Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000

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[1] Agricultural activities have dramatically altered our planet's land surface. To understand the extent and spatial distribution of these changes, we have developed a new global data set of croplands and pastures circa 2000 by combining agricultural inventory data and satellite-derived land cover data. The agricultural inventory data, with much greater spatial detail than previously available, is used to train a land cover classification data set obtained by merging two different satellite-derived products (Boston University's MODIS-derived land cover product and the GLC2000 data set). Our data are presented at 5 min (~10 km) spatial resolution in longitude by longitude, have greater accuracy than previously available, and for the first time include statistical confidence intervals on the estimates. According to the data, there were 15.0 (90% confidence range of 12.2–17.1) million km^2 of cropland (12% of the Earth's ice-free land surface) and 28.0 (90% confidence range of 23.6–30.0) million km^2 of pasture (22%) in the year 2000.

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1. Introduction

[2] Human land use activities are a force of global significance [*Foley et al.*, 2005]. Humans have extensively modified the Earth's land surface, altering ecosystem structure and functioning, and diminishing the ability of ecosystems to continue providing valuable resources such as food, freshwater and forest resources, and services such as regulation of climate, air quality, water quality, soil resources.

[3] Agricultural activities, in particular, have been responsible for a vast majority of these land use related ecosystem consequences [*Richards*, 1990; *Tilman et al.*, 2001; *Green et al.*, 2005]. Nearly 40% of the planet's ice-free land surface is now being used for agriculture, and much of this land has replaced forests, savannas, and grasslands [*Foley et al.*, 2005]. Clearing of tropical forests for cultivation or grazing is responsible for ~12–26% of the total emissions of carbon dioxide to the atmosphere [*DeFries and Achard*, 2002; *Houghton*, 2003], and land use changes can significantly modify regional and global climate [*Pitman et al.*, 1999; *Pielke et al.*, 2002]. Furthermore, ~20–30% of the total available surface water on the planet is withdrawn for irrigation [*Cassman and Wood*, 2005], and nitrogen fixation through fertilizer production and crop cultivation currently equals or even exceeds natural biotic fixation [*Galloway et al.*, 1995; *Smil*, 1999].

[4] As such, agriculture is partly or wholly responsible for environmental concerns such as tropical deforestation and biodiversity loss, fragmentation and loss of habitats, emissions of important greenhouse gases, losses of soil quality through erosion and salinization, decreases in quantity and quality of water resources, alteration of regional climates, reduction in air quality, and increases in infectious diseases [*Foley et al.*, 2005]. On the other hand, agricultural expansion and intensification has provided a crucial service to humanity by meeting the food demands of a rapidly growing population [*Cassman and Wood*, 2005], and thereby involves a trade-off between food production and environmental deterioration [*DeFries et al.*, 2004; *Foley et al.*, 2005].

[5] In order to assess the Earth system consequences of agriculture, both the positive social and economic benefits and the often negative environmental consequences, it is essential to develop global data sets of the geographic distribution of agricultural land use and land cover change [e.g., *Wood et al.*, 2000; *Bauer et al.*, 2003; *Donner and Kucharik*, 2003; *Cassman and Wood*, 2005]. Recent advances have led to the emergence of new continental-to-global-scale data sets of agricultural land cover, developed by merging satellite-derived land cover data sets and ground-based agricultural inventory data sets [*Ramankutty and Foley*, 1998; *Frolking et al.*, 1999; *Ramankutty and Foley*, 1999; *Hurtt et al.*, 2001; *Klein Goldewijk*, 2001; *Cardille et al.*, 2002; *Frolking et al.*, 2002; *Cardille and Foley*, 2003; *Donner*, 2003; *Leff et al.*, 2004; *Ramankutty*, 2004].

[6] Our earlier work, in particular, pioneered the development of a statistical "data fusion" technique to merge a satellite-derived, global, 1-km resolution land cover data set, with ground-based national and subnational cropland inven-

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Table 1. Land Cover Classification Schemes Used by the Two Global Satellite Data Sets

BU-MODIS Legend[a]	GLC 2000 Legend
0: water	1: tree cover, broadleaved, evergreen
1: evergreen needleleaf forest	2: tree cover, broadleaved, deciduous, closed
2: evergreen broadleaf forest	3: tree cover, broadleaved, deciduous, open (15–40% tree cover)
3: deciduous needleleaf forest	4: tree cover, needle-leaved, evergreen
4: deciduous broadleaf forest	5: tree cover, needle-leaved, deciduous
5: mixed forests	6: tree cover, mixed leaf type
6: closed shrublands	7: tree cover, regularly flooded, fresh water (and brackish)
7: open shrublands	8: tree cover, regularly flooded, saline water
8: woody savannas	9: mosaic; tree cover/other natural vegetation
9: savannas	10: tree cover, burnt
10: grasslands	11: shrub cover, closed-open, evergreen
11: permanent wetlands	12: shrub cover, closed-open, deciduous
12: croplands	13: herbaceous cover, closed-open
13: urban and built up	14: sparse herbaceous or sparse shrub cover
14: cropland/natural vegetation mosaic	15: regularly flooded shrub and/or herbaceous cover
15: snow and ice	16: cultivated and managed areas
16: barren or sparsely vegetated	17: mosaic; cropland/tree cover/other natural vegetation
254: unclassified (recoded to 17)	18: mosaic; cropland/shrub or grass cover
255: fill value (recoded to 17)	19: bare areas
	20: water bodies (natural and artificial)
	21: snow and ice (natural and artificial)
	22: artificial surfaces and associated areas
	23: no data

[a]We obtained product 2000289 V003, SDS 01 Land_Cover_Type_1 with IGBP land cover classification scheme.

tory statistics, to develop global maps of the world's croplands in the early 1990s [*Ramankutty and Foley*, 1998], and their historical changes since the year 1700 [*Ramankutty and Foley*, 1999]. These data sets have been widely used by the global change community and have been employed in various analysis and assessments, including analysis of regional food security [*Ramankutty et al.*, 2002b], an assessment of the regions of the world undergoing the most rapid land cover changes over the last decade [*Lepers et al.*, 2005], global carbon cycle modeling [*McGuire et al.*, 2001], analysis of the role of agriculture in carbon cycling [*Bondeau et al.*, 2007], global climate modeling [*Bonan*, 1999; *Brovkin et al.*, 1999; *Bonan*, 2001; *Myhre and Myhre*, 2003; *Brovkin et al.*, 2006], estimation of global soil erosion [*Yang et al.*, 2003], and as input to global economic models [*Lee*, 2005; *Ramankutty et al.*, 2007]. These data have also provided the essential information on historical croplands for other global land use/cover data sets [*Hurtt et al.*, 2006; *Wang et al.*, 2006].

[7] In this paper, we present a critical update to our global agricultural land cover data sets. In particular, we present new global data sets for the year 2000, developed using an order-of-magnitude enrichment of our agricultural inventory data, a combination of two different satellite-derived global land cover data sets for year 2000, and improved methods to merge the satellite data and inventory data. We also present, in addition to an updated map of global croplands for the year 2000, a new map of global pastures, as well as estimated confidence intervals for both of these data sets. These new data sets will form valuable products for the global environmental change community.

2. Data Sets

[8] In this section we describe how we compiled the two different sources of information used in this study: (1) satellite-based global land cover classification data sets; and (2) ground-based agricultural census/inventory data sets.

2.1. Satellite Data Sets

[9] We used two different high-resolution (1-km) satellite-based, global land cover classification data sets that are available for circa 2000: Boston University's Moderate resolution Imaging Spectrometer (MODIS) based global land cover product [*Friedl et al.*, 2002] (BU-MODIS hereafter), and the Satellite Pour l'Observation de la Terre (SPOT) VEGETATION based Global Land Cover 2000 (GLC2000) data set [*Bartholome and Belward*, 2005]. The BU-MODIS land cover product used data acquired from 15 October 2000 to 15 October 2001 to derive 17 land cover classes using a supervised classification scheme (see Table 1 for legend). The GLC2000 data set utilized data acquired from 1 November 1999 to 31 December 2000 to derive 22 global land cover classes on the basis of regional classifications performed with the expertise of regional institutions (Table 1).

[10] We applied a simple set of climatic parameters to mask obviously nonagriculture areas within the satellite data sets, else we obtain some spurious results in the Northern Hemisphere high latitudes (e.g., land classified as open shrublands are found both in the western United States and boreal Canada; because open shrublands have a small fraction of cultivation in the former we end up with croplands in boreal Canada also). This mask included all regions north of 50°N with Growing Degree Day (GDD; base 5°C) less than 1000°C d (see Figure S1). This GDD cutoff approximates that empirically estimated by *Ramankutty et al.* [2002a] (using their previous cropland data set that does not include a mask, hence there is no circularity), and is conservative compared to the 2000°C d cutoff for agriculture used by *Cramer and Solomon* [1993]. GDD data were calculated according to *Ramankutty et al.* [2002a], and interpolated to

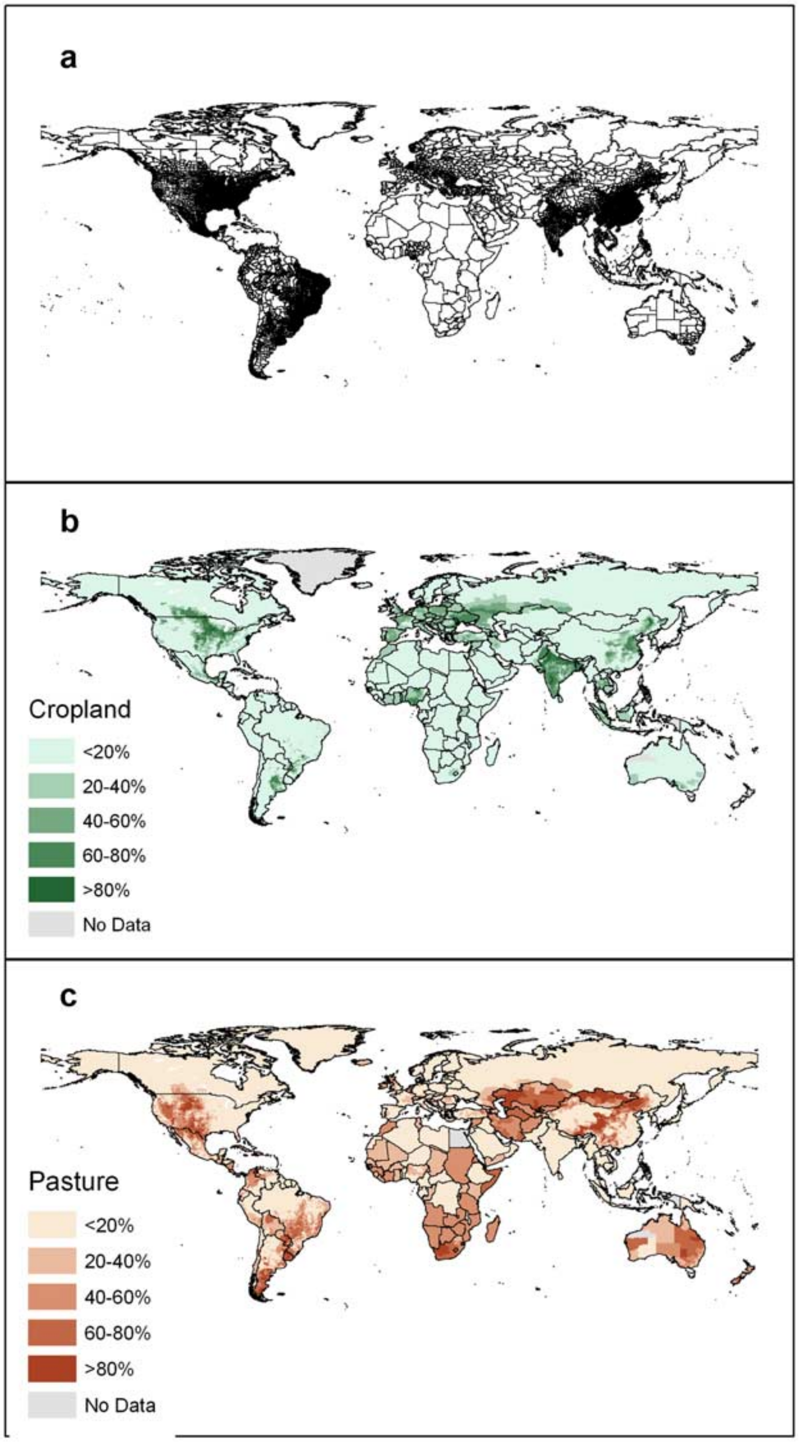

Figure 1. (a) Administrative units for which we calculated agricultural inventory data (n = 15,990 administrative units); (b) percentage cropland within each administrative unit from the agriculture inventory data; and (c) percentage pasture within each administrative unit from the agriculture inventory data.

1km resolution. We also masked out protected/minimal use areas in the central part of the Australian continent (Bureau of Rural Sciences, Land Use of Australia, Version 3: 2000/2001, Department of Agriculture, Fisheries and Forestry, Australian Natural Resources Data Library, Canberra, Australia, available at http://www.nlwra.gov.au/Data_Library/index.aspx), which otherwise gets classified entirely as pasture.

2.2. Agricultural Inventory Data

[11] We extensively compiled cropland and pasture inventory data for the globe at the national and subnational

Table 2. Source of Census Data

Country	Administrative Units	Source	Year of Data
Argentina	499	Instituto Nacional de Estadistica y Censos, Censo Nacional Agropecurio, 2002 (http://www.indec.mecon.ar)	2001–2002
Australia	59	Australian Bureau of Statistics, Agricultural Commodity Survey data from 2002–2004 (data purchased from ABS, 2005) (http://www.abs.gov.au)	2002–2003
Austria	9	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	2000
Belarus	6	cropland data from Ministry of Statistics and Analysis, Minsk, 2004; pasture data from FAO country pasture/forage resource profiles (http://www.fao.org/ag/AGP/AGPC/doc/Counprof/regions/index.htm)	1993; 2000
Belgium	11	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	2000
Bolivia	9	crop-harvested area data from Instituto Nacional de Estadistica, Cuadro 8.03.04 (http://www.ine.gov.bo); livestock units from the Food and Agriculture Organization's GLIPHA database (http://www.fao.org/ag/aga/glipha/index.jsp)	2000
Brazil	5510	Instituto Brasileiro de Geographia e Estatistica, 1995–1996 Census of Agriculture (http://www.ibge.gov.br/)	1996
Bulgaria	28	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	2000
Canada	273	Statistics Canada, Census of Agriculture, 2001 (http://www.statcan.ca/)	2001
Chile	13	Instituto Nacional de Estadísticas, Censo Agropecuario, 1997 (http://www.ine.cl/)	1997
China	2400	*Verburg and Chen* [2000]; *Liu et al.* [2005]	1991, 1996
Colombia	32	Departamento Administrativo Nacional de Estadística, Encuesta Nacional Agropecuaria: Resultados, 2001 (http://www.dane.gov.co/)	2001
Czech Republic	8	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	2000
Ecuador	22	Instituto Nacional de Estadistica y Censos, III Censo Nacional Agropecuario (http://www.inec.gov.ec/)	2003
Finland	6	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	1998
France	22	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	2000
Germany	40	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	1999
Greece	13	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	2000
Hungary	20	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	2000
India	552	(http://indiaagristat.com)	1991– 2002
Indonesia	26	BPS: Statistics Indonesia, land utilization by province, 2003 (http://www.bps.go.id/)	2002
Iran, Islamic Republic of	24	Statistical Centre of Iran, Iran Statistical Year Book 1382 (2003–2004) (http://www.sci.org.ir/)	2003
Ireland	2	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	1999
Italy	20	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	1999
Japan	9	Statistics Bureau, *Historical Statistics of Japan*, chapter 7.8 (http://www.stat.go.jp/)	2000
Kazakhstan	19	*State Committee for Statistics of the Republic of Kazakhstan* [1993]	1993
Korea, Republic of	14	Korea National Statistical Office, statistical database (KOSIS) (http://www.nso.go.kr/)	2000
Lithuania	10	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	2000
Mexico	2402	INEGI, VII Censo Agrícola-Ganadero 1991/Unidad de producción rural/Según uso actual del suelo (http://www.inegi.gob.mx/)	
Mongolia	20	*National Statistical Office of Mongolia* [2004]	
Nepal	14	*Central Bureau of Statistics* [2001]	1991/92
Netherlands	12	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	1994
New Zealand	14	Statistics New Zealand, agriculture statistics, 2002: reference report (http://www.stats.govt.nz/)	2002
Nigeria	31	Forestry Management, Evaluation and Coordinating Unit [FORMECU] [1995]	1993–1995
Norway	19	Statistics Norway, agricultural area, by use 1997–2006 (http://www.ssb.no/)	2004
Pakistan	5	Government of Pakistan Statistics Division, agricultural census 2000 (http://www.statpak.gov.pk/)	2000
Paraguay	19	Ministerio de Agricultura y Ganaderia, Produccion Agropecuaria Ano Agricola 2000/2001 (http://www.mag.gov.py/)	2000
Peru	26	Instituto Nacional de Estadistica y Informatica, III Censo Nacional Agropecuario 1994 (CENAGRO) (http://www.inei.gob.pe/)	1994
Philippines	11	two sources: (1) *Lopez-Meisel and Perez* [1996]; and (2) Philippines National Statistics Office, 2002 scenario of the agriculture sector in the Philippines (http://www.census.gov.ph/).	1991/2002
Poland	16	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	2000
Portugal	7	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	2000
Romania	41	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	2000
Russian Federation	75	*State Committee of the Russian Federation on Statistics* [1995]	1993
Saudi Arabia	14	cropland data from Agro-MAPS (http://www.fao.org/landandwater/agll/agromaps/interactive/page.jspx); pasture data from the Ministry of Economy and Planning (G. Allez, personal communication with Saudi Arabian embassy in Washington D.C., 2005)	2000, 1999
Slovakia	8	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	2000

Table 2. (continued)

Country	Administrative Units	Source	Year of Data
South Africa	11	Central Statistical Service, natural resource accounts: land accounts, 1994/1995 (http://www.statssa.gov.za/)	1995
Spain	17	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	1999
Sri Lanka	24	Department of Census and Statistics, census of agriculture 2002 (http://www.statistics.gov.lk/)	2002
Sweden	8	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	1998
Thailand	72	National Statistical Office, 1993 agricultural census (http://web.nso.go.th/)	1993
Turkey	73	State Institute of Statistics, Prime Ministry, Republic of Turkey, Turkey's statistical yearbook, 2004 (http://www.die.gov.tr/ENGLISH/index.html/)	2001
Ukraine	25	*Bouzaher et al.* [1994]	1991
United Kingdom	12	"Regio" database from Eurostat (http://ec.europa.eu/eurostat/)	2000
United States of America	3077	National Agricultural Statistics Service, U.S. Department of Agriculture, 2002 census of agriculture (http://www.nass.usda.gov/Census_of_Agriculture/)	2002
Uruguay	19	Ministerio de Ganaderia Agricultura y Pesca, Censo General Agropecuario 2000 (http://www.mgap.gub.uy/)	2000
Venezuela	24	Infoagro Zulia, VI Censo Agracute;cola Nacional: Datos Preliminar (http://www.zulia.infoagro.info.ve/)	1997/98
Vietnam	61	General Statistical Office of Vietnam, land use in 2003 and number of livestock (http://www.gso.gov.vn/)	2003

level (Figures 1a–1c and Table 2; more details in Text S1) for circa year 2000. We compiled data for 15,990 different administrative units of the world, ranging from political units like countries, states and counties, which represents a 46-fold improvement in the richness of our inventory data compared to our previous effort (348 units in the work of *Ramankutty and Foley* [1998]). For 57 countries, we compiled census data at the subnational level (e.g., "Level 1" indicating states in the United States or India, provinces in Canada or Argentina, departments in Bolivia or Columbia, etc., and "Level 2" indicating smaller units like U.S. counties, Brazilian municipios, or Indian districts). For 159 countries, we used national level statistics from the Food and Agriculture Organization's (FAO) FAOSTAT database (http://faostat.fao.org); for these 159 countries, we calculated an average around the year 2000 using data from 1998 to 2002. For another 19 countries in our database, no FAOSTAT data was available, and we set the data to be missing (see Text S1 for details).

[12] We compiled the cropland and pasture data to be consistent with the FAO definition of "Arable lands and permanent crops" and "Permanent pastures" respectively. Arable land is defined by FAO (http://faostat.fao.org/site/375/default.aspx) as including "land under temporary crops (double-cropped areas are counted only once), temporary meadows for mowing or pasture, land under market and kitchen gardens and land temporarily fallow (less than 5 years). The abandoned land resulting from shifting cultivation is not included in this category. Data for arable land are not meant to indicate the amount of land that is potentially cultivable." Permanent crops are defined as "land cultivated with crops that occupy the land for long periods and need not be replanted after each harvest, such as cocoa, coffee and rubber; this category includes land under flowering shrubs, fruit trees, nut trees and vines, but excludes land under trees grown for wood or timber." Permanent pastures are defined as "land used permanently (5 years or more) for herbaceous forage crops, either cultivated or growing wild (wild prairie or grazing land). The dividing line between this category and the category 'Forests and woodland' is rather indefinite, especially in the case of shrubs, savannah, etc., which may have been reported under either of these two categories."

[13] The agricultural inventory data were seldom available exactly for the year 2000 because agricultural censuses are only taken every 5–10 years a in most industrialized nations of the world, and less frequently in other countries. We collected inventory data between the years 1998 to 2002 where possible, but in several instances we relied on older data (see Table 2). For nations where the inventory data did not fall within the 1998–2002 period, or where cropland or pasture data were unavailable but some proxies were available (such as harvested area of individual crops or heads of livestock), we estimated cropland and pasture data for circa 2000 by calibrating the available information to national totals from FAOSTAT (see Text S1 for details).

[14] The quality of our census data is varied. Some regions of the world are not well represented in terms of the resolution of inventory data, with the African continent and the Former Soviet Union being the most underrepresented. Sometimes, the national level census statistics were inconsistent with the FAOSTAT data; in such cases we mostly relied on the national statistics (as recommended by FAO), except for a few cases where we believed that FAOSTAT data were more reliable (see Text S1 for details). Inconsistencies were a result of either unclear definitions of the category, or sometimes poor reporting by the national statistics agency. For example, the cropland census statistics for China has been noted by various studies to be particularly problematic [*Crook*, 1993; *Frolking et al.*, 1999; *Seto et al.*, 2000; G. K. Heilig, Can China Feed Itself?: A System for Evaluation of Policy Options, International Institute for Applied Systems Analysis, 1999, available at http://www.iiasa.ac.at/Research/LUC/ChinaFood/index_m.htm]. Here we have used the data for China from the study of *Verburg and Chen* [2000], which seems reliable. The

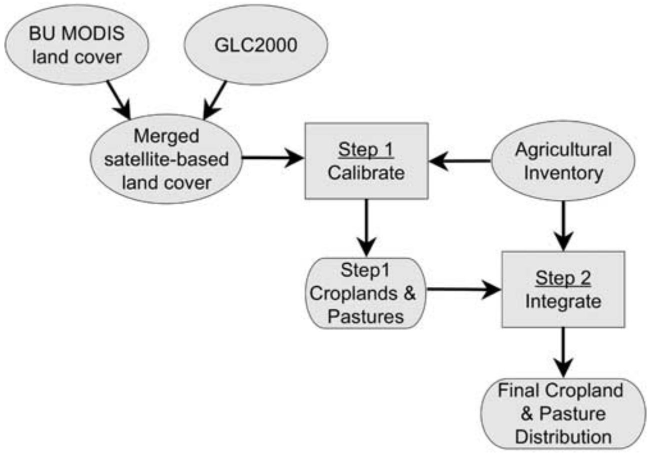

Figure 2. Flowchart depicting our methodology for combining satellite data and agricultural inventory data to derive global data sets of croplands and pastures.

definition of permanent pasture is particularly problematic, as acknowledged by the FAO (http://faostat.fao.org/site/375/default.aspx). Some countries (e.g., the United States) clearly distinguish between grassland pasture and range and forest use land grazed, while most countries do not. So it is not clear whether grazed forest land or semiarid grazing is included under the definition of pastures. One egregious example is Saudi Arabia for which FAOSTAT reports 1.7 million km^2 of permanent pasture in 2000, which is 80% of its total land area. However, most of Saudi Arabia is arid land and it is clear that much of the nomadic grazing areas are included under pasture. The Saudi Arabian subnational census data we obtained reports 486 km^2 of pasture, which is 3500 times smaller; we have chosen to rely on this lower value. Similarly, FAOSTAT reports 4 million km^2 of pasture in China. However, *Verburg et al.* [2000] report a total of only 2.6 million km^2 of grassland in China. In this case, we have used the FAOSTAT value for the total amount of pasture in the country (but our final estimates for China are lower; see section 4.1, paragraph 2). Similar inconsistencies exist in other countries and are reported in Text S1.

[15] In summary, our agricultural inventory database yields a global total of 15 million km^2 of cropland and 31.5 million km^2 of pasture. This compares to 15.3 million km^2 of cropland and 34.4 million km^2 of pasture reported by FAOSTAT; significantly, our census data compilation and interpretation yields about 8% less pasture than FAOSTAT. The difference between FAOSTAT and our own inventory for pasture can mainly be explained by differences in Saudi Arabia (as described earlier in section 2.2, paragraph 4), Australia, Nigeria, Brazil, Mexico, Indonesia, Argentina, Colombia, Russia, and Spain. There were very few countries where the national census pasture area was greater than FAOSTAT; the one exception is Iran, for which FAOSTAT reports 0.4 million km^2 of pasture while the national census reported 0.9 million km^2. For croplands, while the global total areas are comparable between FAOSTAT and our inventory, there are significant national differences. For example, the national inventories of Australia, Brazil, Canada, China and Turkey report lower cropland area compared to FAOSTAT, while Iran, Argentina, Nigeria, Mexico, and Indonesia report greater cropland area.

3. Methodology

[16] The basic methodology for creating the new cropland and pasture data sets originated from our earlier work [*Ramankutty and Foley*, 1998], where we calibrated a high-resolution satellite-derived land cover data set against agricultural inventory data to derive a global map of croplands for 1992. In this paper, however, we updated the methodology in three important ways: (1) Instead of a single satellite-derived land cover data set, here we used a merger of two different satellite data sets; (2) instead of calibrating only the a priori identified agricultural land cover classes against inventory data (as in the work of *Ramankutty and Foley* [1998]), we utilized all the land cover classes in our training procedure (as in the work of *Hurtt et al.* [2001] and *Cardille et al.* [2002]); and (3) because we had much higher-resolution census data compared to our previous efforts, we considered the census data sets to represent an approximate "truth", and used the two-step method developed by *Ramankutty* [2004] whereby the satellite data is used to spatially locate agricultural lands within an administrative unit, but the total area of agricultural land in the administrative unit is derived from the census data (with some exceptions; see section 3.5). The following section provides a detailed description of the steps taken to create the final data set (see Figure 2 for a flowchart of our algorithm).

Table 3. Examples of Combined Land Cover Categories

BU-MODIS	GLC2000	Combined Category
1 (evergreen needleleaf forest)	1 (tree cover, broadleaved, evergreen)	1 (BU1GLC1)
1 (evergreen needleleaf forest)	2 (tree cover, broadleaved, deciduous, closed)	2 (BU1GLC2)
1 (evergreen needleleaf forest)	3 (tree cover, broadleaved, deciduous, open)	3 (BU1GLC3)
1 (evergreen needleleaf forest)	4 (tree cover, needle-leaved, evergreen)	4 (BU1GLC4)
...	...	...
10 (grasslands)	11 (shrub cover, closed-open, evergreen)	218 (BU10GLC11)
10 (grasslands)	12 (shrub cover, closed-open, deciduous)	219 (BU10GLC12)
10 (grasslands)	13 (herbaceous cover, closed-open)	220 (BU10GLC13)
10 (grasslands)	14 (sparse herbaceous or sparse shrub cover)	221 (BU10GLC14)

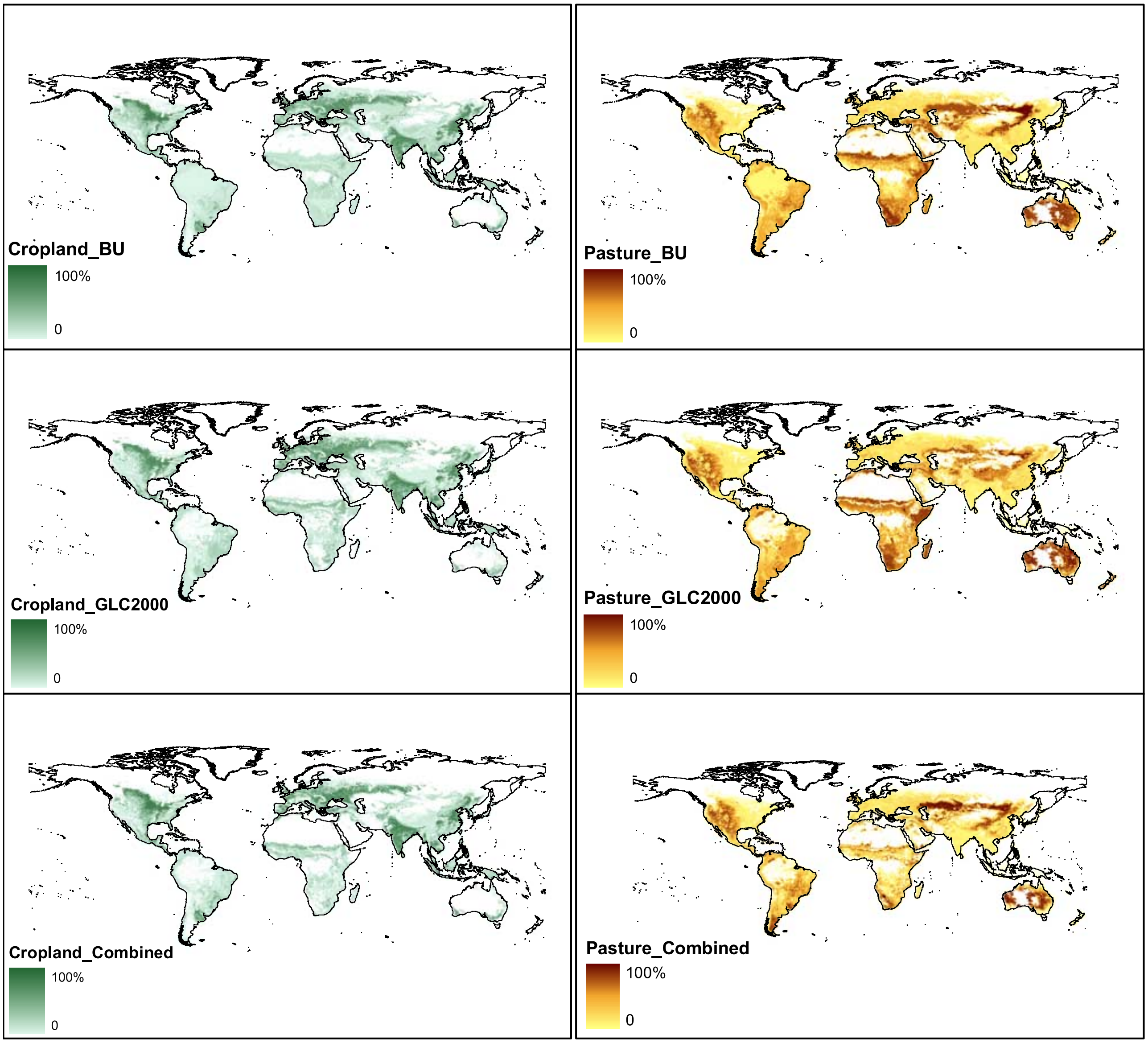

Figure 3. Maps of croplands and pastures from Step 1 of our regression procedure, obtained by calibrating the inventory data against each of the satellite-based land cover data sets separately (BU-MODIS and GLC2000) and by calibrating against the combined land cover data set (combined).

3.1. Combining the Two Satellite-Derived Land Cover Classification Data Sets

[17] *Giri et al.* [2005] compared the GLC2000 and BU-MODIS land cover data sets and found some consistency at the aggregate class level, but widespread disparities in the details. A few other studies have also tried to intercompare and harmonize these two and other global land cover data sets [*Herold et al.*, 2005; *Jung et al.*, 2006; *See and Fritz*, 2006]. The GLC2000 data set was developed using SPOT vegetation data with the assistance of regional experts and used a flexible classification scheme. The BU-MODIS data set, on the other hand, was developed using a globally consistent procedure with a fixed classification scheme, but without regional expertise. The two data sets therefore bring different kinds of expertise and information that are potentially complimentary. Here we decided to capitalize on both by combining them into a single land cover data set. To do so, we overlaid the BU-MODIS and GLC2000 data sets and developed new land cover classes that contain all possible combinations of the individual land cover classes (see Table 3 for an example). The resulting combined land cover data set consists of 391 possible land cover types and is shown later in section 3.3 to provide more accurate results when calibrated against the inventory data, as opposed to using either data set individually.

3.2. Step 1: Calibrating the Satellite Data Sets Against the Agricultural Inventory Data

[18] We followed methods developed in previous efforts [*Ramankutty and Foley*, 1998; *Cardille et al.*, 2002;

Table 4. Weighted Correlation Coefficient Between Inventory Data and Model Predictions From Step 1[a]

Region	Administrative Units	BU-MODIS		GLC2000		COMBINED	
		Cropland	Pasture	Cropland	Pasture	Cropland	Pasture
Africa and Middle East	242	0.54	0.70	0.65	0.55	0.41	0.73
Europe and Russia	448	0.93	0.87	0.95	0.85	0.95	0.84
Asia	3190	0.83	0.79	0.87	0.66	0.91	0.85
North America	5752	0.90	0.84	0.89	0.84	0.93	0.89
South America	6201	0.77	0.67	0.59	0.70	0.83	0.79
Australia/NZ	71	0.90	0.90	0.81	0.86	0.91	0.74

[a]Each data point is weighted by the area of the administrative unit.

Ramankutty, 2004] to merge the satellite data sets and the agricultural inventory data to develop global maps of croplands and pastures for the year 2000. As mentioned in section 3 (paragraph 1), our statistical data fusion procedure is different from *Ramankutty and Foley* [1998] in a couple of major ways. First, to allow for potential misclassifications in the satellite-derived land cover data sets [e.g, *Hurtt et al.*, 2001; *Cardille et al.*, 2002], and also because pasture is not explicitly identified as a land cover class by the satellite-derived data sets, we utilized all land cover classes in our training procedure, as described below. Second, we used the two-step procedure of *Ramankutty* [2004] which assumes that the inventory data is the "truth" (except for identified outliers), and uses the satellite data to spatially disaggregate the census data within each administrative unit.

[19] For each administrative unit, i, the proportion of cropland and pasture area from the inventory data, cf_i and pf_i respectively, was calculated by dividing the inventory cropland and pasture areas by the total land area (A_i) for the administrative unit. Then, we determined $\lambda_{j,i}$, which is the proportion of each of the satellite-derived land cover classes, j, within administrative unit i.

[20] We have $\sum_{j=1}^{n_\lambda} = 1.0$, where n_λ is the number of land cover categories in the satellite data set.

[21] We formulated a linear model relating the satellite-derived data sets to the agricultural inventory data, as follows:

$$cf_i = \sum_{j=1}^{n_\lambda} \left(\alpha_j \times \lambda_{j,i}\right) + \varepsilon_{c,i}, \tag{1}$$

and

$$pf_i = \sum_{j=1}^{n_\lambda} \left(\beta_j \times \lambda_{j,i}\right) + \varepsilon_{p,i}, \tag{2}$$

where α_j and β_j are unknown parameters associated with each land cover category j, and $\varepsilon_{c,i}$ and $\varepsilon_{p,i}$ are error terms that represent the residual difference between the inventory and linear model predicted cropland and pasture proportions respectively.

[22] Additionally, (1) and (2) were subject to the following constraints,

$$\begin{gathered} 0 \le \alpha_j \le 1, \text{ and} \\ 0 \le \beta_j \le 1, \text{ and} \\ \alpha_j + \beta_j \le 1. \end{gathered} \tag{3}$$

These constraints ensured that the cropland or pasture proportions in any pixel (when the model is later applied at pixel level) will be between 0 and 100%, and that the sum of cropland and pasture proportions will be less than or equal to 100%.

[23] We used a least squares minimization method to solve for the parameters α_j and β_j. In particular, we specified the weighted least squares error (*LSE*) to be minimized as:

$$LSE = \sum_{i=1}^{n_i} \omega_i \left[\left(\varepsilon_{c,i}\right)^2 + \left(\varepsilon_{p,i}\right)^2\right], \tag{4}$$

where n_i is the number of administrative units, and ω_i is a term that weights the residuals $\varepsilon_{c,i}$ and $\varepsilon_{p,i}$ by the land area, A_i, of each administrative unit, normalized by the maximum value, i.e.,

$$\omega_i = \frac{A_i}{\max(A_i)}. \tag{5}$$

To estimate the parameters in equations 1 and 2, we used a multiple linear regression model from the STARPAC package (http://www.cisl.ucar.edu/softlib/STARPAC.html). We developed three separate models, first using the BU-MODIS and GLC2000 data sets separately, and then using the combined land cover data set. In each case, we started with a complete model specifying all the land cover classes as potentially being cropland or pasture; the following classes: BU13 (urban), BU15 (snow and ice), BU16 (barren), BU17 (no data), GLC19 (bare), GLC20 (water), GLC21 (snow and ice), GLC22 (artificial surfaces), and GLC23 (no data), and their combinations in our combined land cover data set, were left out of the model. We then used stepwise regression using backward selection to estimate the parameters. The details of this procedure are outlined in Text S2.

[24] We applied our optimization procedure separately to six different regions of the world (Figure S2), similar to *Ramankutty and Foley* [1998]. These six regions were a compromise between selecting small enough regions with similar agricultural characteristics, but large enough regions to have enough observations within each to obtain robust parameter estimates. Clearly some of the regions extend across different types of agricultural land uses, but sub-dividing the world into smaller regions resulted in too few observations in some regions to get robust model estimates.

[25] The estimated parameter values (not shown) were used to make global cropland and pasture maps at 5 min

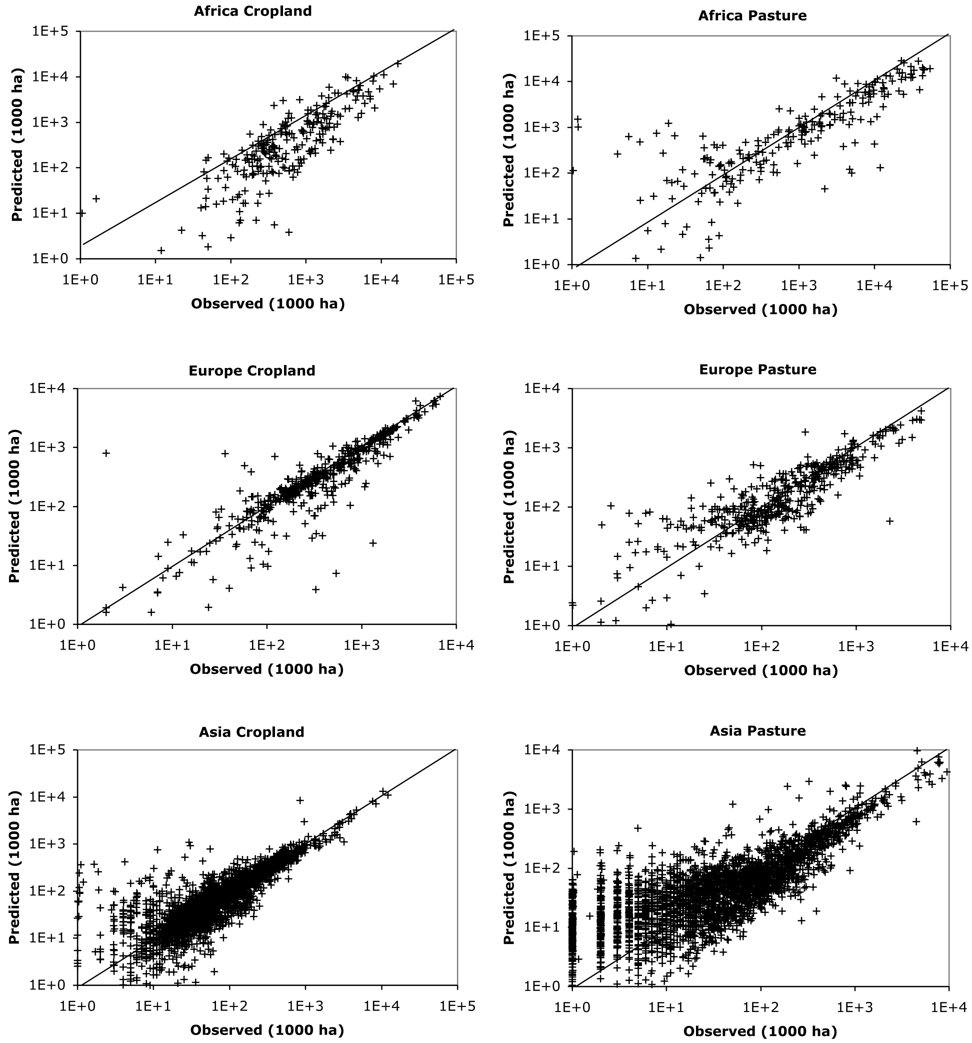

Figure 4. Comparison of agricultural inventory data on croplands and pastures against the model predictions from calibration Step 1 aggregated to the administrative unit level. Note the logarithmic scales for the axes.

spatial resolution in latitude by longitude for the BU-MODIS and GLC2000 data sets individually, and for the combined land cover data set (Figure 3). For each 5 min grid cell, x, y (latitude by longitude), we determined $\lambda_{j,x,y}$, which is the proportion of each of the satellite-derived land cover classes, j, within 5 min grid cell x, y. Using the estimates of α_j and β_j, we calculated cropland and pasture proportions in each 5 min grid cell, $cf_{x,y}$ and $pf_{x,y}$ respectively, using:

$$cf_{x,y} = \sum_{j=1}^{n_\lambda} \left(\alpha_j \times \lambda_{j,x,y}\right) \tag{6}$$

and

$$pf_{x,y} = \sum_{j=1}^{n_\lambda} \left(\beta_j \times \lambda_{j,x,y}\right). \tag{7}$$

3.3. Comparison of the Performance of BU-MODIS, GLC2000, and Combined Data Sets

[26] We now present a comparison of the inventory agricultural land area to the predicted values for each data set from calibration Step 1 (from equations 6 and 7, aggregated from 5 min resolution to the administrative level) (Table 4). The cropland and pasture areas predicted using the combined satellite data set is better correlated to the inventory data compared to the models using either the BU-MODIS or GLC2000 data sets alone in every region except for a few exceptions (croplands in Africa/Middle East, and pastures in Europe and Russia and Australia/NZ). Further, neither the BU-MODIS nor the GLC2000 data set always performs better than the other; for example, in *Africa and Middle East*, GLC2000 predicts cropland much better than BU-MODIS, but the reverse is true for pastures. We next present a regional comparison of the inventory and predicted agricultural land areas from the combined data set (Figures 4a and Figures 4a and 4b). The most notable

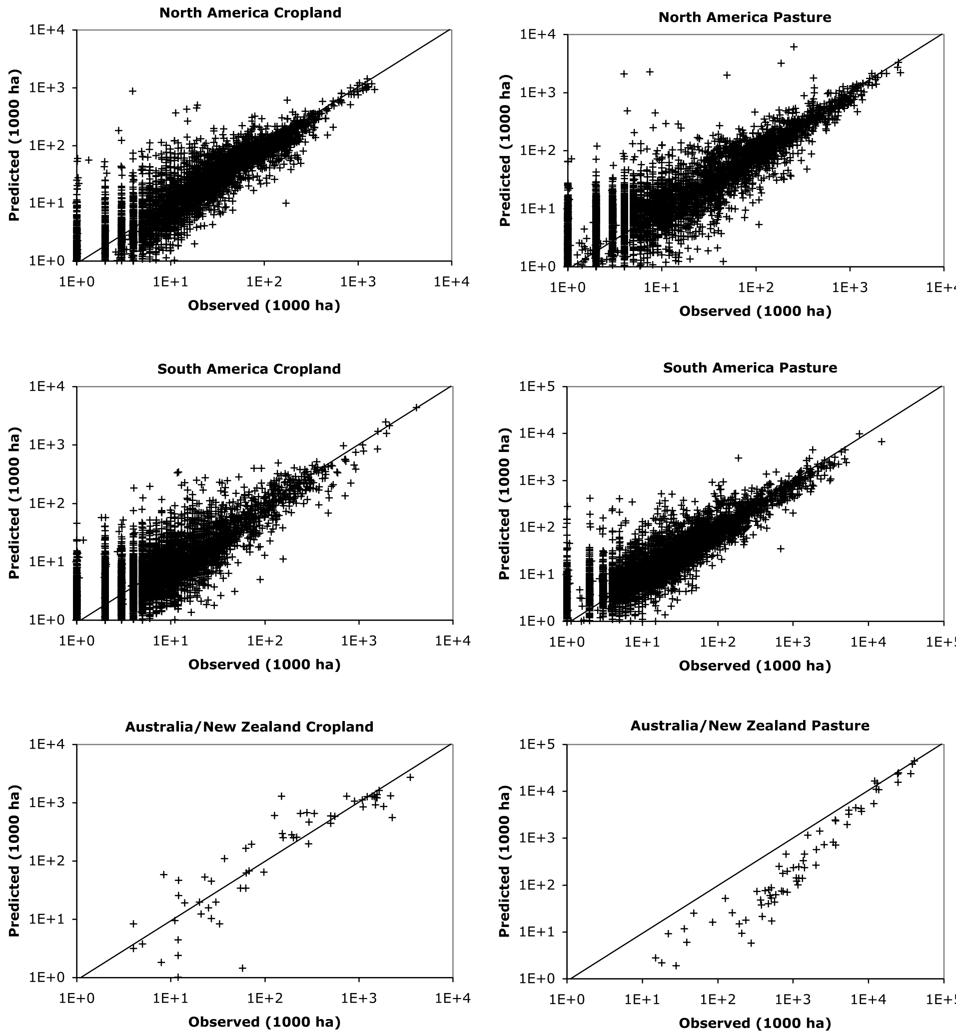

Figure 4. (continued)

differences lie in the underestimation of pasture areas in Asia and Australia/New Zealand. We will discuss the significance of this underestimation in the next section.

[27] We now consider the spatial patterns of predicted agricultural land from the combined data set versus the individual data sets, using South American pastures as an example (Figure 5). In Figure 5a the inventory data shows large extent of pasture along the arc of deforestation, along coastal and southern Brazil, in Uruguay, and in the Patagonia region of Argentina. Figures 5b and 5c are the BU-MODIS and GLC2000 based pasture maps. Both do a reasonable job of reproducing the inventory data in Figure 5a. The most glaring difference is in the Nordeste (northeast) region of Brazil, where both data sets overestimate the distribution of pasture as compared to the inventory data in Figure 5a. The combined land cover data was able to best reproduce the inventory data, especially in the Brazilian Nordeste region and Patagonia (Figure 5d).

[28] Thus by using the combined data set we are able to capitalize on whichever satellite-based land cover data set is best suited to each region. If we were to use either the BU-MODIS or GLC2000 data sets alone, we would get reasonably good global results, but would lose accuracy in some regions. The use of the combined land cover data set especially yields marked improvements over Asia and South America (Table 4). Therefore we use the combined data set in the next step of this study.

3.4. Bootstrap Procedure to Estimate Uncertainty

[29] We further used a bootstrap technique in order to estimate the uncertainty in our parameter estimates. This procedure was applied at this stage for only the combined land cover data set. We performed 1000 bootstrap runs, where the entire census data was sampled with replacement each time, and reestimated our regression model using the combined satellite-based land cover data set (Sampling with replacement used the standard statistical procedure wherein the census data formed the population (of n_i values, the total number of administrative units), and for each of the 1000 sample sets we randomly selected n_i values from the population, with the sampled value being replaced back into the population. Each sampling outcome is therefore

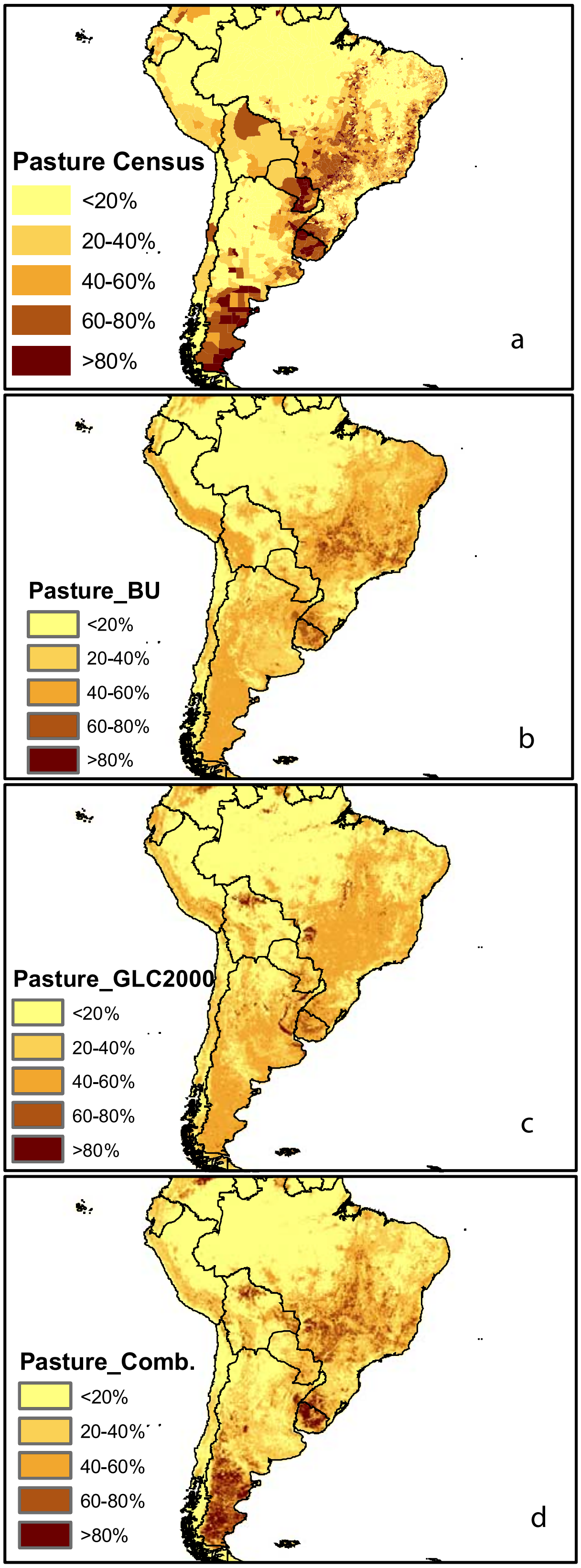

Figure 5. Comparison of pasture inventory data in South America against Step 1 model predictions for pasture using the BU-MODIS satellite data set, GLC2000, and combined land cover data set.

independent of the previous outcome; that is, every census data value has equal probability of being chosen during every sampling event, no matter whether it has been chosen before). This yielded a distribution of values for each parameter α_j and β_j, and we report the mean and 90% confidence intervals here (see Data Set S1).

[30] Using the 1000 estimates of α_j and β_j, we calculated 1000 estimates of cropland and pasture proportions in each 5 min grid cell, $cf_{x,y}$ and $pf_{x,y}$ respectively, using:

$$cf_{x,y}(k) = \sum_{j=1}^{n_\lambda} \left(\alpha_j(k) \times \lambda_{j,x,y}\right), k = 1, 1000 \tag{8}$$

and

$$pf_{x,y}(k) = \sum_{j=1}^{n_\lambda} \left(\beta_j(k) \times \lambda_{j,x,y}\right), k = 1, 1000. \tag{9}$$

From these 1000 estimates, we calculated the mean, 5th percentile and 95th percentile values of the cropland and pasture values, represented as $cf_{x,y}^{mean}$, $cf_{x,y}^{5th\%;ile}$, and $cf_{x,y}^{95th\%;ile}$, and as $pf_{x,y}^{mean}$, $pf_{x,y}^{5th\%;ile}$, and $pf_{x,y}^{95th\%;ile}$, respectively (figures not shown from this stage of analysis).

3.5. Step 2: Adjusting the Predicted Cropland and Pasture Data to Match Inventory Data

[31] In this final step, we followed the methods of *Ramankutty* [2004], to adjust our spatially explicit predictions from Step 1 (the bootstrap model estimates using the combined data set) to match the inventory data at the administrative level where available. To do so, we first aggregated our 5 min resolution cropland and pasture data sets to the administrative level. We then compared them to the inventory data to derive a correction factor for each administrative unit. The correction factors were, however, constrained to be within a factor of 5 (i.e., to lie between 0.2 and 5.0) for administrative units that were considered outliers in the regression, thereby trusting the satellite-based land cover data more than the inventory data in those cases. Outliers were determined to be those administrative units with residuals (predicted cropland area from the Step 1 calibration procedure minus inventory cropland area) that were greater than 2 standard deviations from the mean. Correction factors were set to 1.0 for administrative units with missing data, thereby relying on the satellite-estimated spatial patterns from Step 1 in these units. We then applied Pycnophylactic Interpolation [*Tobler*, 1979] to the administrative level correction factors to obtain a smooth surface of correction factors at 5 min resolution (without this smoothing, artificial boundaries between administrative units might appear in the final product; note, however, that only the correction factors were smoothed, so any real boundaries in the original satellite data will remain). The spatial correction factors were then applied to our results from Step 1 to derive our final maps of cropland and pastures at 5 min resolution (Figure 6) and respective

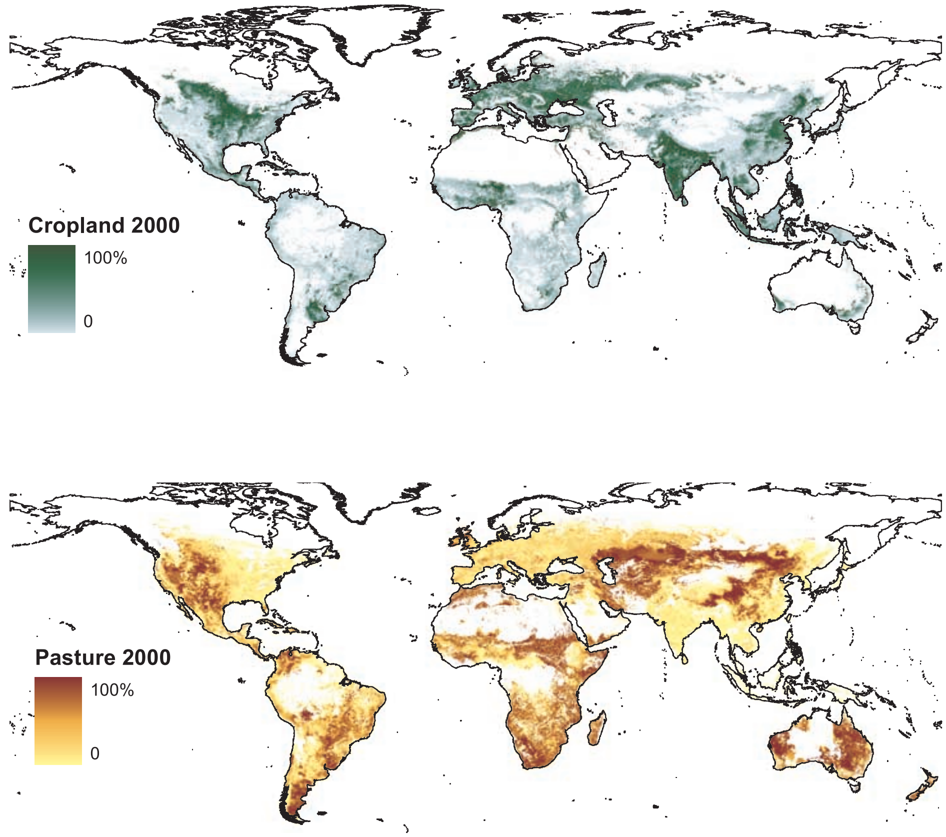

Figure 6. Final estimates of croplands and pastures from this study. This is the final result obtained by calibrating the combined land cover data set against the agricultural inventory data (Step 1), using 1000 bootstrap estimates for the parameters, and then further adjusting the predictions to match the inventory data at the administrative unit level (Step 2).

confidence intervals (Figure 7). The final equations for cropland and pasture proportions can be represented as

$$\begin{aligned} Cropland_{x,y}^{mean} &= \mu cf_{x,y} \times cf_{x,y}^{mean} \\ Cropland_{x,y}^{5th\%ile} &= \mu cf_{x,y} \times cf_{x,y}^{5th\%ile} \\ Cropland_{x,y}^{95th\%ile} &= \mu cf_{x,y} \times cf_{x,y}^{95th\%ile} \end{aligned}, \quad (10)$$

and,

$$\begin{aligned} Pasture_{x,y}^{mean} &= \mu pf_{x,y} \times pf_{x,y}^{mean} \\ Pasture_{x,y}^{5th\%ile} &= \mu pf_{x,y} \times pf_{x,y}^{5th\%ile} \\ Pasture_{x,y}^{95th\%ile} &= \mu pf_{x,y} \times pf_{x,y}^{95th\%ile} \end{aligned}, \quad (11)$$

where $\mu cf_{x,y}$ and $\mu pf_{x,y}$ are the spatially explicit correction factors for cropland and pasture respectively.

4. Results

4.1. Total Global Area of Croplands and Pastures in 2000

[32] Our final results (Figure 6) indicate that there were 15.0 (95% confidence range of 12.2–17.1) million km^2 of cropland and 28.0 (95% confidence range of 23.6–30.0) million km^2 of pasture in the world in the year 2000. This compares to 15.3 million km^2 of cropland and 34.4 million km^2 of pasture reported by the FAOSTAT database. Thus we predict significantly lower extent of pasture (by 6.1 million km^2 or ~18% lower) than reported by FAO. Our own inventory data reports 15.0 million km^2 of cropland and 31.5 million km^2 of pasture. Thus our inventory data for pasture is already lower than FAO statistics; this difference was explained earlier in section 2.2. Our cropland extent for the year 2000 of 15.3 million km^2 is lower than the 18.0 million km^2 of cropland in 1992 from our previous study [*Ramankutty and Foley*, 1998]. This does not mean that cropland extent has decreased from 1992 to 2000; rather the difference is a result of changes in methodology: We plan to reconstruct a consistent historical time series; until then a comparison of our 1992 and 2000 data sets is precluded.

[33] Our final predicted pasture area is even lower than our inventory data, especially in Asia and Australia/New Zealand (as already evidenced in Figures 4a and 4b). We anticipated that this problem would be overcome in Step 2, when we scaled our spatial cropland and pasture data to match our inventory data, but despite this our final predicted extent of pasture differs significantly from our inventory data. This is because we did not allow pixels with predicted agriculture proportions of 0% in Step 1 to be scaled, and

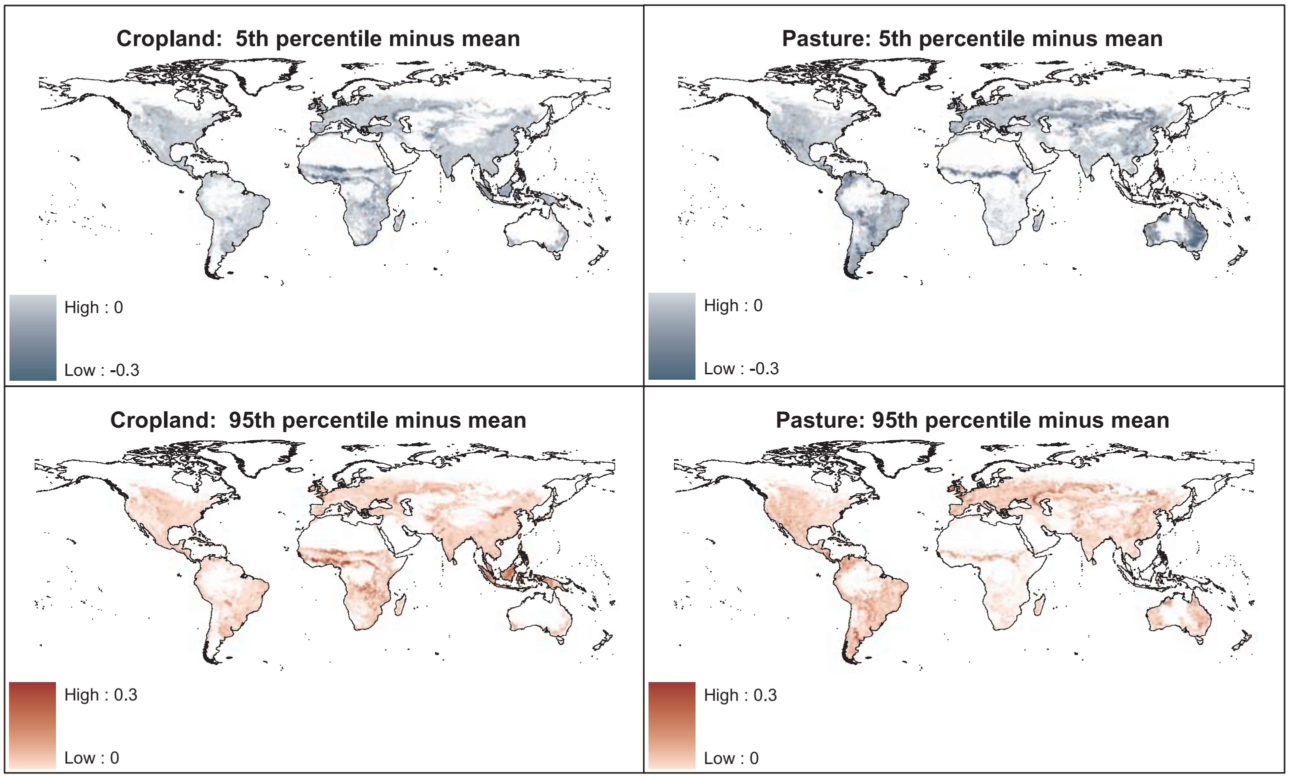

Figure 7. The 90% confidence intervals on our final estimates; here we show the difference between the 5th and 95th percentiles from the mean estimate. Note that the scales indicate absolute differences in the percentage of grid cells occupied by agriculture (e.g., if cropland mean = 50% and cropland 5th percentile = 30%, then the difference is shown as 20%). The figures show that the greatest uncertainty with respect to both croplands and pastures lies in the Sahelo-Sudan region of west and central Africa. There is also large uncertainty with respect to cropland extent in Southeast Asia and pasture extent in Australia and parts of Asia and South America.

each pixel was limited to have a maximum agriculture proportion of 100%. The biggest difference is in China, where the inventory reports 4 million km^2 of pasture, but we estimate a final area of only 2.9 million km^2. Our estimate, however, is similar to the 2.6 million km^2 of grassland reported by *Verburg et al.* [2000]. *Verburg and van Keulen* [1999] discuss that much nontraditional grazing occurs in China, with goats grazing along roads, dry river beds, and in fields after harvest, and pigs in back yards; it is not clear how these landscapes should be characterized. It is also likely that grazed forestland and semiarid land are included under the pasture category in the Chinese inventory. Other

Table 5. Cropland and Pasture Areas by Different Regions of the World

Biome	Land Area, million km^2	Cropland, million km^2	Pasture, million km^2	Cropland, % of Land Area	Pasture, % of Land Area
Canada	8.88	0.41	0.20	4.6	2.3
United States, east of Mississippi	2.20	0.53	0.11	24.0	5.0
United States, west of Mississippi	6.87	1.26	2.16	18.3	31.4
Mexico and Central America	2.63	0.50	0.83	19.1	31.4
South America, northern Portions	13.85	0.74	3.15	5.4	22.7
Argentina, Uruguay, and Chile	3.63	0.37	1.20	10.2	33.0
Tropical Africa	24.18	1.94	7.28	8.0	30.1
North Africa and Middle East	11.42	0.84	1.45	7.4	12.7
Europe	4.67	1.25	0.67	26.8	14.4
Former Soviet Union	21.41	2.07	2.73	9.7	12.8
China	10.83	1.40	3.54	12.9	32.7
South Asia	5.64	2.22	0.49	39.4	8.8
Southeast Asia	3.70	0.97	0.06	26.3	1.7
Pacific developed countries	8.99	0.40	2.94	4.5	32.7

Table 6. Cropland and Pasture Areas by Different Biomes of the World

Biome	Land Area, million km^2	Cropland, million km^2	Pasture, million km^2	Cropland, % of Biome Area	Pasture, % of Biome Area
Tropical evergreen forest	16.77	1.81	1.48	10.8	8.8
Tropical deciduous forest	5.86	1.58	1.43	27.0	24.4
Temperate broadleaf evergreen forest	1.13	0.27	0.23	24.2	20.2
Temperate needleleaf evergreen forest	3.61	0.72	0.37	20.0	10.3
Temperate deciduous forest	4.84	1.46	0.82	30.1	16.9
Boreal evergreen forest	5.98	0.09	0.10	1.5	1.7
Boreal deciduous forest	2.22	0.04	0.05	1.7	2.1
Evergreen/deciduous mixed forest	14.96	1.16	0.71	7.7	4.8
Savanna	19.18	3.02	6.49	15.7	33.8
Grassland	14.29	2.74	7.25	19.2	50.7
Dense shrubland	5.99	1.07	1.87	17.9	31.2
Open shrubland	11.94	0.87	5.15	7.3	43.1
Tundra	7.01	0.04	0.92	0.6	13.1
Desert	15.34	0.13	1.22	0.9	7.9
Polar desert/rock/ice	1.21	0.00	0.02	0.1	1.7

big differences in pasture area arise in Australia (inventory area of 3.2 million km^2 versus our prediction of 2.7 million km^2), Mongolia (inventory of 1.3 million km^2 versus our estimate of 0.9 million km^2), Mauritania (inventory of 0.4 million km^2 versus our 0.1 million km^2), Iran (inventory of 0.9 million km^2 versus our 0.6 million km^2), and the United States (inventory of 2.3 million km^2 versus our 2.1 million km^2). It is interesting to note that all of these countries have significant amount of semiarid land. One potential explanation could be the variability in grazing associated with the interannual changes in climate that can be quite extreme in semiarid regions; the satellite data set only captures a single year of land cover condition, which can vary from year to year. For croplands, while the global totals agree, there are compensating national level differences but these differences are less significant compared to the differences in pasture areas.

[34] Our final predicted cropland extent of 15.0 million km^2 in year 2000 amounts to roughly 12% of the global land area (excluding Greenland and Antarctica), and pasture extent of 28.0 million km^2 amounts to 22% of global land area. Thus humans are using 34% of the global land area for their agricultural needs.

4.2. Geographic Distribution of Croplands and Pastures in Year 2000

[35] We analyzed the distribution of agricultural regions by 14 different regions of the world (Table 5). The greatest proportion of croplands in the world are found in South Asia, Europe, Southeast Asia, and United States, east of the Mississippi, while the greatest proportion of pastures are found in Argentina, Uruguay and Chile, Pacific developed countries, China, Mexico and Central America, United States, west of the Mississippi, and tropical Africa. The smallest proportion of croplands are found in Canada, the Pacific developed Countries, and northern South America, while the smallest proportion of pastures are found in Southeast Asia, Canada, and United States, east of the Mississippi.

[36] We also examined which potential natural vegetation types of the world have been most affected by agriculture (Table 6). We overlaid our agricultural maps over the global map of potential natural vegetation developed by *Ramankutty and Foley* [1999]. We find that croplands have mostly replaced temperate deciduous forests (in Europe and eastern United States), and tropical deciduous forests (in South Asia), while, pastures have mostly replaced grasslands, savannas, and shrubland. Roughly 30% of temperate deciduous forests have been converted to cropland, while 50% of grasslands have been converted to pasture. However, this global picture varies regionally (Table 7). While forests have been cleared for croplands predominantly in Asia, a substantial amount of savanna and grasslands have been converted to croplands in North America, Africa, and the Former Soviet Union. Also, a significant amount of forests in South America have been cleared for pastures, even though globally most pastures have replaced savanna/grasslands.

[37] Next, we examined the amount of spatial overlap between croplands and pastures (Figure 8). Our analysis shows that cropland and pastures are distinct biomes over

Table 7. Cropland and Pasture Areas by Different Regions and Biomes of the World

	Forest		Savanna/Grassland		Shrubland		Other Land	
Area in million km^2	Cropland	Pasture	Cropland	Pasture	Cropland	Pasture	Cropland	Pasture
North America	1.03	0.71	1.55	1.42	0.16	1.20	0.00	0.00
South America	0.37	1.51	0.45	2.26	0.25	0.43	0.01	0.12
Africa	0.54	1.11	1.64	4.99	0.44	2.12	0.05	0.98
Europe	0.99	0.55	0.12	0.04	0.17	0.06	0.00	0.00
Former Soviet Union	0.75	0.39	1.24	2.02	0.09	0.83	0.02	0.19
Asia	3.33	0.87	0.63	1.84	0.66	0.79	0.09	0.84
Pacific developed	0.11	0.07	0.13	1.16	0.17	1.62	0.00	0.00

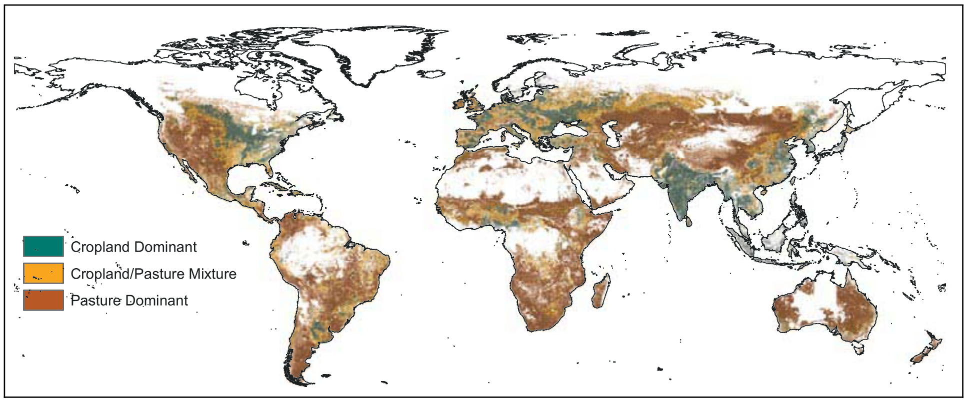

Figure 8. Map showing the amount of overlap between croplands and pastures. Croplands or pastures were considered to be dominant when they were a factor of 3 greater in magnitude than the other category and mixed otherwise.

much of our planet's land surface. The regions of the world with significant overlap lie along the western edge of cultivation in the midwestern United States and in Texas, northeast Brazil, in parts of West Africa, eastern China, Europe, and the former Soviet Union, scattered regions elsewhere. This is not to say that grazing does not occur in cultivated regions of the world; many regions of the world are characterized by multifunctional agricultural lands, subject to different uses during different parts of the year (e.g., grazing occurs following the harvest of a crop) [*Reenberg and Fog*, 1995]. Therefore this lack of overlap partly reflects the inability of global monitoring systems, including satellite data and agriculture inventory data, to characterize multiple uses, and land is often classified as a single category. Our final estimates likely underestimate the real overlap between cultivation and grazing, especially the multiple uses that occur within a year.

[38] We also investigated the frequency distribution of croplands and pastures globally, and across the 14 different regions of the world. We calculated probability distributions using all pixels with nonzero cropland or pasture values, and estimated what proportion of total cropland or pasture area can be attributed to different categories of cropland or pasture proportions (Figure 9). Globally, we find that a large proportion of the total cropland area comes from land that is between 60% and 80% cultivated. This pattern is observed in most regions of the world, except in northern South America, tropical Africa, and North Africa and Middle East (where larger number of pixels with low proportion of cultivation contribute most to the total cropland area, although in the latter two regions, there are a few pockets of greater than 90% cropland). With pastures, the total area is dominated by pixels with greater than 90% pasture. This pattern is true over most regions of the world, but is reversed in the eastern United States, Europe, and Southeast Asia (and South Asia, to a lesser extent). However, it is to be noted that the proportion of pasture in a grid cell provides no information on the grazing intensity in that grid cell; an area of grassland with very low stocking density of livestock would have the same proportion of pasture as one with very high stocking densities.

4.3. Evaluation Against Other Independent Data Sets

[39] While there are no consistent, global spatial data sets of agriculture in the year 2000 to evaluate our products against, there are numerous regional products against which we can compare our global products (see Figures S3–S12). While many of these regional data are not for the year 2000 (and are sometimes a decade older), they nevertheless provide an independent measure of the large-scale spatial patterns of agriculture in these regions. These data were not always available in a consistent digital format; they were often in vector format that is difficult to quantitatively compare to our raster data and sometimes only available as images in publications. Therefore rather than making quantitative comparisons we present detailed regional maps from our data set compared to these independent regional maps, as online supplements (Figures S3–S12)[1].

[40] Our regional comparisons are mostly for croplands because there are few spatial data sets depicting pastures (likely because it is difficult to distinguish between natural and grazed grasslands). Visual comparison (Figures S3–S12) suggests that our distribution of croplands is reasonable in North America (United States, Canada, and Mexico), and so is the distribution of pastures in the United States (except for noticeable differences in northeastern Texas, and eastern Oklahoma, arising from lower pasture census values). In the Amazon Basin, our distribution of both croplands and pastures shows similar geographic patterns but greater intensity compared to *Cardille et al.* [2002]. This may be a result of our data being representative of 2000, while *Cardille et al.* [2002] data is for the mid 1990s (changes in the southern Amazon are rapid) or because of differences in statistical methods with the regression tree method of *Cardille et al.* [2002] not able to deal well with extremes. In China also, our geographic patterns of crop-

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gb/2007gb002952. Other auxiliary material files are in the HTML.

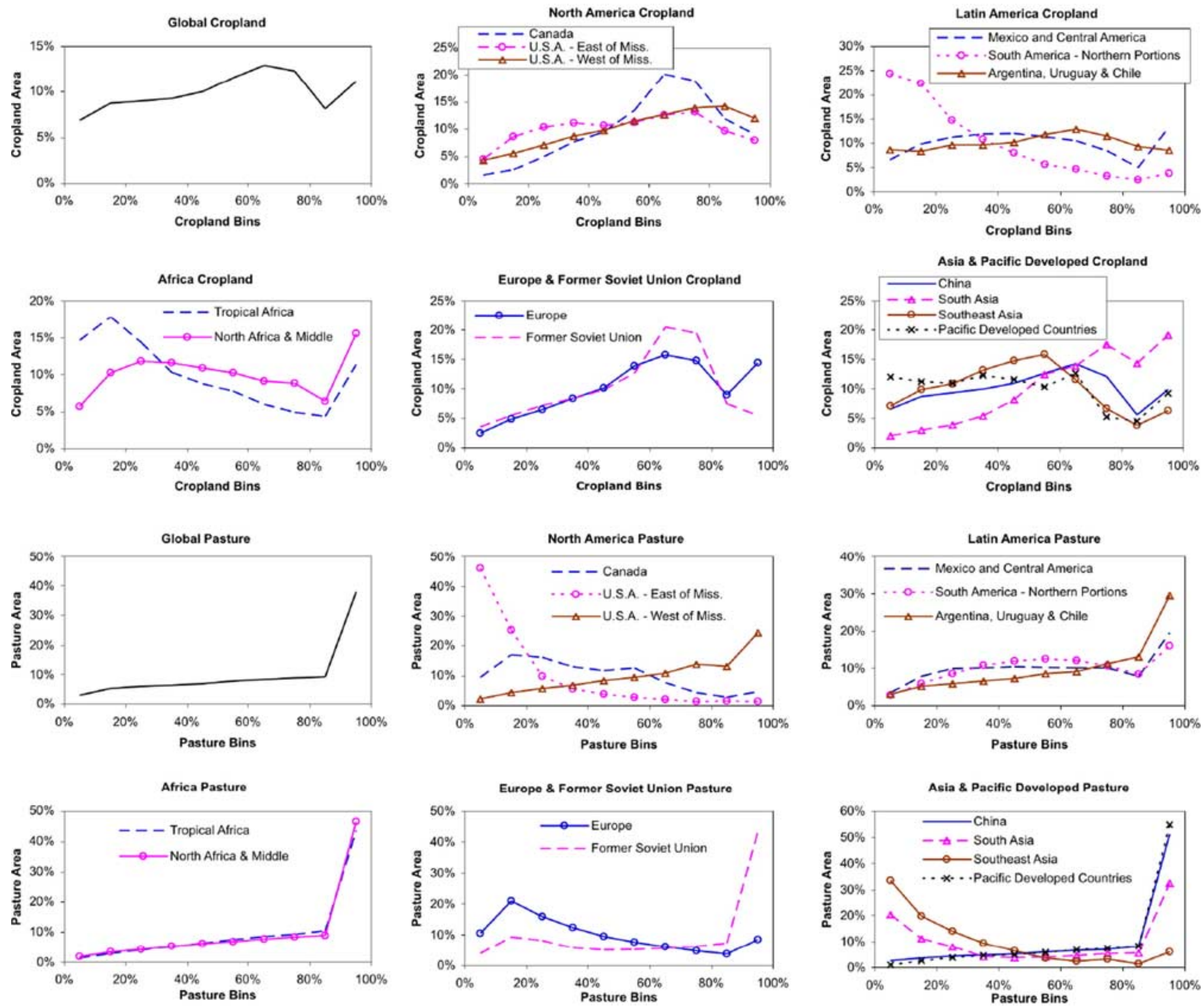

Figure 9. Probability distribution of cropland and pasture areas as a function of the different proportions (or ''intensities'') of cropland and pastures for the different regions of the world. The figures indicate the percentage of the total area of cropland or pasture that is contributed by different intensities of cropland and pasture values (e.g., globally, croplands in grid cells that have between 60% and 70% cropland contribute to 13% of the total area of cropland).

lands matches well with that of *Liu et al.* [2005], but our intensity is lower (the differences are greater than can be explained by the different spatial resolutions of the two data sets). In West Africa, our cropland distribution from this study is a significant improvement over our earlier work [*Ramankutty and Foley*, 1998], but consistent with our more recent effort [*Ramankutty*, 2004]. Our distribution of croplands compares reasonably well with Africover data in East Africa [*Latham*, 2001] (http://www.africover.org/) but is not a significant improvement over our earlier effort, while in South Africa, our estimated patterns are an improvement over our previous effort but of much lower intensity. In Europe, our data set of croplands compares well to the CORINE land cover database. We seem to underestimate croplands in eastern Australia, while our distribution of pastures is significantly underestimated in the Northern Territory. The problem with pastures in Australia actually emerges from Step 2, with the census data in the Northern Territory suggesting very little pastures; our predicted pattern from Step 1 compares better to the data from the Australian Natural Resources Atlas.

5. Discussion and Conclusions

[41] We have merged two different satellite-based land cover classification data sets with an extensive compilation of national and subnational level agricultural census statistics to develop global maps of croplands and pastures for the year 2000. These maps form the first comprehensive characterization of the distribution of global agricultural lands in the year 2000, describing the spatial extent of croplands and pastures within 5 min resolution (~10km)

grid cells in latitude by longitude; in addition, 90% confident intervals on the mean estimates are presented for the first time. In creating these new data sets, we have built on our earlier work in 1998 [*Ramankutty and Foley*, 1998], where we developed a statistical "data fusion" method to merge satellite data and census data to map global croplands in 1992. Here we have improved our statistical methods, combined two new satellite data sets, and enriched our agricultural census data to update our global croplands map to the year 2000, and to create a new global pasture data set for 2000. We would like to strongly caution that our two croplands maps from 1992 and 2000 cannot be directly compared to detect changes over that time period: Changes in methodology and data sources preclude such a direct comparison. We plan to develop a consistent historical time series of croplands and pastures in the future.

[42] The global area of cropland from this study for the year 2000 of 15.0 million km^2 is smaller than the area of 18 million km^2 for 1992 estimated by our earlier study [*Ramankutty and Foley*, 1998]. This is not a real decrease, but rather an artifact of change in methodology between the two studies. In this study, we used our Step 2 to scale the calibrated cropland patterns to identically match the census data. In our earlier study our final result was directly out of the calibration and we did not do any scaling. We have changed our philosophy here to trust the total area of agricultural land reported by the census data (unless they are outliers in the Step 1 calibration procedure), and use the satellite data sets for information on the spatial distribution within each census administrative unit.

[43] The global area of pasture of 28.0 million km^2 is 18% lower than the standard FAOSTAT estimate of 34.4 million km^2. The major differences are found in Saudi Arabia, Australia, China, and Mongolia. This is likely because the census data on pasture reported to FAOSTAT include grazed forestland and semiarid land. The definition of pasture has always been problematic, as acknowledged by FAOSTAT (http://faostat.fao.org/site/375/default.aspx), and one way to improve the situation in the future may be to develop global maps of livestock density [e.g., *Kruska et al.*, 2003; W. Wint, Global Livestock Distributions, 2005, data archive prepared by Environmental Research Group Oxford Limited for the Pro-Poor Livestock Policy Initiative of the Animal Production and Health Division of the Food and Agriculture Organization of the United Nations, Rome, Italy, available at http://ergodd.zoo.ox.ac.uk/agaagdat/index.htm], and overlay that data with an independent global estimate of herbaceous vegetation.

[44] Although we now have new global estimates of the distribution of cropland and pastures, several caveats need to be noted. First, there is much misunderstanding and confusion regarding the definitions of croplands and pastures. In this study, we have followed the FAO definition, as described in section 2.2 (paragraph 2). For croplands, this includes temporary fallow lands (less than 5 years), which are not cultivated. It is not clear how strictly this restriction of less than 5 years was applied when accounting for fallow land. For example, the U.S. data on croplands used by FAOSTAT includes idled cropland, which includes land under the Conservation Reserve Program that amounts to roughly 9% of the total cropland area, and is often idled for longer than 5 years [*Lubowski et al.*, 2002]. Secondly, in tropical nations characterized by extensive fallow cropping systems, such a definition may include much land that is not currently cultivated, and therefore portray a misleading picture of what may be commonly thought of as cropland. Finally, these definitions of croplands say nothing about the productivity of the land, but this is the topic of our companion article [*Monfreda et al.*, 2007].

[45] The definition of pasture is subject to even greater uncertainty. The definition of pasture is not consistently clear in the census data that we compiled in this study, or any of the maps we compared our data against (Figures S3–S12). Where is the dividing line between herding and grazing? For example, is reindeer herding reported under pastureland? Does the data represent both planted pastures and natural pastures? Is grazing underneath a forest cover or in semiarid areas included in the pasture data? In other words, pasture is only a subset of the land (on herbaceous vegetative cover) that is used for grazing. The data on extent of pasture also says nothing about the intensity of grazing: An acre of land with one cow and another acre with 10 cows would both be considered 1 acre of pastureland.

[46] An additional concern related to the definition of croplands and pastures arises from the existence of multifunctional landscapes, as discussed in section 4.2 (paragraph 3) [*Reenberg and Fog*, 1995]. In some countries, especially in Asia and Africa, land is cropped for a while, and then after harvest, is grazed for the remainder of the year. Thus during the year the land is put to multiple uses, and it is not clear how to classify these lands, and how these lands were accounted for in the census statistics. Mixed use classifications need to be used to characterize such landscapes rather than discrete classes such as cropland and pasture. It is not clear how much of the global agricultural land area is influenced by such multifunctional land use practices. Future agricultural census data compilation methods need to be encouraged to deal explicitly with multifunctional landscapes.

[47] Finally, our synthesized data sets have uncertainty related to the fact that we are trying to merge two different observation systems: remote-sensing based and ground based. Remote sensing satellites can only observe land cover, i.e., the top of the vegetative canopy, and have little information on what happens below the canopy. The ground-based land use data, on the other hand, may include different information. For example, the cropland census data include permanent crops such as tree crops. It is not clear whether the remote sensing observations consider tree crops as tree cover or whether they classify them as cropland. Similarly, as discussed in section 2.2 (paragraph 4), census data may not distinguish between grazing on grasslands, forests, and bare ground.

[48] There is great demand by the global environmental change community to understand how global agricultural lands are changing and evaluate their implications for a sustainable future [e.g., *Tilman et al.*, 2001; *Foley et al.*, 2005]. Therefore despite large uncertainties we need to make progress toward developing new methods to characterize the spatial patterns of global agricultural lands. Here

we have obtained the best available global data on agricultural lands and synthesized them to create a single homogeneous database of the world's croplands and pastures. We believe that these data sets would be enormously useful to at least two different communities of scientists/practitioners: (1) global change scientists, interested in the consequences of global agriculture for climate, carbon cycle, water resources, etc., who would use these data sets for global-scale analysis or as inputs to climate and ecosystem models [e.g., *McGuire et al.*, 2001; *Myhre and Myhre*, 2003; *Jain and Yang*, 2005]; and (2) ecologists and conservation practitioners, interested in the role of agriculture in modifying natural ecosystems and habitats, reducing biodiversity, and enhancing species extinction [e.g., *Green et al.*, 2005; *Vandermeer et al.*, 2005].

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References

Bartholome, E., and A. S. Belward (2005), GLC2000: A new approach to global land cover mapping from Earth Observation data, *Int. J. Remote Sens.*, *26*, 1959–1977.

Bauer, E., M. Claussen, and V. Brovkin (2003), Assessing climate forcings of the Earth system for the past millennium, *Geophys. Res. Lett.*, *30*(6), 1276, doi:10.1029/2002GL016639.

Bonan, G. B. (1999), Frost followed the plow: Impacts of deforestation on the climate of the United States, *Ecol. Appl.*, *9*, 1305–1315.

Bonan, G. B. (2001), Observational evidence for reduction of daily maximum temperature by croplands in the midwest United States, *J. Clim.*, *14*, 2430–2442.

Bondeau, A., P. C. Smith, S. Zaehle, S. Schaphoff, W. Lucht, W. Cramer, D. Gerten, H. Lotze-Campen, C. Muller, and M. Reichstein (2007), Modelling the role of agriculture for the 20th century global terrestrial carbon balance, *Global Change Biol.*, *13*, 679–706.

Bouzaher, A., A. Carriquiry, and H. Jensen (1994), *The Structure of Ukrainian Agriculture: Comparative Efficiency and Implications for Policy Reform*, 115 pp., Cent. for Agricul. and Rural Dev., Iowa State Univ., Ames..

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

Brovkin, V., M. Claussen, E. Driesschaert, T. Fichefet, D. Kicklighter, M. F. Loutre, H. D. Matthews, N. Ramankutty, M. Schaeffer, and A. Sokolov (2006), Biogeophysical effects of historical land cover changes simulated by six Earth system models of intermediate complexity, *Clim. Dyn.*, *26*(6), 587–600, doi:10.1007/s00382-005-0092-6.

Cardille, J. A., and J. A. Foley (2003), Agricultural land-use change in Brazilian Amazonia between 1980 and 1995: Evidence from integrated satellite and census data, *Remote Sens. Environ.*, *87*, 551–562.

Cardille, J. A., J. A. Foley, and M. H. Costa (2002), Characterizing patterns of agricultural land use in Amazonia by merging satellite classifications and census data, *Global Biogeochem. Cycles*, *16*(3), 1045, doi:10.1029/2000GB001386.

Cassman, K. G., and S. Wood (2005), Cultivated systems, in *Ecosystems and Human Well-being: Current State and Trends*, vol. 1, edited by R. Hassan et al., pp. 745–794, Island Press, Washington, D. C.

Central Bureau of Statistics (2001), *Statistical Year Book of Nepal 2001*, 8th ed., 447 pp., Cent. Bur. of Stat., Kathmandu.

Cramer, W. P., and A. M. Solomon (1993), Climatic classification and future global redistribution of agricultural land, *Clim. Res.*, *3*, 97–110.

Crook, F. (1993), Underreporting of China's cultivated land area: Implications for world agricultural trade, in *China International Agriculture and Trade Report*, pp. 33–39, *Situation Outlook Ser. RS-93-4*, U. S. Dep. of Agricul., Washington, D. C.

DeFries, R., and F. Achard (2002), New estimates of tropical deforestation and terrestrial carbon fluxes: Results of two complementary studies, *LUCC Newsl.*, *8*, 7–9.

DeFries, R. S., J. A. Foley, and G. P. Asner (2004), Land-use choices: Balancing human needs and ecosystem function, *Frontiers Ecol. Environ.*, *2, 249–257.*

Donner, S. D. (2003), The impact of cropland cover on river nutrient levels in the Mississippi River Basin, *Global Ecol. Biogeogr.*, *12*, 341–355.

Donner, S. D., and C. J. Kucharik (2003), Evaluating the impacts of land management and climate variability on crop production and nitrate export across the Upper Mississippi Basin, *Global Biogeochem. Cycles*, *17*(3), 1085, doi:10.1029/2001GB001808.

Foley, J. A., et al. (2005), Global consequences of land use, *Science*, *309*, 570–574.

Forestry Management, Evaluation and Coordinating Unit (FORMECU) (1995), *An Assessment of Land Use and Vegetation Changes in Nigeria Between 1978–1993*, 75 pp., Geomatis, Ontario, Canada.

Friedl, M. A., et al. (2002), Global land cover mapping from MODIS: Algorithms and early results, *Remote Sens. Environ.*, *83*, 287–302.

Frolking, S., X. M. Xiao, Y. H. Zhuang, W. Salas, and C. S. Li (1999), Agricultural land-use in China: A comparison of area estimates from ground-based census and satellite-borne remote sensing, *Global Ecol. Biogeogr.*, *8*, 407–416.

Frolking, S., J. J. Qiu, S. Boles, X. M. Xiao, J. Y. Liu, Y. H. Zhuang, C. S. Li, and X. G. Qin (2002), Combining remote sensing and ground census data to develop new maps of the distribution of rice agriculture in China, *Global Biogeochem. Cycles*, *16*(4), 1091, doi:10.1029/2001GB001425.

Galloway, J. N., W. H. Schlesinger, H. Levy II, A. Michaels, and J. L. Schnoor (1995), Nitrogen fixation: Anthropogenic enhancement-environmental response, *Global Biogeochem. Cycles*, *9*, 235–252.

Giri, C., Z. Zhu, and B. Reed (2005), A comparative analysis of the Global Land Cover 2000 and MODIS land cover data sets, *Remote Sens. Environ.*, *94*, 123–132.

Green, R. E., S. J. Cornell, J. P. W. Scharlemann, and A. Balmford (2005), Farming and the fate of wild nature, *Science*, *307*, 550–555, doi:510.1126/science.1106049.

Herold, M., C. Woodcock, A. DiGregorio, P. Mayaux, A. Belward, J. Latham, and C. C. Schmullius (2005), A joint initiative for harmonization and validation of land cover datasets, *IEEE Trans. Geosci. Remote Sens.*, *44*(7), 1719–1727.

Houghton, R. A. (2003), Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000, *Tellus, Ser. B*, *55*, 378–390.

Hurtt, G. C., L. Rosentrater, S. Frolking, and B. Moore (2001), Linking remote-sensing estimates of land cover and census statistics on land use to produce maps of land use of the conterminous United States, *Global Biogeochem. Cycles*, *15*, 673–685.

Hurtt, G. C., S. Frolking, M. G. Fearon, B. Moore, E. Shevliakova, S. Malyshev, S. W. Pacala, and R. A. Houghton (2006), The underpinnings of land-use history: Three centuries of global gridded land-use transitions, wood-harvest activity, and resulting secondary lands, *Global Change Biol.*, *12*, 1–22.

Jain, A. K., and X. Yang (2005), Modeling the effects of two different land cover change data sets on the carbon stocks of plants and soils in concert with CO_2 and climate change, *Global Biogeochem. Cycles*, *19*, GB2015, doi:10.1029/2004GB002349.

Jung, M., K. Henkel, M. Herold, and G. Churkina (2006), Exploiting synergies of global land cover products for carbon cycle modeling, *Remote Sens. Environ.*, *101*, 534–553.

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

Kruska, R. L., R. S. Reid, P. K. Thornton, N. Henninger, and P. M. Kristjanson (2003), Mapping livestock-oriented agricultural production systems for the developing world, *Agricul. Syst.*, *77*, 39–63.

Latham, J. (2001), AFRICOVER eastern Africa, *LUCC Newsl*, *7*, 15–16.

Lee, H.-L. (2005), The GTAP Land use data base and the GTAPE-AEZ model: Incorporating agro-ecologically zoned land use data and land-based greenhouse gases emissions into the GTAP framework, paper presented at the 8th Annual Conference on Global Economic Analysis, Inst. of Market Anal. and Agricul. Trade Policy, Lübeck, Germany, 9–11 June. (Available at https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID = 1839)

Leff, B., N. Ramankutty, and J. Foley (2004), Geographic distribution of major crops across the world, *Global Biogeochem. Cycles*, *18*, GB1009, doi:10.1029/2003GB002108.

Lepers, E., E. F. Lambin, A. C. Janetos, R. DeFries, F. Achard, N. Ramankutty, and R. J. Scholes (2005), A synthesis of information on rapid land-cover change for the period 1981–2000, *Bioscience*, *55*, 115–124.
Liu, J., M. Liu, H. Q. Tian, D. Zhuang, Z. Zhang, W. Zhang, X. Tang, and X. Deng (2005), Spatial and temporal patterns of China's cropland during 1990–2000: An analysis based on Landsat TM data, *Remote Sens. Environ.*, *98*, 442–456.
Lopez-Meisel, D., and J. Perez (1996), *1991 Census of Agriculture of the Philippines*, 18 pp., Econ. and Stat. Admin., Bur. of the Census, U. S. Dep. of Comm., Washington, D. C.
Lubowski, R. N., M. Vesterby, S. Bucholtz, A. Baez, and M. J. Roberts (2002), *Major Land Uses in the United States, 2002*, *Econ. Inf. Bull. EIB-14*, 54 pp., U. S. Dep. of Agricul., Econ. Res. Serv., Washington, D. C.
McGuire, A. D., et al. (2001), Carbon balance of the terrestrial biosphere in the twentieth century: Analyses of CO_2, climate and land use effects with four process-based ecosystem models, *Global Biogeochem. Cycles*, *15*, 183–206.
Monfreda, C., N. Ramankutty, and J. A. Foley (2007), Farming the Planet. part 2: Geographic distribution of crop areas, yields, physiological types, and NPP in the year 2000, *Global Biogeochem. Cycles*, doi:10.1029/2007GB002947, in press.
Myhre, G., and A. Myhre (2003), Uncertainties in radiative forcing due to surface albedo changes caused by land use changes, *J. Clim.*, *16*, 1511–1524.
National Statistical Office of Mongolia (2004), *Mongolia in a Market System Statistical Yearbook: 1989–2002*, 328 pp., Natl. Stat. Off., Ulaanbaatar.
Pielke, R. A., G. Marland, R. A. Betts, T. N. Chase, J. L. Eastman, J. O. Niles, D. D. S. Niyogi, and S. W. Running (2002), The influence of land-use change and landscape dynamics on the climate system: Relevance to climate-change policy beyond the radiative effect of greenhouse gases, *Philos. Trans. R. Soc. London, Ser. A*, *360*, 1705–1719.
Pitman, A., R. Pielke Sr., R. Avissar, M. Claussen, J. Gash, and H. Dolman (1999), The role of the land surface in weather and climate: Does the land surface matter?, *IGBP Newsl.*, *39*, 4–9.
Ramankutty, N. (2004), Croplands in West Africa: A geographically explicit dataset for use in models, *Earth Interactions*, *8*, 1–22.
Ramankutty, N., and J. A. Foley (1998), Characterizing patterns of global land use: An analysis of global croplands data, *Global Biogeochem. Cycles*, *12*, 667–685.
Ramankutty, N., and J. A. Foley (1999), Estimating historical changes in global land cover: Croplands from 1700 to 1992, *Global Biogeochem. Cycles*, *13*, 997–1027.
Ramankutty, N., J. A. Foley, J. Norman, and K. McSweeney (2002a), The global distribution of cultivable lands: Current patterns and sensitivity to possible climate change, *Global Ecol. Biogeogr.*, *11*, 377–392.
Ramankutty, N., J. A. Foley, and N. J. Olejniczak (2002b), People on the land: Changes in population and global croplands during the 20th century, *Ambio*, *31*(3), 251–257.
Ramankutty, N., T. Hertel, H.-L. Lee, and S. K. Rose (2007), Global agricultural land use data for integrated assessment modeling, in *Human-Induced Climate Change: An Interdisciplinary Assessment*, edited by M. Schlesinger et al., pp. 252–265, Cambridge Univ. Press, New York.
Reenberg, A., and B. Fog (1995), The spatial pattern and dynamics of a Sahelian agro-ecosystem, *GeoJournal*, *37*, 489–499.
Richards, J. F. (1990), Land transformation, in *The Earth as Transformed by Human Action*, edited by B. L. Turner et al., pp. 163–178, Cambridge Univ. Press, New York.
See, L. M., and S. Fritz (2006), A method to compare and improve land cover datasets: Application to the GLC-2000 and MODIS land cover products, *IEEE Trans. Geosci. Remote Sens.*, *44*, 1740–1746.
Seto, K. C., R. K. Kaufmann, and C. E. Woodcock (2000), Landsat reveals China's farmland reserves, but they're vanishing fast, *Nature*, *406*, 121.
Smil, V. (1999), Nitrogen in crop production: An account of global flows, *Global Biogeochem. Cycles*, *13*, 647–662.
State Committee of the Russian Federation on Statistics (1995), *Sel'skoe khoziaistvo Rossii: Statisticheskii sbornik*, 503 pp., Gos. komt Rossiiskoi Federatsii po Statistike, Moscow.
State Committee for Statistics of the Republic of Kazakhstan (1993), *Rural Facilities Statistics of Kazakhstan: Statistical Compendium*, State Comm. for Stat. of the Repub. of Kazakhstan, Almaty, Kazakhstan.
Tilman, D., J. Fargione, B. Wolff, C. D'Antonio, A. Dobson, R. Howarth, D. Schindler, W. Schlesinger, D. Simberloff, and D. Swackhamer (2001), Forecasting agriculturally driven global environmental change, *Science*, *292*, 281–284.
Tobler, W. R. (1979), Smooth pycnophylactic interpolation for geographical regions, *J. Am. Statist. Assoc.*, *74*, 519–530.
Vandermeer, J., I. Perfecto, R. E. Green, S. J. Cornell, J. P. W. Scharlemann, and A. Balmford (2005), The future of farming and conservation, *Science*, *308*, 1257–1258, doi:1210.1126/science.1308.5726.1257b.
Verburg, P. H., and Y. Chen (2000), Multiscale characterization of land-use patterns in China, *Ecosystems*, *3*, 369–385.
Verburg, P. H., and H. van Keulen (1999), Exploring changes in the spatial distribution of livestock in China, *Agricul. Syst.*, *62*, 51–67.
Verburg, P. H., Y. Chen, and T. A. Veldkamp (2000), Spatial explorations of land use change and grain production in China, *Agricul. Ecosyst. Environ.*, *82*, 333–354.
Wang, A., D. T. Price, and V. Arora (2006), Estimating changes in global vegetation cover (1850–2100) for use in climate models, *Global Biogeochem. Cycles*, *20*, GB3028, doi:10.1029/2005GB002514.
Wood, S., K. Sebastian, and S. J. Scherr (2000), Pilot analysis of global ecosystems: Agroecosystems, 110 pp, Int. Food Policy Res. Inst. and World Resour. Inst., Washington, D. C.
Yang, D. W., S. Kanae, T. Oki, T. Koike, and K. Musiake (2003), Global potential soil erosion with reference to land use and climate changes, *Hydrol. Proc.*, *17*, 2913–2928.

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