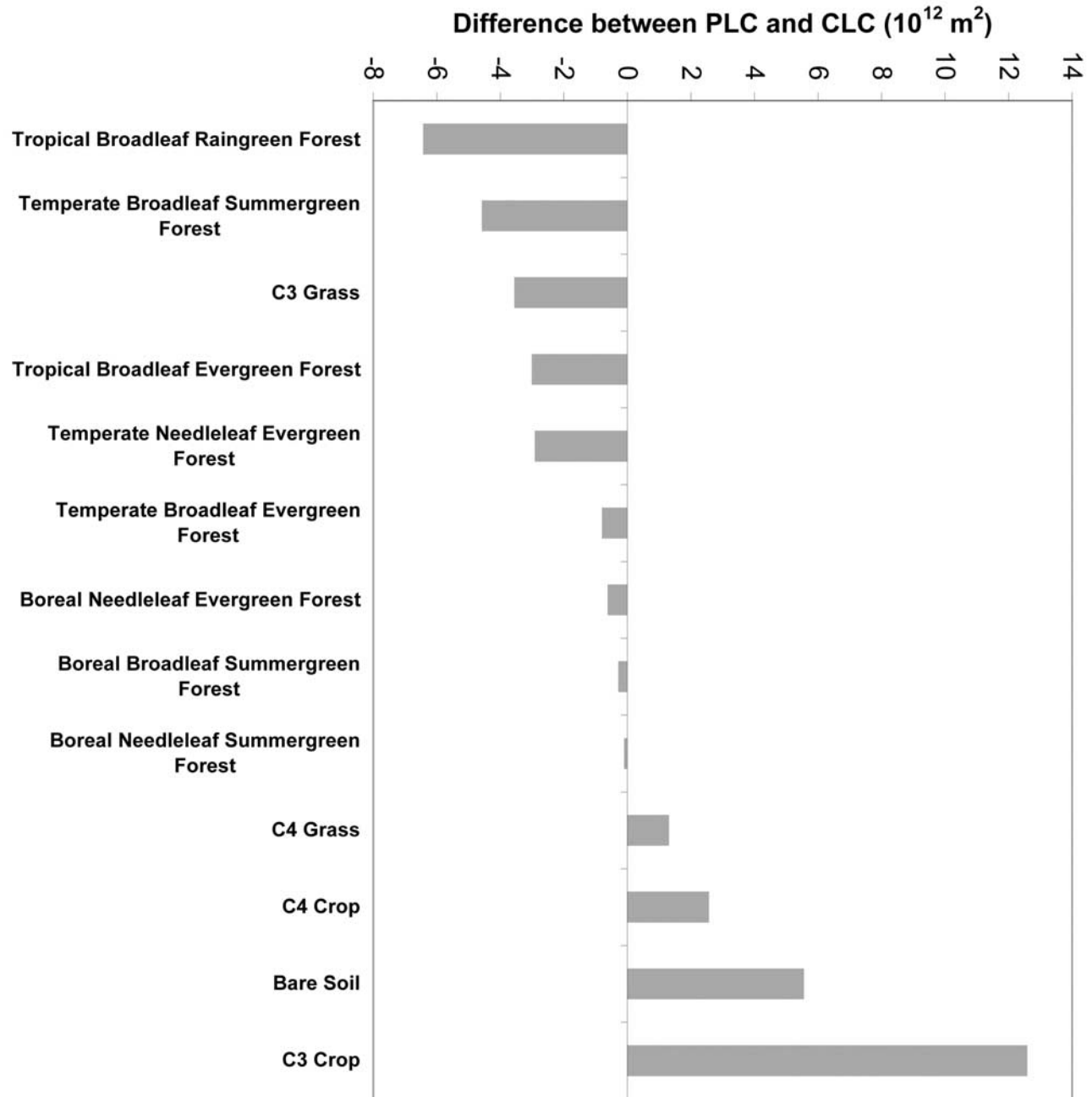


Figure 4. Difference between plant functional types (PFTs) for the PLC and CLC land cover scenarios. Grazing is censored.

the censored version of grazing land.

[38] The resulting inventory of changes in PFTs (Table 4 and Figure 4) provides a different picture than that from land cover change. Tropical broadleaf raingreen forest has the largest losses associated with anthropogenic land cover change, and human activities have caused the loss of about 72% of this plant functional type. Temperate broadleaf summergreen forest undergoes the next largest losses of all PFTs, with half of this PFT being removed by human activities. The total loss of trees PFTs is 1.9 E + 13 m², over a

quarter of the potential amount of trees on the planet. This area of lost trees is larger than estimates of forest loss in the land cover change inventory because it includes additional trees lost in savannas. The boreal forest PFT has undergone a very small reduction compared to other forest types (3.5% as compared with tropical forests of 42% loss, and temperate forests of 48% loss); the losses of this PFT are likely underestimated because of the lack of tree plantation mapping.

[39] Grassland PFTs undergo a much smaller change than do forests from anthropogenic land cover (-6.1%), as some

Table A1. Global Cropland Area^a

Source	Area	Notes
<i>Anthor et al.</i> [1998]	$14.8 \times 10^{12} \text{ m}^2$	modified secondary
C. M. Biradar et al., A global map of rainfed cropland areas (GMRCAs) using time series data from multiple satellite sensors, submitted to <i>International Journal of Applied Earth Observation and Geoinformation</i> , 2008, in review.	$1.53 \text{ e} + 13 \text{ m}^2$	derived from work on GIAM, in review, and C. M. Biradar, personal communication, 14 April 2008
<i>DeFries and Los</i> [1999]	$13.94 \times 10^{12} \text{ m}^2$	area in IGBP Discover Product;
<i>Loveland et al.</i> [2000]		AVHRR satellite data
<i>Food and Agriculture Organization of the U. N. (FAO)</i> [1990, 1991]	$14 \times 10^{12} \text{ m}^2$	$4700 \times 10^6 \text{ ha}$ is used by humans, 30% of this is devoted to crops, including tree crops as well as annual row crops
FAO (2000, FAOSTAT Web site, available at http://www.fao.org) [FAO, 1993]	$15.1 \times 10^{12} \text{ m}^2$	arable and permanent crops; for 1998, country survey
<i>Hansen et al.</i> [2000]	$11.1 \times 10^{12} \text{ m}^2$	University of Maryland 1-km project; AVHRR satellite data
<i>Houghton</i> [1999]	$1360 \times 10^6 \text{ ha}$	synthesis of records
<i>Klein Goldewijk</i> [2001]	$1,477,600 \text{ E} + 03 \text{ ha}$	compilation of secondary information, Netherlands Environmental Assessment Agency, available at http://www.mnp.nl/en/themasites/hyde/index.html
<i>Lal and Pierce</i> [1991]	1.5 billion ha	area of arable land cultivated to produce food
<i>Ramankutty and Foley</i> [1998]	$17.92 \times 10^6 \text{ km}^2$	represents the area in croplands during the early 1990s for each grid cell on a global satellite 5-min resolution latitude-longitude grid; combined a satellite-derived land cover data set with a variety of national and subnational agricultural inventory data; uses adjusted FAO data from <i>Alexandratos</i> [1995]; does not include plantations and shifting cultivation
A. Strahler (personal communication, 2002)	$14,671,396 \text{ km}^2$	croplands from the "Consistent Year Product"
<i>Tilman et al.</i> [2001]	$1.54 \times 10^9 \text{ ha}$	
<i>Warnant et al.</i> [1994]	$13.4 \times 10^{12} \text{ m}^2$	using CARAIB mechanistic model
<i>World Resources Institute (WRI)</i> [2000]	$27,890,000 \text{ km}^2$	global agricultural area
<i>Wood et al.</i> [2000] <i>WRI</i> [2000]	$36,234,000 \text{ km}^2$	based on PAGE ecosystem boundaries, defined independently; for agricultural areas
World Resources Institute (WRI) (2003, <i>Earth Trends: The Environmental Information Portal</i> , Washington, D. C., available at http://earthtrends.wri.org/)	$1501452.0 \times 10^3 \text{ ha}$	arable and permanent crops
<i>Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen (WBGU)</i> [1998]	$16.0 \times 10^6 \text{ km}^2$	global cropland area
Mean	$1.7\text{E} + 13 \text{ m}^2$	
Standard Deviation	$6.1\text{E} + 12 \text{ m}^2$	

^aMaps of global cropland include C. M. Biradar et al. (2008, in review), *van Velthuisen et al.* [2007], *Leff et al.* [2004], *Ramankutty and Foley* [1998], and *Klein Goldewijk* [2001]. Maps of irrigated lands include FAO (2007, Land use patterns and land cover, module 5, Food Insecurity, Poverty and Environment Global GIS Database (FGGD), Rome, available at <http://geonetwork.unocha.org/mapsondemand/srv/en/metadata.show?id=23713>), *Siebert et al.* [2005a; 2005b], and *Thenkabail et al.* [2006].

natural grasslands and savannas are replaced by grazing land, which includes the grassland PFT. The global ratio of C_3/C_4 plants (more water intensive versus more water efficient) undergoes an 8% increase from 1.8 to 1.9 in the potential vegetation scenario, suggesting that the total water use efficiency of crops and grasses has slightly decreased.

[40] Of all PFTs, human activity causes the largest increase in C_3 cropland (Figure 4). Next largest increase is bare soil, with an increase of 19%, reflecting the increased land disturbance in anthropogenic land covers. C_4 grassland also experiences an increase in area, related to replacement of C_3 forests with C_4 pasture grasses in the tropics (as given by *Still et al.* [2003]).

[41] The PFT classes which undergo the largest losses from anthropogenic activities are not the same as the land cover classes which undergo the largest losses, which were found to be grasslands and savannas (Figure 2a). The reason for the differences in results from when one considers land cover classes and PFTs is that, in some cases, the ALC that replaces the PLC has the same dominant PFT, as is in the case with tropical savanna (C_4 grass) being replaced by grazing (C_4 grass), although there is concurrent increase in bare soil and reduction in tree cover. Note that the functional changes caused by grazing on tundra, open shrubland, and desert land are not included in this inventory, but would likely result in an increase in percent bare soils for these biomes, yet some nutrient-limited ecosystems may see a

Table A2. Global Built-Up Areas (or Human-Occupied Land)^a

Source	Area	Notes
<i>Amthor et al.</i> [1998]	$2.0 \times 10^{12} \text{ m}^2$	modified secondary, http://www-eosdis.ornl.gov/NPP/other_files/worldnpp1.txt
<i>WRI</i> [2000]	256,332 km ²	WRI (2003)
<i>Hansen et al.</i> [2000]	260,092 km ²	p. 1350, Table 4, based on 1-km resolution from the AVHRR
<i>Loveland et al.</i> [2000]	260,117 km ²	p. 1320, Table 8
B. Miteva (2004)	500,000 km ²	
A. Strahler (personal communication, 2002)	243,617 km ²	urban and built-up area in “Consistent Year Product”
<i>WRI</i> [2000]	4,745,000 km ²	p. 260, defined by the NOAA/NGDC nighttime lights of the world database (IGBP data); the location of stable lights online supplemental database; land for settlement and infrastructure
<i>Wackernagel et al.</i> [2002]	275,102,000 ha	
Mean	1.4e + 12 m²	
Standard Deviation	1.7e + 12 m²	

reduction in bare soil, as grazing may add nutrients to the system.

5. Discussion and Conclusions

[42] The results are limited by the quality of the maps used, including the potential vegetation map, and each ALC map. Further, generalization of land cover at a global scale inevitably requires some assumptions that will not necessarily hold at finer resolutions, and this database is not designed for use at finer scales. Land cover data sets are inherently uncertain, both in mapping the correct location of land cover [*Iwao et al.*, 2006] and the total area of land cover altered (Figure 3).

[43] This work highlights the need for improvements on land cover mapping. Grazing land has a huge impact upon the Earth, and improvements in mapping of grazing areas are important. And it is important to improve how LSMs account for grazing, for example, by taking into account grazing intensity. Further, we also underline the importance of the creation of a map of global tree plantations and “industrial/managed forests.” The current lack of available maps on global tree plantations is unfortunate, as it has been estimated that timber plantations in North America and oil-palm plantations in Southeast Asia now cover $1.9 \text{ E} + 12 \text{ m}^2$ worldwide [*Foley et al.*, 2005] and should continue to

increase, as signatory countries work to meet carbon reduction requirements stipulated in the Kyoto Protocol, and as large tracts of rain forest and wetlands are being replaced by palm tree plantations in areas such as Malaysia and Brazil to meet the rising demand for biofuel oil [*Rosenthal*, 2007]. And improved mapping of boreal forest loss through industrial forestry is also important because boreal forest loss has been identified to have important impacts on surface temperature because of altered albedo [e.g., *Betts et al.*, 2007].

[44] One important step in modeling land cover in LSMs is the choice percentage bare soil assigned to occur in each land cover, as required in the reclassification matrix between land covers and PFTs. The percentage of bare soil drives the major land surface fluxes and properties, determining, among others, LAI and albedo. However, in general, the percent bare soil that is included in each land class is not presented. Recently, *Wang et al.* [2006] have made this bare soil consideration transparent in their land cover/PFT data set for modeling studies by publishing the conversion table between land cover classes and PFTs; however, in this table, they do not discuss how the percent bare soil was chosen. For our reclassification matrix, we chose the bare soil percentages on the basis of literature estimates (Table 3), albeit regional in nature. With our simulation, we see percentage bare soil increase with human

Table A3. Global Grazing Land Area^a

Source	Area	Notes
FAO (2000)	3,476,886,000 ha	
<i>FAO</i> [1990]	$3300 \times 10^6 \text{ ha}$	70% of $4700 \times 10^6 \text{ ha}$ (land used by humans) is in permanent pastures)
FAO (2007), <i>van Velthuizen et al.</i> [2007]	$3.6 \text{ e} + 13 \text{ m}^2$	26.6% of land surface (for 2001)
<i>Klein Goldewijk</i> [2001]	$3,450,617 \text{ E} + 03 \text{ ha}$	Netherlands Environmental Assessment Agency, http://www.mnp.nl/en/themasites/hyde/index.html
N. Ramankutty (2004)	$3.6 \text{ e} + 13 \text{ m}^2$	
<i>White et al.</i> [2000]	$3.4 \times 10^9 \text{ ha}$	area of forest land converted to grazing land
Mean	3.4e + 13 m²	
Standard deviation	1.5e + 13 m²	assumed to be 45% of the mean, as the three sources above do not appear independent of each other

^aMaps of global grazing area include *van Velthuizen et al.* [2007] and N. Ramankutty (2004).

Table A4. Global Impounded Water Area^a

Source	Area	Notes
<i>St. Louis et al.</i> [2000]	$1.5 \times 10^6 \text{ km}^2$	International Commission on Large Dams (ICOLD)'s database
Mean	$1.5e + 12 \text{ m}^2$	
Standard Deviation	$6.7e + 11 \text{ m}^2$	assumed to be 45% of the mean

^aMaps of global impounded water area include [*Lehner and Döll*, 2004].

impact (Table 4) in line with expectations that human disturbance to land cover causes an increase in bare soil, even though our bare soil percentages for cropland and grazing land are conservative (Table 3). In contrast, the land cover change data set presented by *Wang et al.* [2006] shows a decrease in bare soil with human impact, which may be due to their noninclusion of grazing land in the study, and the percent bare soils being relatively high in natural grassland and savanna and quite low in cropland. Indeed, the main difference between our classification of grazing and grassland is the percentage bare soil. Such decisions can have major impacts on the simulation results and need to be transparent. A global standard of percent bare soils for land cover classes is needed, and may help to reduce the large variability in LSM output that are driven by the same forcing data, as found in the GWSP2 program [*Dirmeyer et al.*, 2006]. A good place to start would be to generate statistics on bare soil for major land covers from the data on global fractional cover of bare soil that is independently described from MODIS and AVHRR satellite imagery [*DeFries et al.*, 1999; *Hansen et al.*, 2003].

[45] Here we have created a mapping LUCC database that provides a coherent comparison of potential and current land cover, for which all change is limited to anthropogenic action, thus allowing for direct tests of impacts of LUCC. Here we have improved the state of the art by making a mapping data set available to modelers that increases awareness of the importance of area and in the inclusion of a broad range of hydrologic major anthropogenic land cover changes, including significant alterations to the African savannas, which are not seen in many data sets [e.g., *Betts et al.*, 2007], and which can have large impacts on the water cycle [*Sterling*, 2005]. The relatively fine resolution (5 min) of the map allows it to be used in a variety of global LSMs.

[46] The database is tailored for use in LSMs to assess the direct impact of LUCC on land surface fluxes, water and

carbon cycle, and climate, for both coupled and uncoupled simulations. It has a transparent conversion to PFTs that enables improved interpretation and comparison of LSM studies on LUCC. The straightforward conversion of land covers to PFT categories is illustrated for the ORHCHIDEE LSM to assess the impact of LUCC on PFT distribution.

[47] Our land cover change database documents the large impacts humans have had on the land surface of the planet, reducing some biomes by up to 92%. It also provides insight into how humans have changed the ecological functioning, such as by reducing the natural tree cover by 27%, and increasing the proportion of C₃ to C₄ plants. Thus, the biome with the greatest losses from the natural state are the natural grassland biomes, yet the largest changes to ecological functioning in the world are resulting from loss of forests, because grazing does not change the dominant functional type of grassland, although bare soil is increased.

[48] We emphasize that an important step to address land cover change uncertainty in LSM studies is to document fully anthropogenic land cover areas (%ALC) that are used, to aid in the interpretation and intercomparison of results. We show here that the LUCC database presented here reflects well our current understanding of the extent of human transformation of the Earth surface, yet there is a wide range of %ALC in other commonly used land cover databases, all of which underestimate the %ALC, some by more than 2 standard deviations of the estimated literature mean of 44%.

Appendix A: Literature Estimates of Area of Anthropogenic Land Covers

[49] We assemble estimates of transformed areas for each anthropogenic land cover type, including the following human-dominated land covers in our analysis: agriculture, tree plantations, built-up land areas, grazing land, land inundated by dams, and biomass burning, on the basis of

Table A5. Global Tree Plantation Area (A_p)^a

Source	Area	Notes
<i>Winjum and Schroeder</i> [1997]	130,000,000 ha	for 1990; based on the work of <i>Allan and Lanly</i> [1991]
<i>Pandey</i> [1997], <i>Brown</i> [1999], and <i>Matthews et al.</i> [2000]	1.03 million km ²	in recent FAO surveys, industrial wood plantation forests worldwide; for 1995
<i>Pandey</i> [1995]	$150 \times 10^6 \text{ ha}$	for 1990
<i>Dixon et al.</i> [1994]	$112 \times 10^6 \text{ ha}$	for 1987–1990
<i>Sedjo</i> [1999]	99.3 million ha	drawn from <i>Bazett</i> [1993]; area of industrial plantations worldwide
<i>Sharma</i> [1992]	135 million ha	sum of area of tropical and temperate forest plantations
Mean	$1.2e + 12 \text{ m}^2$	
Standard deviation	$2.0e + 11 \text{ m}^2$	

^aTo date, a map of global tree plantations is not yet available.

the criteria that they each cover at least 0.1 percent of the Earth's terrestrial surface and reflect direct use (Tables A1–A5). Area estimates are constrained to be recent (published since 1990). We do not include “indirect” anthropogenic cover changes such as desertification, inadvertent draining of the Aral Sea, fire suppression, climate change, pollution induced changes, deforested lands that are abandoned, or lands impacted by war. Our estimates of land cover change are thus conservative. In the estimate of the area of grazing land the four estimates do not appear independent.

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A. Ducharne, Laboratoire Sisyphe, CNRS, Université Pierre et Marie Curie, Boite 105, 4 place Jussieu, 75252 Paris CEDEX 05, France.

S. Sterling, Department of Geography, University of Toronto, Sidney Smith Hall, 100 St. George Street, Room 5047, Toronto, ON M5S 3G3, Canada. (sterling@geog.utoronto.ca)