MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling

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Received 3 December 2008; revised 13 August 2009; accepted 2 September 2009; published 13 March 2010.

[1] To support global-scale assessments that are sensitive to agricultural land use, we developed the global data set of monthly irrigated and rainfed crop areas around the year 2000 (MIRCA2000). With a spatial resolution of 5 arc min (about 9.2 km at the equator), MIRCA2000 provides both irrigated and rainfed crop areas of 26 crop classes for each month of the year. The data set covers all major food crops as well as cotton. Other crops are grouped into categories (perennial, annual, and fodder grasses). It represents multicropping systems and maximizes consistency with census-based national and subnational statistics. According to MIRCA2000, 25% of the global harvested areas are irrigated, with a cropping intensity (including fallow land) of 1.12, as compared to 0.84 for the sum of rainfed and irrigated harvested crops. For the dominant crops (rice (1.7 million km^2 harvested area), wheat (2.1 million km^2), and maize (1.5 million km^2)), roughly 60%, 30%, and 20% of the harvested areas are irrigated, respectively, and half of the citrus, sugar cane, and cotton areas. While wheat and maize are the crops with the largest rainfed harvested areas (1.5 million km^2 and 1.2 million km^2, respectively), rice is clearly the crop with the largest irrigated harvested area (1.0 million km^2), followed by wheat (0.7 million km^2) and maize (0.3 million km^2). Using MIRCA2000, 33% of global crop production and 44% of total cereal production were determined to come from irrigated agriculture.

Citation: Portmann, F. T., S. Siebert, and P. Döll (2010), MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling, *Global Biogeochem. Cycles*, *24*, GB1011, doi:10.1029/2008GB003435.

1. Introduction

[2] The conversion of natural ecosystems to agricultural systems and the related land use practices have strongly influenced and altered many components of the Earth system like the Earth surface [*Ellis and Ramankutty*, 2008; *Foley et al.*, 2005], biogeochemical cycles [*Galloway and Cowling*, 2002; *Van Oost et al.*, 2007], or the water cycle [*Rost et al.*, 2008a, 2008b; *Scanlon et al.*, 2007]. On the other hand, agriculture provides more than 80% of the energy in human diet and supports the income of more than 2.6 billion people [*Food and Agriculture Organization of the United Nations* (*FAO*), 2007]. To investigate past, present, and future changes in food security, water resources and water use, nutrient cycles, and land management, it is therefore required to know the agricultural land use, in particular, which crop grows where and when. Since crop productivity and water use differ significantly between rainfed and irrigated agriculture [*Bruinsma*, 2003; *Rost et al.*, 2008a], it is furthermore required to distinguish rainfed and irrigated crops. While cropping pattern, seasonality, and irrigation status are often known at the local scale, regional or global data sets containing this information are still very rare. There are three major approaches for developing these data sets, each having specific advantages and shortcomings: remote sensing–based methods, census-based methods, and modeling.

[3] Remote sensing–based land cover classification approaches have the advantage that satellite imagery used as input has a high spatial resolution. Additionally, it is possible to detect changes in land cover by using imagery taken at different times. However, global remote sensing–based land cover classifications [e.g., *Boston University*, 2008; *GlobCover*, 2008; *Loveland et al.*, 2000; *Joint Research Centre of the European Commission* (*JRC*), 2008] contain only one to six agricultural land classes, do not distinguish specific crops, and detect only the dominant land cover category (without subpixel information). Other products [*European Environment Agency* (*EEA*), 2008; *FAO*, 2003; *Multi-Resolution Land Characteristics Consortium* (*MRLC*),

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0886-6236/10/2008GB003435

2008] contain more agricultural categories but are limited in spatial coverage. Global land cover maps developed by the International Water Management Institute (IWMI) show irrigated and rainfed cropland including multicropping and source of water [*IWMI*, 2007]. However, the low spatial resolution of the satellite imagery and the classification algorithm result in high uncertainty. In the two major irrigation countries, India and China, irrigated areas as estimated by IWMI are more than twice the area estimated by national censuses. Besides, IWMI products do not specify crop-specific growing areas.

[4] Census-based land use data sets [e.g., *FAO*, 2008; *National Agricultural Statistics Service* (*NASS*), 2008] have the advantage that during the surveys a large number of variables related to land use, but also related to crop production, harvested area, fertilizer use, livestock, use of machinery, tenancy, water use, etc., are collected and that these variables can be linked directly to the land use statistics. For many countries, time series of these statistical data are available, but spatial resolution of these statistics is limited because of the sampling scheme. Furthermore it is difficult to maintain global census databases at high spatial resolutions because boundaries and names of subnational units change from year to year. Also, definitions of census variables and accuracy of the results vary from country to country.

[5] Modeling of land use is common if it is necessary to assess long time periods or to run scenarios of the future, e.g., in climate models or in models of the carbon cycle. Here, remote sensing products as well as statistics are not available, and the cropping pattern is simulated on the basis of suitability of climate and soil, resulting potential crop yields, and population densities [*Leemans and van den Born*, 1994; *Zuidema et al.*, 1994; *Schaldach et al.*, 2006].

[6] Recently, a number of global land use and land cover products have been developed by combining satellite imagery, census statistics, and modeling. *Heistermann* [2006] developed a data set that provides the dominant crop class for each 5 arc min cell, without subgrid fractions for different crops. His data set, comprising 17 crop classes and the sum of assigned crop area, is consistent to census-based statistics and was intended as a basis for land use modeling. Most of the global data sets provide fractions of land cover or land use at the 5 arc min resolution. The general procedure in these data sets to combine the different data inputs has been to use census-based statistics to define the total areas in the related spatial statistical units. Then geospatial data such as satellite imagery or GIS vector layers and/or crop suitability modeling define the spatial pattern inside the statistical unit. These global data sets quantify, for example, cropland extent [*Ramankutty et al.*, 2008; *Ramankutty and Foley*, 1998] or extent of the areas equipped for irrigation (*Döll and Siebert* [2000] and *Siebert et al.* [2005], updated by *Siebert et al.* [2007]). More complex data sets describe a few basic land use categories like cropland or grazing [*Erb et al.*, 2007; *Klein Goldewijk et al.*, 2007] or several crop classes [*Fischer et al.*, 2008; *Leff et al.*, 2004]. One comprehensive data set contains harvested areas for all 175 crops currently covered by the statistics of the Food and Agriculture Organization of the United Nations (FAO) [*Monfreda et al.*, 2008]. Irrigated and rainfed crops are rarely distinguished so far, for example, by separating irrigated and rainfed crops on the basis of a general maximum entropy approach [*Cai et al.*, 2007; *You and Wood*, 2006] or by applying simple assumptions on the importance of irrigation for different crop categories [*Bondeau et al.*, 2007; *Rost et al.*, 2008a]. These approaches have the limitation that they do not account for multicropping practices when generating the crop distribution pattern, besides two exceptions: *Cai et al.* [2007] used multicropping factors for major crops to limit irrigated area, and *Bondeau et al.* [2007] allowed multicropping for rice in tropical Asia. Crops growing at the same time of the year cannot grow in the same place, while crops growing in different periods can share the same field. This fact needs to be considered when generating crop distribution patterns for multicropping systems, because the available growing area is limited by cropland extent and additionally by the area equipped for irrigation in the case of irrigated crops.

[7] Here we present the novel global data set of monthly irrigated and rainfed crop areas around the year 2000 (MIRCA2000) that distinguishes irrigated and rainfed areas for 26 crop classes, among them 21 major crops and the crop groups of pulses, citrus crops, fodder grasses, other perennial crops, and other annual crops. For each month of the year, MIRCA2000 provides information on growing areas that is representative for the period 1998 to 2002. It explicitly includes multicropping systems. MIRCA2000 aims to maximize consistency with subnational statistics collected by national institutions and by the FAO. MIRCA2000 consists of four different products which are likely to be applied for different purposes by the data users:

[8] 1. Monthly growing area grids for irrigated and rainfed crops (MGAG-I + MGAG-R) provide the growing area for each of the 26 irrigated and rainfed crops and each month of the year for each 5 by 5 arc min grid cell (on land).

[9] 2. Condensed crop calendars for irrigated and rainfed crops (CCC-I + CCC-R) report harvested area, start, and end of cropping periods for each of the 402 spatial units distinguished in this inventory. Up to five distinct subcrops are used in order to represent multicropping practices.

[10] 3. Similarly, cropping period lists (CPL) provide harvested area, start, and end of cropping periods for each 5 arc min grid cell.

[11] 4. Maximum monthly growing area grids for irrigated and rainfed crops (MMGAG-I + MMGAG-R) report for each grid cell the maximum of the monthly growing areas within the year for each of the 26 irrigated and rainfed crops.

[12] The first three products provide harvested area and crop seasonality as a consistent bundle. Crop-specific grids of irrigated and rainfed annual harvested area are also provided for users who are interested in this information only. As these grids can be derived from the aforementioned products, they are not mentioned here as a separate product. Users who prefer to simulate cropping periods by themselves (e.g., using a dynamic vegetation model) are referred to the fourth data product; these users should analyze consistency of derived harvested areas with statistical data. Additionally, we provide all products aggregated to the 30 arc min resolution that is still the standard in many global models.

Figure 1. Spatial units for which crop calendars were established.

The products are available for download at http://www.geo.uni-frankfurt.de/ipg/ag/dl/forschung/MIRCA/index.html.

[13] Input data and the methods used to generate the main elements of the data set, the monthly growing area grids for irrigated and rainfed crops (MGAG-I and MGAG-R), and the related condensed crop calendars (CCC-I and CCC-R) are presented in section 2 of this paper, while we present the results in section 3. MIRCA2000 is compared to other data sets in section 4 and discussed in section 5. Finally, in section 6 we draw conclusions, give recommendations on the use of the products, and cite an application of MIRCA2000. For the exact meaning of the terminology used in this publication we refer to the glossary (Text S1).[1]

2. Data and Methods

[14] In this section we describe characteristics and sources of input data (section 2.1) and methods (section 2.2) used to define cropping periods of 26 crop classes and up to five subcrops at the 5 arc min grid cell level. The basic procedure used here was to first define cropping periods and growing areas for 402 spatial units ("calendar units," Figure 1) and then to downscale this information to the grid cell level (Figure 2). The 402 calendar units include all countries as well as first-level subnational units for China, India, United States, Brazil, Argentina, Indonesia, and Australia.

2.1. Data

[15] Seven categories of input data were used to develop this inventory (Table 1). For a more detailed documentation of data sources related to cropping periods and harvested areas of irrigated crops we refer to *Portmann et al.* [2008].

[16] Crop calendars defining start and end of cropping periods were obtained from several inventories [e.g., *FAO*, 2005a, 2005b; *International Rice Research Institute* (*IRRI*), 2005; *United States Department of Agriculture* (*USDA*), 1994; USDA, Monthly normal crop calendar, accessed April 2006, available at http://www.fas.usda.gov/pecad/weather/Crop_calendar/crop_cal.pdf] or national reports. This data was available for 142 individual countries but mostly for selected crops only. For China, India, and Indonesia, the FAO provided information on start and end of cropping periods for three, four, and two climatically different subzones, respectively [*FAO*, 2005a].

[17] Crop-specific harvested areas of irrigated crops were derived from several census-based inventories [e.g., *FAO*, 2005a, 2005c; *NASS*, 2004; *Statistical Office of the European Communities* (*EUROSTAT*), 2008a; *Indiaagristat*, 2005; *Australian Bureau of Statistics* (*ABS*), 2002, 2001; *National Bureau of Statistics of China*, 2001; *Fundacao Instituto Brasileiro de Geografia e Estatistica* (*IBGE*), 1997; *Instituto Nacional de Estadística y Censos de la República Argentina* (*INDEC*), 2002]. For the 179 spatial units with areas equipped for irrigation, information on crop-specific harvested areas were available, but not for all crops. Information on cereals existed for almost all units with significant area equipped for irrigation. In contrast, harvested areas of rainfed crops were computed for each of the 402 spatial units (Figure 1) as the difference between total harvested crop area [*Monfreda et al.*, 2008] and irrigated harvested crop area (section 2.2.2) (Figure 2).

[18] To define total annual harvested crop area, we used an inventory at 5 arc min resolution [*Monfreda et al.*, 2008]. This data set consists of grids for 175 crops consistent to the

[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GB003435.

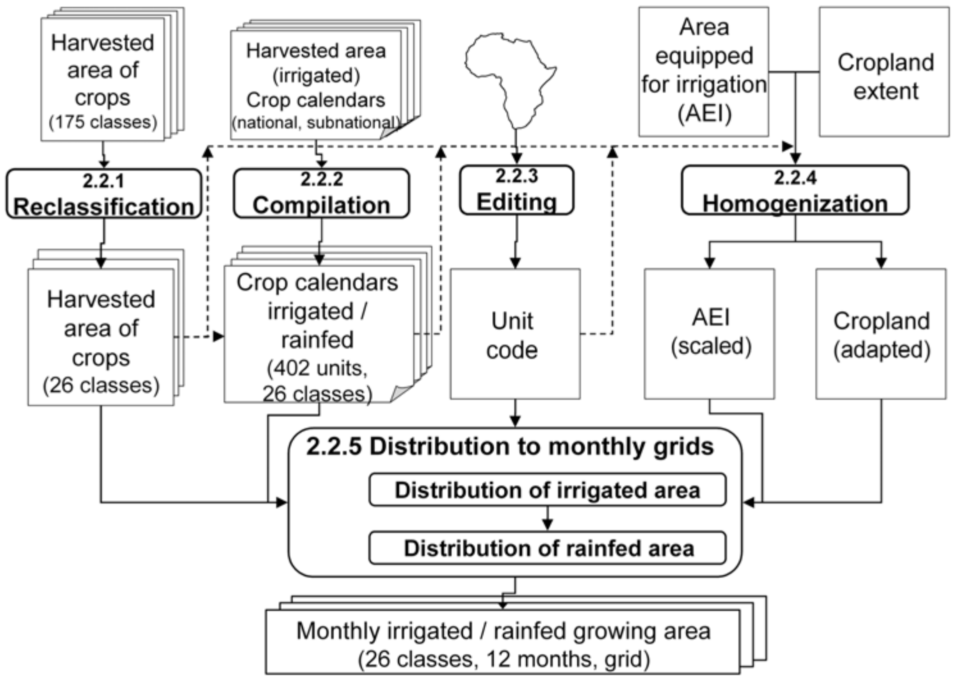

Figure 2. Data processing scheme for the derivation of monthly growing area grids of irrigated and rainfed crops.

crop categorization of the statistical database of the FAO (FAOSTAT) and refers to the period around year 2000. However, it does not distinguish rainfed and irrigated crops in a crop-specific manner. It was developed by distributing harvested crop areas derived from subnational statistics to cropland areas [*Ramankutty et al.*, 2008] using different potential cropping intensities in cells with area equipped for irrigation (AEI) and in cells without AEI. Statistics for 2299 spatial units of the first level below the national and for 19,751 second level units were used [*Monfreda et al.*, 2008]. Data resolution differed between crops and countries. The total global harvested crop area reported in this data set

Table 1. Characteristics and Sources of Input Data Used to Develop Monthly Growing Area Grids of 26 Irrigated and Rainfed Crops

Data Description	Characteristics and Resolution	Data Sources
Crop calendars for irrigated and rainfed crops	Data for 402 spatial units (countries, provinces) indicating start and end of cropping period	National agricultural census statistics [e.g., *NASS*, 2004], national reports, databases [e.g., *EUROSTAT*, 2007a], FAO [e.g., *FAO*, 2005a], and United States Department of Agriculture (USDA) [e.g., *USDA*, 1994]; for detailed information on data sources, see *Portmann et al.* [2008]
Harvested area of irrigated crops	Census-based statistics for 402 spatial units	National reports [e.g., *NASS*, 2004], databases [e.g., *EUROSTAT*, 2007a], and FAO [e.g., *FAO*, 2005a]
Crop-specific annual harvested area	5 arc min grid, data layers for 175 different crops	*Monfreda et al.* [2008]
Cropland extent	5 arc min grid	*Ramankutty et al.* [2008]
Area equipped for irrigation	5 arc min grid	*Siebert et al.* [2007]
Administrative boundaries of countries and subnational units	GIS-Shapefile	*ESRI* [2004]
Ancillary information (climate, topography)	Monthly mean precipitation and air temperature for 28,106 climate stations, monthly mean air temperature at 10 arc min resolution, mean elevation at 5 arc min resolution	*FAO* [2001], our own expert knowledge on climatology and cropping periods, *New et al.* [2002], and *National Geophysical Data Center* [1988]

was 12.8 million km^2, and at the grid cell level, the harvested area can be larger than the total cell area if multicropping occurs. The data set can be downloaded from http://www.geog.mcgill.ca/landuse/pub/Data/175crops2000/.

[19] Cropland extent around the year 2000 was derived from a data set that was developed by combining national cropland statistics to remote sensing–based land cover classifications [*Ramankutty et al.*, 2008]. The total extent of cropland according to this inventory was 15.0 million km^2 and included temporary fallow land. The product consists of one grid that provides for each 5 arc min grid cell the fraction that was used as cropland. It is available at http://www.geog.mcgill.ca/landuse/pub/Data/Agland2000/.

[20] The fraction of each 5 arc min grid cell that was equipped for irrigation around year 2000 was taken from the Global Map of Irrigation Areas (GMIA), version 4 (*Siebert et al.* [2005], updated by *Siebert et al.* [2007]). GMIA was developed by combining irrigation statistics for 26,909 subnational units to geospatial information on the location and extent of irrigation schemes. Total area equipped for irrigation was 2.8 million km^2. However, the area actually used for irrigation is significantly lower because of several reasons, e.g., crop rotation, damaged infrastructure, and water shortage. This aspect is considered in MIRCA2000. The data set and related documentation are available at http://www.fao.org/nr/water/aquastat/irrigationmap/index.stm.

[21] To downscale crop calendars and harvested crop area statistics from the calendar unit level to the grid cell level (Figure 2), it is necessary to use a consistent data set of national and subnational unit boundaries. We used a geodata package that is distributed along with standard GIS software [*Environmental Systems Research Institute* (*ESRI*), 2004].

[22] To define start and end of cropping periods in crop calendars in case of missing data (section 2.2.2) and to define grid cells suitable for growing winter cereals with vernalization requirements (section 2.2.5), we used climate and elevation data. Mean monthly precipitation and temperature for 28,106 stations were available from the FAO agroclimatic database FAOCLIM2 [*FAO*, 2001] while long-term mean monthly temperature at 10 arc min resolution was derived from the version 2.0 of the climate data set of the Climatic Research Unit (CRU) of the University of East Anglia (CRU CL 2.0) data set [*New et al.*, 2002]. Mean elevation for each 5 arc min grid cell was taken from the ETOPO5 elevation data set [*National Geophysical Data Center*, 1988].

2.2. Methods

[23] In this section we describe how we combined and processed the input data to develop monthly growing area grids at the 5 arc min resolution (Figure 2). National and international agricultural statistics report harvested crop areas for a large number of specific crops. In contrast, statistics distinguishing irrigated and rainfed crops and related crop calendars are often limited to a few crop categories that differ between countries. Therefore we classified crops into 26 classes comprising all major food crops (wheat, rice, maize, barley, rye, millet, sorghum, soybeans, sunflower, potatoes, cassava, sugarcane, sugar beets, oil palm, rapeseed/canola, groundnuts/peanuts, pulses, citrus, date palm, grapes/vine, cocoa, coffee), cotton as an industrial crop with particular importance in irrigated agriculture, and unspecified other crops (perennial, fodder grasses, annual) (see Table 4; cotton listed before cocoa and coffee for historical reasons) accounting for both the availability of information and the importance of specific crops in irrigated agriculture and for food consumption. Since the classification system was different in most of the original input data we first describe the reclassification of grid cell–based (section 2.2.1) and unit level–based (section 2.2.2) input data. By combining these reclassified harvested area statistics, we compiled crop calendars at the unit level (section 2.2.2), the so-called "Condensed Crop Calendars" (CCC) that report harvested area as well as start and end of cropping periods for each of the 402 spatial units. To downscale these CCCs to the grid cell level, it was necessary to assign each grid cell to one spatial unit (section 2.2.3) and to preprocess input data sets of cropland extent and area equipped for irrigation to reduce inconsistencies of these to harvested area data (section 2.2.4). The downscaling process itself is described in section 2.2.5.

2.2.1. Reclassification of Total Harvested Crop Area at the Grid Cell Level

[24] Total crop-specific harvested area (without distinction of irrigated and rainfed crops) was available for 175 crops [*Monfreda et al.*, 2008]. We assigned each of these 175 crops to one of the 26 MIRCA2000 crop classes (Figure 2). For example, harvested area of the MIRCA2000 crop maize was computed as the sum of harvested areas of three crops by *Monfreda et al.* [2008] (Table S1). Harvested areas of rye and sorghum were the sum of two original crops, 11 original crops formed the MIRCA2000 crop class "pulses," five formed the class "citrus," 57 formed the group "other perennial crops," 72 formed the group "other annual crops," and five original crops formed the MIRCA2000 group "forage grasses" (Table S1). The harvested area of the original crop class "Forage products, other" that contained annual and perennial crops was equally distributed with 50% share to the crop classes of "forage grasses" and "other annual crops" (Table S1).

2.2.2. Compilation of Condensed Crop Calendars

[25] "Condensed Crop Calendars" (CCC) for each of the 402 spatial units were derived by combining data on harvested area with information on cropping periods (Figure 2). Harvested areas of irrigated crop classes were mainly defined based on national and international statistical databases. Harvested areas of rainfed crops were then computed as the difference between total harvested area of the crop class (section 2.2.1) and irrigated harvested area. Consequently, CCCs were first defined for irrigated crops.

2.2.2.1. Condensed Crop Calendars for Irrigated Crops

[26] Harvested areas of irrigated crops on a national or subnational level were derived from agricultural statistics and survey reports [e.g., *FAO*, 2005a; *NASS*, 2004; *EUROSTAT*, 2008a; *Indiaagristat*, 2005; *ABS*, 2002; *IBGE*, 1997; *INDEC*, 2002]. Cropping periods of irrigated crops (if available also for subnational units), were extracted from data available at the FAO and at the International Rice Research Institute [*FAO*, 2005a; *IRRI*, 2005]. Next, cropping periods of these calendars were extended to crops and countries not men-

tioned in these data sources by using data for similar crops or climatically similar countries. Besides, calendars that did not distinguish rainfed and irrigated crops were consulted [e.g., *FAO*, 2005b; *USDA*, 1994]. Since the spatial resolution of the harvested area statistics was better than related data on start and end of the cropping periods, it was required either to adapt existing FAO calendars for subnational cultivation zones (three for China, four for India, and two for Indonesia) or to establish calendars according to climatic zones and climatic classifications based on station data or reports (six for Argentina, eight for Australia, five for Brazil, and eight for United States). The subnational climatic zones were designed to delineate areas with similar climate and cropping systems. Start and end of the cropping periods were applied to all of the subnational units within the respective zone.

[27] Data sources often grouped specific crops into crop classes that differed from the crop classes used in this inventory. Additionally, in many cases only harvested areas of the major irrigated crops were reported in a crop-specific way. Through ancillary information (e.g., mentioning of specific further crops in a descriptive text, e.g., "mostly maize" for "other cereals"), the primary data were disaggregated to fit to the 26 MIRCA2000 classes. This resulted in so-called detailed crop calendars that often listed more than one crop for the crop classes used in the MIRCA2000 inventory, e.g., different types of fruits and vegetables in crop class "other annual crops" [*Portmann et al.*, 2008]. The cropping periods in these detailed crop calendars for irrigated crops were then aggregated through summation of growing areas of crops belonging to the same crop class and growing during exactly the same months of the year. By doing so, up to five so-called subcrops were defined in the resulting Condensed Crop Calendars (CCC-I). Thus, subcrops can represent multicropping systems, e.g., double cropping or triple cropping of rice in southern Asia. They can also represent different specific subgroups of a crop class that grow during different parts of the year, also with overlapping cropping periods. This is typically the case for the groups of "other annual" and "other perennial crops."

[28] The whole procedure of developing the CCC-I is described in detail by *Portmann et al.* [2008]. This report includes a country-wise documentation of data sources and of disaggregation estimates. It also shows the detailed crop calendars used as input for the CCC-I for each of the 402 calendar units.

2.2.2.2. Condensed Crop Calendars for Rainfed Crops

[29] Rainfed harvested areas were computed for each spatial unit from the difference between crop-specific total harvested area and the crop-specific irrigated harvested area defined in the CCC-I. Total harvested area was computed for each unit and crop class as the sum of the crop-specific harvested area described in section 2.2.1 over all grid cells belonging to that unit. Because of inconsistencies between the irrigation statistics used here and the harvested area statistics used by *Monfreda et al.* [2008], crop-specific irrigated area for a given crop was sometimes larger than the related total harvested crop area, in particular in arid calendar units. In these cases, the crop-specific rainfed harvested area was set to zero but the crop-specific irrigated harvested area was not reduced. In order to maximize the consistency to the total sum of harvested area over all crops, we tried to compensate in those cases in the groups of "other annual" or "other perennial crops" for the difference between irrigated harvested crop area and total harvested crop area.

[30] Cropping periods for rainfed crops were derived using additional crop calendars that do not distinguish between rainfed and irrigated crops like those of the FAO Global Information and Early Warning System (GIEWS) [*FAO*, 2005b] and the United States Department of Agriculture [*USDA*, 1994; USDA, Monthly normal crop calendar, accessed April 2006]. In addition, we used rainfall and air temperature data of the FAOCLIM2 database [*FAO*, 2001] to avoid an assignment of cropping periods to dry and cold seasons and further information on the length of cropping periods and temperature requirements [*Doorenbos and Pruitt*, 1977]. Irrigated cropping periods, as determined above, were used to derive rainfed cropping periods for crops that are grown under both rainfed and irrigated conditions. As a result, in selected units, some crops are grown during the summer season as irrigated crops and during the winter season as rainfed crops.

2.2.2.3. Multicropping Systems and Varieties of Rice, Cassava, and Temperate Cereals

[31] If a crop is grown more than once a year, the sum of the growing areas of the subcrops equals the crop-specific total (annual) harvested area, which follows general definitions of multicropping, e.g., by the FAO. In MIRCA 2000, the growing area of each subcrop can be different, e.g., spring wheat can have a smaller share of the total annual harvested area than winter wheat, or vice versa.

[32] The distinction of cropping periods and varieties of irrigated rice and rainfed rice followed the classification of the International Rice Research Institute (IRRI) [*IRRI*, 2005]. Irrigated rice was assumed to be always paddy rice, in accordance with other studies, other modeling approaches, and input data to CCC-I, with up to three cropping periods per year. For rainfed rice we distinguished upland, deepwater, and paddy rice in the CCCs. The standard lengths of their cropping periods were drawn from IRRI data, other inventories, or plant physiological studies by considering local climate conditions [*FAO*, 2001]. We assigned a cropping period of mainly 7 to 8 months to upland rice, which is cultivated in similar manner as other cereals. For deepwater rice, which grows under natural seasonal flooding conditions in natural river banks during preflood, flood, and postflood conditions, a standard growing period of 7 months was defined [*Catling*, 1992; *Central Rice Research Institute* (*CRRI*), 2006; *Jupp et al.*, 1995]. For rainfed paddy rice, up to three cropping periods were established, typically each with an estimated length of 4 months. The number of cropping periods was defined on the basis of FAOCLIM2 climate data [*FAO*, 2001]. Relative shares of upland, deepwater, and paddy rice areas were close to those from *IRRI* [2005] after cross-check with data from *Catling* [1992]. Subnational data [*Frolking et al.*, 2006] were used to define rice cropping periods for India.

[33] We distinguished two different varieties of cassava as documented in the literature: an early ripening one with a cropping period of about 8 months and a late ripening one

with a cropping period of about 21 months [*Rehm and Espig*, 1991]. It was assumed that the short-period variety was cultivated under irrigation, while both varieties occurred in rainfed agriculture.

[34] Generally, temperate cereals can be grown during two distinct cropping periods that are often associated with different plant varieties: winter varieties that require vernalization and spring varieties that do not. Winter varieties such as winter wheat, winter barley, and winter rye are planted in autumn and are typically harvested in the following midsummer. They have a longer cropping period than spring varieties and typically allow higher yields. Spring varieties have shorter cropping periods, are typically planted in spring, and are harvested in midsummer, often a bit later than winter varieties. Durum wheat is a typical spring wheat variety. In subtropical countries with mild winters, spring varieties are also often grown during winter months, while other cereals like maize or sorghum are grown during summer. The extent of spring varieties versus winter cereals depends not only on climatic conditions, but also on the demand for spring or winter varieties. While breweries and pasta producers prefer spring varieties, winter varieties are mainly used as animal fodder and in bakeries.

[35] To accommodate for this complex situation, several distinctions for temperate cereals were made in MIRCA2000. Irrigated durum wheat was assumed to always grow during summer as spring wheat variety, as any water deficit would be met by irrigation. If, in the original data source, only irrigated harvested area of wheat was given, without any further hint or distinction of winter or summer varieties, we assumed it to be the globally dominating winter wheat and assigned a cropping period starting in autumn or winter. In some cases we deviated from this principle [*Portmann et al.*, 2008]: In India, for example, the irrigated harvested area of wheat outnumbered the available area equipped for irrigation if the single cropping period listed by *FAO* [2005a] was used. Therefore, we introduced a second cropping period during summer in the subnational zone of north India. Cropping periods for irrigated rye and barley were assigned depending on the climatic conditions within the spatial unit. Other irrigated temperate cereals such as oats were classified as "other annual crops" and were generally supposed to be grown only during summer.

[36] Production statistics for wheat, rye, and barley released by *EUROSTAT* [2007b] and our own expert knowledge were used to define a general scheme for the relative proportions of rainfed winter and spring cereal varieties that was used to replace missing data: harvested area in high latitudes was attributed to one cropping period during summer because of the low minimum temperatures during winter time. For temperate climate conditions, the percentage of harvested area assigned to winter varieties was 100% for rye, 95% for barley, and 90% for wheat. For units in subtropical climate, selected by using climatologic classifications like *Troll and Paffen* [1964] and a latitude between 30 and 40 degrees, we assumed that spring varieties with a short cropping period were grown during the winter season. In the tropics, relative percentages of harvested area and the length of cropping periods were defined on the basis of monthly climate data of precipitation amount and air temperature [*FAO*, 2001] with up to three cropping periods of spring varieties. Relative shares of harvested areas of rainfed winter wheat and spring wheat for several Chinese provinces were defined on the basis of another inventory [*Frolking and Li*, 2007]. For the rest of China, rainfed wheat was generally estimated to be 90% winter wheat and 10% spring wheat, following the previously explained general scheme.

2.2.2.4. Example of a Condensed Crop Calendar

[37] An example for a CCC for irrigated crops is given for the calendar unit California (Table 2). For each crop class and up to five subcrops the growing area and the start and end month of the cropping period are provided. California has the unit number 840005 (Table 2, "Unit Code" column). The crop class is given in the "Crop Class" column, and the number of subcrops is given in the "Number of SC" column. Beginning with the "SC1 Area" column, total growing area, first month, and last month of the cropping period are listed for each subcrop. Thus, the first line can be interpreted as follows: In unit 840005 (California), there are two subcrops of crop 1 (wheat). Subcrop 1 is growing on 98,723.06 ha in the period September (9) to June (6), and subcrop 2 is growing on 38,363.79 ha in the period April (4) to August (8). Here subcrop 1 represents irrigated winter wheat while subcrop 2 is irrigated spring wheat. For the permanent crops sugarcane (crop class 12), oil palm (14), citrus (18), date palm (19), grapes (20), cocoa (22), coffee (23), other perennial crops (24), and fodder grasses (25), the first month of the cropping period is always January (1), and the last month is always December (12). We never assigned more than one subcrop to these permanent crops. Crop class 26 (other annual crops) consists of four subcrops (SC) that were composed from different individual crops: oats for grain and safflower (SC1, months 4 to 9), sweet potatoes and mint (SC2, months 4–10), and vegetables (cropped twice in SC3, months 3 to 6, and SC4, months 7 to 10). The CCC for rainfed crops has the same structure.

2.2.3. Development of a Full Coverage Spatial Unit Mask

[38] To combine information collected at the calendar unit level (CCCs) with information available at the grid cell level (area equipped for irrigation AEI, cropland extent, and harvested area of crops AH; see Table 1), it was necessary to assign each grid cell to the related spatial calendar unit (country or subnational unit). Usually such an assignment is done by converting a polygon shapefile containing unit boundaries to a raster data set of the required resolution. As cropland is often located in lowland cells close to the ocean or near lake coastlines, and as different land masks or polygon shapefiles were used to develop the three grid input data sets of AEI, cropland extent, and AH, it occurred frequently that grid cells close to water bodies had data values in one input data set but were masked out as water in another input data set. In order to ensure that all grid values were completely assigned to the respective unit and no data values were lost, a procedure was developed to assign ocean, lake, and wetland cells to the unit that is closest to the related grid cell (Figure 2).

2.2.4. Preprocessing of Grid Input Data

[39] As data sources and methodologies used to generate the grid input data (AEI, cropland extent, and AH) were different,

Table 2. Example of Condensed Crop Calendar for Irrigated Crops in California Listing Growing Area of Each Subcrop in Hectare and the Calendar Month of Start and End of Subcrop Cropping Period

Unit Code	Crop Class[a]	Number of SC	SC1 Area	SC1 Start	SC1 End	SC2 Area	SC2 Start	SC2 End	SC3 Area	SC3 Start	SC3 End	SC4 Area	SC4 Start	SC4 End
840005	1	2	98723.06	9	6	38363.79	4	8						
840005	2	1	226418.38	4	9									
840005	3	1	215015.15	4	10									
840005	4	1	18769.72	4	9									
840005	5	1	51.80	4	9									
840005	6	1	24.28	4	9									
840005	7	1	6222.04	4	9									
840005	8	0												
840005	9	1	6218.40	4	9									
840005	10	1	19512.73	4	10									
840005	11	0												
840005	12	0												
840005	13	1	22532.90	3	9									
840005	14	0												
840005	15	1	33.18	4	9									
840005	16	1	8.90	4	9									
840005	17	1	23414.30	4	10									
840005	18	1	138423.94	1	12									
840005	19	0												
840005	20	1	360532.82	1	12									
840005	21	1	281116.10	4	11									
840005	22	0												
840005	23	0												
840005	24	1	660482.18	1	12									
840005	25	1	705988.67	1	12									
840005	26	4	26964.20	4	9	5134.65	4	10	207412.72	3	6	207412.72	7	10

[a]MIRCA2000 crop classes: 1, wheat; 2, maize; 3, rice; 4, barley; 5, rye; 6, millet; 7, sorghum; 8, soybeans; 9, sunflower; 10, potatoes; 11, cassava; 12, sugarcane; 13, sugar beet; 14, oil palm; 15, rape seed; 16, groundnuts; 17, pulses; 18, citrus; 19, date palm; 20, grapes; 21, cotton; 22, cocoa; 23, coffee; 24, other perennial; 25, fodder grasses; 26, other annual. SC, subcrop.

there are inconsistencies between these data sets. AEI, for example, was about 30% larger than cropland extent of *Ramankutty et al.* [2008], in the arid country of Egypt [*Portmann et al.*, 2008]. At the grid cell level, spatial mismatch also occurred in more humid regions. Furthermore, we found inconsistencies between the grid data sets and monthly growing areas in the CCCs. We would expect, for example, that the sum of the growing areas of all irrigated crops in the CCCs is, for each unit and each month, smaller or equal to the sum of AEI. Additionally, for each unit and each month, the sum of the growing areas of all crops in the CCCs should be smaller or equal to the cropland extent. In some spatial units, however, this was not the case, mainly because of different statistics (or different reference years of the statistics) used to generate the grid input data on the one hand and the CCCs on the other hand. By preprocessing the AEI and cropland extent grids as described in the following two paragraphs, such inconsistencies were partially fixed (Figure 2). The method to downscale monthly growing areas from the unit level to the grid cell level accounted for the remaining inconsistencies (Figure 2).

[40] In calendar units where AEI according to GMIA was smaller than the maximal monthly sum of growing area of irrigated crops in the CCCs, AEI in each grid cell was increased by the same factor such that total AEI was equal to the maximal monthly sum of growing area of irrigated crops in the CCCs. This procedure was necessary in 30 calendar units in 18 countries and increased global AEI by 3502 km^2 or 0.13%. Most of these 30 units belonged to countries where statistics on AEI were not available when developing the GMIA and statistics on actually irrigated area within a specific reference year had to be used instead, e.g., in Australia and India. In other units, mainly small islands, AEI was valid for less recent years than the statistics used to define the CCCs.

[41] Additional cropland extent was generated in grid cells where harvested crop area AH [*Monfreda et al.*, 2008] existed, but cropland extent [*Ramankutty et al.*, 2008] was zero. This occurred in 27,150 grid cells mainly located close to water bodies. For these cells, cell-specific cropland extent was calculated by dividing cell-specific total harvested areas by the overall cropping intensity computed on the basis of the other cells of the spatial unit, thus accounting for multi-cropping. If cell-specific AEI was larger than this so computed cropland extent, then the new cropland extent was set to AEI. As a result of this preprocessing, total cropland extent was increased by 129,441 km^2 or 1% of the global cropland extent used as input data set [*Ramankutty et al.*, 2008].

2.2.5. Downscaling of CCCs to the Grid Cell Level

[42] The CCCs (section 2.2.1) provide information on the monthly growing areas of each of the crop classes and related subcrops (e.g., winter wheat and spring wheat), under irrigated and rainfed conditions, in the 402 calendar units (section 2.2.3). This information was downscaled to provide growing areas within each of the 5 by 5 arc min grid cells, using grid cell data of crop-specific AH (section 2.2.1), AEI, and cropland extent (as modified in section 2.2.4), and applying a distribution procedure as described in the

Table 3. Priority Levels for Downscaling of Condensed Crop Calendars to 5 arc min Monthly Growing Area Grids[a]

Priority	5 arc min Data Set	Goal
1	Area equipped for irrigation [*Siebert et al.*, 2007] (modified as described in section 2.2.4)	In each month and grid cell the sum of crop-specific irrigated areas is lower than or equal to the area equipped for irrigation.
2	Cropland extent [*Ramankutty et al.*, 2008] (modified as described in section 2.2.4)	In each grid cell and month the sum of crop-specific irrigated and rainfed areas is lower than or equal to the cropland extent.
3	Harvested crop area [*Monfreda et al.*, 2008]	In each grid cell and for each crop class the annual sum of the irrigated and rainfed harvested crop area is equal to the total (rainfed and irrigated) harvested area of the specific crop.

[a]Priority decreases from 1 to 3.

following paragraphs of this section (see Figure 2). As shown before, the three grid input data sets are inconsistent such that priorities had to be defined with which the input data sets had to be treated during the downscaling (Table 3). AEI was given the highest priority, and AH was given the lowest. AEI and cropland extent need not necessarily be "used up" when assigning growing areas to the crops as both include fallow land. However, the total annual harvested area AH given for each grid cell should be disaggregated to monthly growing areas under either irrigated or rainfed conditions (Table 3).

[43] Downscaling of monthly growing areas of subcrops in the 402 units to grid cells was done in up to seven steps (Figure 3). These steps ensured that the priorities (Table 3) were implemented and that for the given unit the sum of the cell-level growing areas distributed to the subcrop was the same as the growing area of the subcrop reported in the CCC. Furthermore, consistency to AEI (priority 1 in Table 3) was assured, while consistency to cropland extent and crop harvested areas (priorities 2 and 3) was maximized. Further boundary conditions were that, like in reality, annual rainfed crops can be grown on areas equipped for irrigation

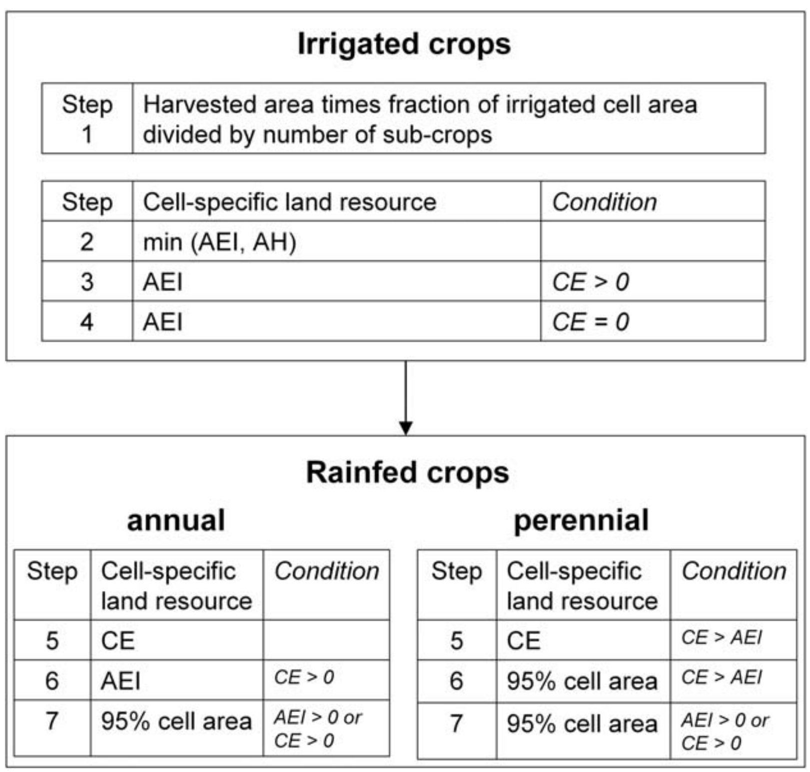

Figure 3. Steps for downscaling of Condensed Crop Calendar (CCC) growing area of each of the 402 spatial units to the grid cell for each subcrop and cropping period, with the respective cell-level land resources that can be used for downscaling. "Condition" defines under which conditions the land resource is taken into account in the respective step and grid cell. Land resources are area equipped for irrigation (AEI), crop-specific harvested area (AH), and preprocessed cropland extent (CE; compare with section 2.2.4).

if these areas are not occupied by irrigated crops. In contrast, permanent rainfed crops were likewise only allowed to grow on areas not equipped for irrigation.

[44] Irrigated growing areas were assigned first (steps 1 to 4, Figure 3), followed by rainfed growing areas (steps 5 to 7, Figure 3). The distribution steps were performed unit by unit, crop by crop, and subcrop by subcrop. In step 1, the irrigated growing area of a subcrop in a grid cell in any month of the cropping period reported in the CCC was estimated as the total AH of the crop times the fraction of the cell area that is equipped for irrigation, divided by the number of subcrops. Thus, equal shares of the irrigated harvested area were assigned to each subcrop without surpassing AEI in any month. Step 1 helped to obtain multicropping in case of nonoverlapping growing periods, in particular in the case of rice subcrops. As in all other steps, the sum of the assigned grid cell growing areas within the spatial extent of the CCC unit was compared to the monthly growing area for the calendar unit as provided in the CCC. If the growing area in the calendar unit was not reached by a step, the next step was taken (Figure 3). To distribute all irrigated monthly growing areas given in the CCCs, steps 2 to 4 were performed for each unit and each irrigated subcrop starting with the subcrop with the largest (irrigated) harvested area in that unit. For each grid cell and each step, the available growing area was computed in each month of the considered subcrop cropping period as difference of land resource area (defined in Figure 3) and already occupied area. The monthly minimum of the available growing areas was selected. In step 2, irrigated crop areas were assigned to the amount of still available AEI and harvested area in the grid cell for the crop and subcrop. In step 3, it was sufficient to have AEI left and that there is any cropland at all in the cell. In the last step for irrigated crops, remaining area in the calendar unit was assigned to cells with remaining AEI even if no cropland extent was indicated. When the distribution of growing areas was finished for all irrigated subcrops, steps 5 to 7 were performed to assign growing areas for rainfed subcrops to grid cells. Annual and permanent crops were treated differently (Figure 3). In step 5, monthly growing area of rainfed annual crops within a unit was distributed to the total cropland extent that was still available after the distribution of irrigated crops, while rainfed permanent crops were allowed to grow only on cropland that was not equipped for irrigation. In steps 6 and 7, distribution even outside the cropland extent was allowed by considering AEI or 95% of grid cell area as available land resource (Figure 3). The total grid cell area was not completely filled up to account for otherwise occupied areas such as settlements or roads.

[45] In addition to constraints set by AEI and cropland extent, the available land resource was also limited in steps 5 to 7 by the crop-specific annual AH in the grid cell. Since the crop-specific shares of AH at the grid cell level differed from the average share at the calendar unit level, it happened frequently that the crop calendar defined at the unit level was not applicable at the grid cell level. In those cases we tried to compensate at the grid cell level between AH of specific crops and AH in the "other annual crops" category to ensure consistency to crop calendars and total cell-specific AH.

[46] Starting with step 2 in the distribution process, crops and subcrops were processed following a specific order which strongly affected the spatial pattern of monthly crop growing areas because monthly growing area occupied by one crop was no longer available for crops processed afterward and growing in the same month. Three levels of sorting criteria were used to decide which crop or subcrop had to be processed first, for each of the 402 calendar units:

[47] 1. Specific perennial crops (sugarcane, oil palm, citrus, date palm, grapes/vine, cocoa, and coffee) were processed first, followed by other perennial crops and fodder grasses, and then by specific annual crops (wheat, maize, rice, barley, rye, millet, sorghum, soybeans, sunflower, potatoes, cassava, sugar beets, rapeseed/canola, groundnuts/peanuts, pulses, and cotton). Finally, the group of "other annual crops" was processed.

[48] 2. The decision which of the specific crops had to be processed first was based on the amount of annual harvested area of the crop in the CCC; the crop with the largest harvested crop area was processed first.

[49] 3. If a crop class had several subcrops, the subcrops were processed in order of their growing area.

[50] No location preference was made when assigning rainfed growing areas for upland rice, deepwater rice, and paddy rice because information on the potential location of growing areas of these crops was poor. These different rice varieties were treated as individual subcrops and, different from the general rules described before, growing areas were always assigned for upland rice first, then for deepwater rice and finally for paddy rice.

[51] To account for the vernalization requirements of winter varieties of wheat, barley, and rye, we distributed them preferably to grid cells with climate conditions that comply with the vernalization requirements. Winter variety subcrops of these temperate cereals were defined by selecting all cropping periods (subcrops) with a minimum length of 5 months that included December (Northern Hemisphere) or July (Southern Hemisphere). Then grid cells were defined to be suitable for winter cereals if the coldest month of a year has a long-term average monthly air temperature between −10°C and +6°C [*Heistermann*, 2006]. For this purpose, mean monthly air temperature for the period 1961–1990 at 10 arc min resolution [*New et al.*, 2002] was downscaled to 5 arc min resolution by applying an altitude correction using the ETOPO5 data set [*National Geophysical Data Center*, 1988] with the adiabatic lapse rate set to −0.0065°C m^{-1}.

[52] The assignment of harvested areas of crops and subcrops in steps 3, 4, 6, and 7 resulted in an increase of cropland extent to 16,000,368 km^2 at the global scale. The MIRCA2000 cropland extent CE_{MIRCA} as reported for countries (Table S2) and United Nations (UN) regions (Table 5) and discussed in the following sections was about 7% larger than the input cropland extent [*Ramankutty et al.*, 2008].

3. Results

[53] In this section we first present global values of crop-specific irrigated and rainfed harvested areas and describe the importance of different irrigated and rainfed crops for UN regions and countries (section 3.1). Then, the seasonality

Table 4. Crop-Specific Harvested Area Around the Year 2000[a]

Crop Name	Total Area Harvested	Rainfed Area Harvested	Irrigated Area Harvested	Percentage Irrigated
Wheat	2,145,606	1,479,284	666,322	31.1
Maize	1,515,227	1,216,220	299,007	19.7
Rice	1,657,216	626,018	1,031,197	62.2
Barley	551,268	504,810	46,458	8.4
Rye	103,999	99,576	4,423	4.3
Millet	336,386	318,949	17,437	5.2
Sorghum	401,519	367,154	34,366	8.6
Soybeans	748,108	687,782	60,327	8.1
Sunflower	207,578	194,891	12,687	6.1
Potatoes	197,086	159,631	37,455	19.0
Cassava	154,536	154,424	112	0.1
Sugarcane	209,460	107,570	101,890	48.6
Sugar beet	61,932	46,192	15,740	25.4
Oil palm	96,514	96,404	110	0.1
Rapeseed	246,359	212,321	34,038	13.8
Groundnuts	227,207	190,449	36,758	16.2
Pulses	671,202	616,644	54,558	8.1
Citrus	74,820	39,194	35,627	47.6
Date palm	9,184	1,950	7,234	78.8
Grapes	71,417	54,150	17,267	24.2
Cotton	331,516	168,994	162,522	49.0
Cocoa	67,538	67,413	125	0.2
Coffee	101,622	99,883	1,739	1.7
Other perennial	731,402	602,872	128,530	17.6
Fodder grasses	1,046,725	929,885	116,840	11.2
Other annual	1,087,904	886,517	201,387	18.5
Total	13,053,334	9,929,175	3,124,159	23.9

[a]Total, rainfed, and irrigated harvested crop area as area (km^2 yr^{-1}) and as percentage of total harvested area (%).

of specific crops (section 3.2) and the spatial distribution of different types of cropping intensities (section 3.3) are shown.

3.1. Harvested Area of Irrigated and Rainfed Crops

3.1.1. Results at the Global Scale

[54] Total harvested area in MIRCA2000 is 13.0 million km^2 yr^{-1}, of which 9.9 million km^2 yr^{-1} is rainfed, and 3.1 million km^2 yr^{-1} is irrigated (Table 4). The share of irrigated harvested area is 24%, which is larger than AEI [*Siebert et al.*, 2007], which is 18% when expressed as a percentage of the total cropland extent [*Ramankutty et al.*, 2008]. This reflects that average cropping intensity on irrigated land is higher than average cropping intensity in rainfed agriculture.

[55] Harvested area is largest for wheat (2.1 million km^2 yr^{-1}), rice (1.7 million km^2 yr^{-1}), and maize (1.5 million km^2 yr^{-1}). The three crops account for 40% of the total harvested area. Rice (1.0 million km^2 yr^{-1}, 33% of total irrigated harvested area) and wheat (0.7 million km^2 yr^{-1}, 21% of total irrigated harvested area) are the most important irrigated crops while wheat (1.5 million km^2 yr^{-1}, 15% of total rainfed harvested area) and maize (1.2 million km^2 yr^{-1}, 12% of total rainfed harvested area) are the most important rainfed crops (Table 4).

[56] The importance of irrigation differs significantly among the crops. Seventy-nine percent of the date palm harvested area, 62% of the rice harvested area, and 49% of the cotton and sugarcane harvested areas are irrigated. In contrast, harvested areas of cassava, oil palms, cocoa, and coffee are almost completely rainfed. The large harvested area shares of the three crop groups “other perennial,” “other annual,” and “fodder grasses” clearly indicate the diversity of today’s world agriculture (Table 4).

3.1.2. Results at the Regional Scale

[57] Sixty-seven percent of the global AEI and 77% of the total irrigated harvested area are located in Asia. The percentage of harvested area that is irrigated is 41% for Asia, 13% for America, 11% for Oceania, 9% for Africa, and 7% for Europe (Table 5). There are, however, large differences between different subregions and continents (Table 5) or between specific countries (Table S2).

[58] The dominant crops in irrigated and rainfed agriculture differ from region to region and indicate again the diversity of cropping systems (Table 5). In irrigated agriculture, rice is the crop with the largest harvested area share in 7 out of the 19 UN regions, fodder grasses in 3 regions, maize and wheat in 2 regions, and sugarcane, cotton, potatoes, “other perennial,” and “other annual” in 1 region, respectively. In rainfed agriculture, wheat is the crop with the largest harvested area share in 7 regions, maize in 3 regions, rice in 2 regions, and cassava, sorghum, millet, sugarcane, sunflower, fodder grasses, and “other annual” in 1 region, respectively. The shares of the two dominant crops are, in most regions, larger in irrigated agriculture than in rainfed agriculture which indicates that rainfed cropping is more diverse than irrigated cropping and to a lesser extent dominated by specific crops.

[59] The spatial pattern of rainfed and irrigated harvested area as percentage of grid cell area (Figure 4 (top) and 4 (middle)) represents a combination of cropland density and cropping intensity. It shows the absence or scarce occurrence of agricultural crops in higher latitudes where ice

Table 5. Crop Characteristics and Dominant Rainfed and Irrigated Crops in UN Regions[a]

Region[b]	CE_{MIRCA}	AHT	AEI	AHI Area	AHI %	Dominant Crops Irrigated	Dominant Crops Rainfed
Africa	2,317,889	1,675,413	134,578	149,601	9	Other annual (22), wheat (13)	Maize (14), sorghum (12)
Eastern	550,037	389,422	24,645	24,440	6	Rice (50), maize (12)	Maize (22), other annual (16)
Middle	279,680	149,898	1,623	1,419	1	Rice (36), other annual (23)	Cassava (20), maize (18)
Northern	419,963	317,212	82,019	99,573	31	Other annual (27), wheat (13)	Sorghum (20), wheat (20)
Southern	179,675	81,631	15,598	17,194	21	Fodder grasses (25), pulses (8)	Maize (50), fodder grasses (16)
Western	888,535	737,250	10,694	6,976	1	Rice (42), other annual (17)	Millet (17), pulses (12)
America	4,051,076	2,950,491	484,315	375,623	13	Maize (20), fodder grasses (13)	Maize (21), wheat (16)
Caribbean	78,788	47,919	13,142	11,912	25	Sugarcane (44), Maize (14)	Sugarcane (21), other perennial (19)
Central	460,498	223,758	69,068	64,807	29	Maize (26), sorghum (12)	Maize (47), pulses (14)
North	2,277,798	1,670,035	287,033	212,556	13	Rice (23), fodder grasses (21)	Wheat (22), fodder grasses (20)
South	1,233,992	1,008,778	115,073	86,348	9	Rice (28), other perennial (14)	Sunflower (27), maize (18)
Asia	6,200,995	5,803,003	1,876,391	2,402,153	41	Rice (40), wheat (25)	Rice (16), wheat (12)
Central	352,175	251,963	96,454	88,045	35	Cotton (29), fodder grasses (23)	Wheat (67), fodder grasses (17)
Eastern	1,725,876	1,789,669	598,621	906,218	51	Rice (46), wheat (24)	Other annual (18), maize (14)
Southeastern	1,217,671	968,210	167,957	240,553	25	Rice (82), sugarcane (6)	Rice (31), other perennial (24)
Southern	2,444,548	2,452,046	873,857	1,057,434	43	Wheat (33), rice (33)	Rice (19), pulses (15)
Western	460,725	341,115	139,501	109,904	32	Wheat (30), other annual (15)	Wheat (41), barley (21)
Europe	3,088,153	2,367,962	267,727	169,073	7	Maize (21), other annual (16)	Wheat (23), fodder grasses (20)
Eastern	2,083,113	1,489,577	111,170	59,312	4	Fodder grasses (33), maize (18)	Wheat (23), fodder grasses (23)
Northern	216,226	180,914	11,384	5,041	3	Potatoes (29), other annual (19)	Fodder grasses (31), barley (22)
Southern	430,014	362,791	104,608	82,775	23	Other perennial (22), maize (20)	Wheat (21), other perennial (17)
Western	358,800	334,679	40,565	21,945	7	Maize (41), other annual (18)	Wheat (25), other annual (14)
Oceania	342,255	256,466	29,019	27,709	11	Fodder grasses (45), cotton (15)	Wheat (51), barley (16)
World	16,000,368	13,053,334	2,792,030	3,124,159	24	Rice (33), maize (21)	Wheat (15), maize (12)

[a]MIRCA2000 cropland extent CE_{MIRCA} (km^2), total harvested area AHT (km^2 yr^{-1}), area equipped for irrigation AEI (km^2), irrigated harvested area AHI expressed as area (km^2 yr^{-1}) and as percentage of total harvested area (%), and dominant rainfed and irrigated crop classes (selected by harvested area, with represented percentage of total irrigated or total rainfed harvested area in brackets).
[b]Compare with Text S2 for a definition of the regions.

shields or boreal forest exist, such as Greenland, northern Canada, Alaska, Scandinavia, and Siberia. Cropland is found only exceptionally in tropical forests of South America (Amazon basin) and of Africa (Congo basin). In contrast, there is cropland in the tropical regions of Southeast Asia. In subtropical deserts cropland occurs mainly in irrigation oases, e.g., in the Sahara, the Arabian Peninsula, Somalia, Iran, central Asia, parts of Tibet, Mongolia, central Australia, southern Africa, along the western coast of South America, in southwestern United States, and northern Mexico.

[60] Harvested areas of rainfed crops (Figure 4, top) are concentrated in western and southern Asia, Europe, southern Canada, the eastern United States, the northeastern part of Argentina, southern Brazil, West Africa, around Lake Victoria, and along the southwestern and southeastern coast of Australia.

[61] Irrigated harvested area (Figure 4, middle) is particularly high in parts of Asia (Bangladesh, China, northern India, Indonesia, Pakistan, Thailand, and Viet Nam) and the Nile basin. In some grid cells it is even larger than total cell area. This is, to a great extent, due to the double or triple cropping of rice, or single or double rice cropping in combination with other crops [*Frolking et al.*, 2002, 2006; *Frolking and Li*, 2007]. Large irrigated harvested areas also occur at specific places in other parts of Asia, the United States, especially in California and the Great Plains, and in Europe in the river Po basin in northern Italy. In 53% of the grid cells with irrigation, less than 1% of the cell area is irrigated.

[62] When the irrigated harvested area (AHI) is compared to the total harvested area (AHT) for each grid cell (Figure 4, bottom), there is a strong contrast between, on one side, arid, semiarid, and rice-dominated growing areas with high percentages of AHI and, on the other side, humid and temperate growing areas with low percentages (unless rice is grown, like in southern China and Japan). In addition to that, grid cells with a large AHI as compared to total cell area (Figure 4, middle) usually have large values of AHI as a fraction of AHT (Figure 4, bottom). On the other hand, low values of AHI (Figure 4, middle) can be related to very high AHI as fractions of AHT (Figure 4, bottom), showing the dominance of small, disperse irrigation schemes in arid regions. These grid cells are found in the Sahara, southern Africa, the Arabian Peninsula, Iran, central Asia, the Mediterranean, northern Mexico, and the western United States, but also in the southern part of Florida. Similarly, in South America, irrigation is important in the desert areas along the west coast, in Argentina, the Andes, and Chile. However, there are also some hot spots in Brazil, Colombia, and Venezuela.

[63] The high values of AHI in percent of AHT in northern and central Australia and New Zealand (Figure 4, bottom) are artifacts that have two reasons: First, harvested areas

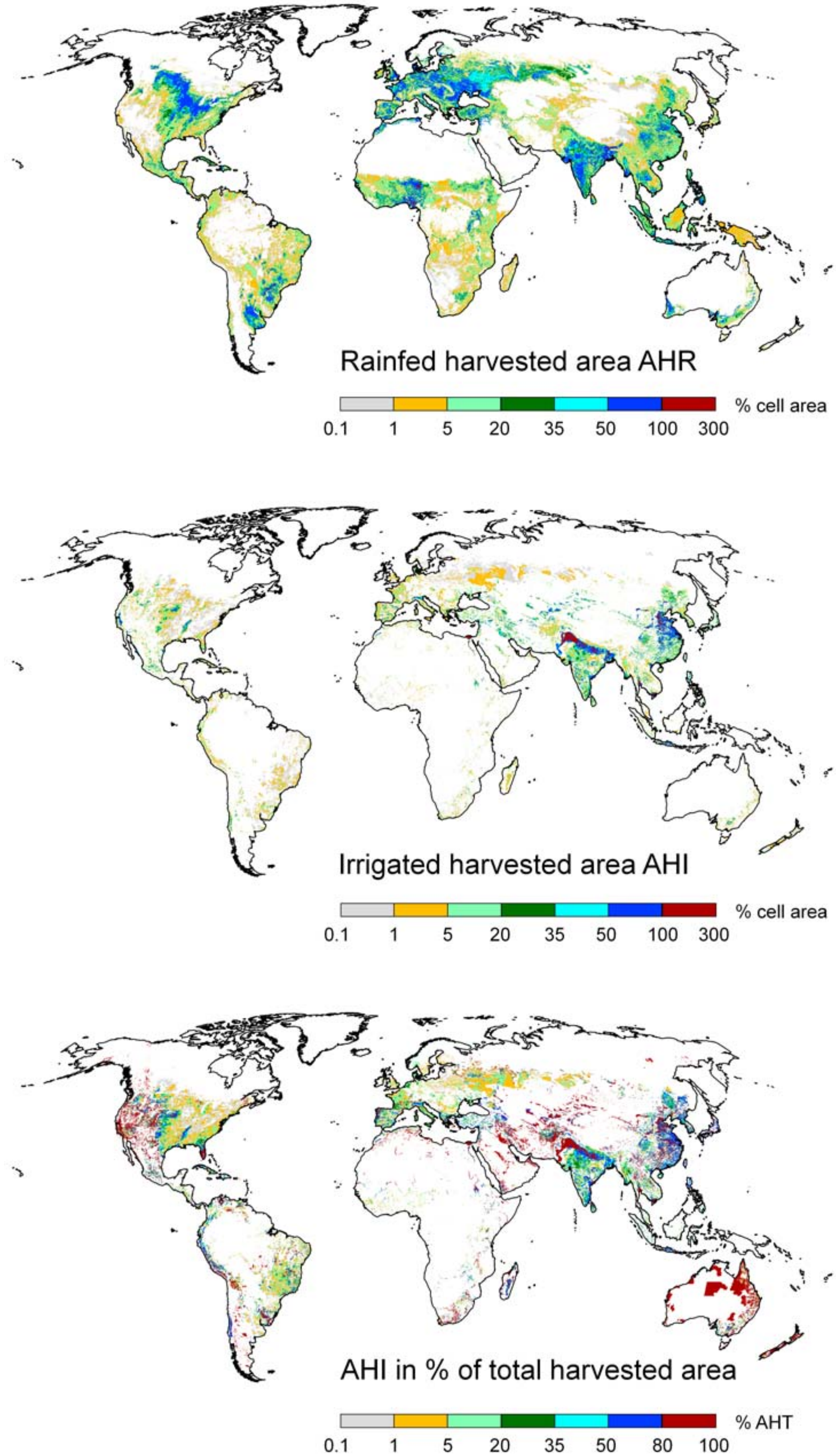

Figure 4. Global distribution of (top) rainfed harvested area (AHR) and (middle) irrigated harvested area (AHI) in percent of grid cell area, and (bottom) AHI in percent of total harvested area (AHT), for 1998–2002.

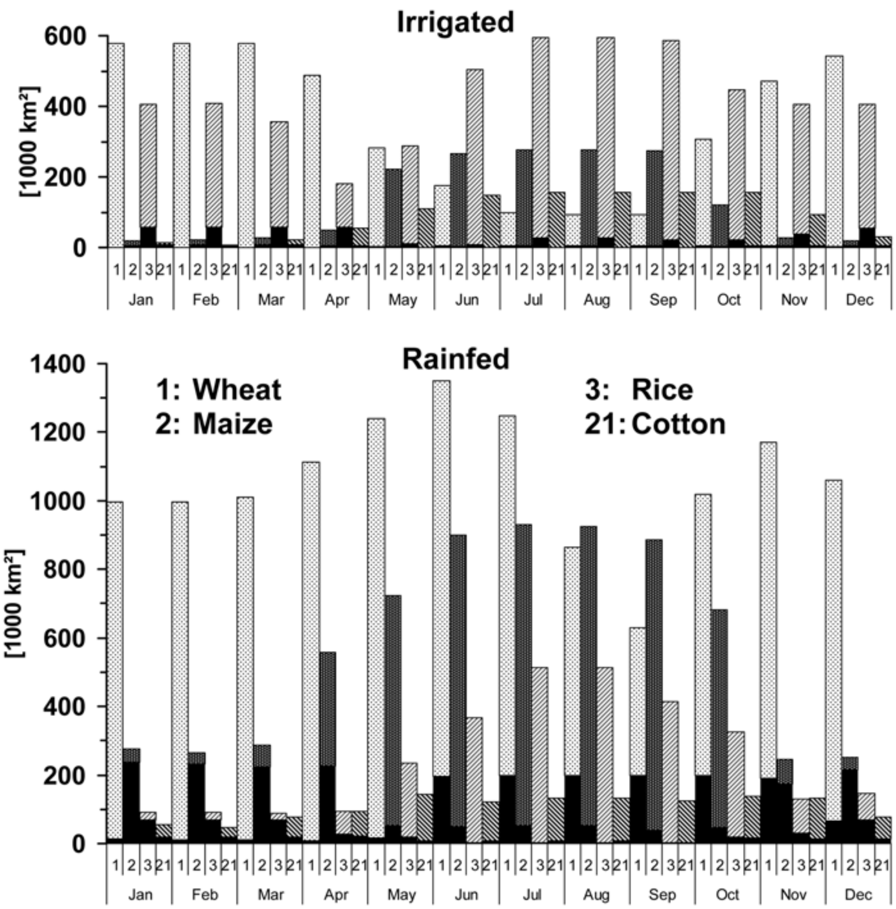

Figure 5. Global monthly growing areas of wheat (crop class 1), maize (crop class 2), rice (crop class 3), and cotton (crop class 21) (top) irrigated and (bottom) rainfed, with distinction of areas of Northern Hemisphere (upper part of columns) and Southern Hemisphere (lower part of columns, in black), in km^2, for 1998–2002.

in the most affected zones are very small (compare to Figures 4 (top) and 4 (middle)) and, in GMIA, small areas of irrigation infrastructure reported for large administrative units were distributed equally over the whole administrative units because geospatial information on the location of irrigation areas was missing. This resulted in very small irrigated areas in each grid cell of the respective units. Since rainfed agriculture is not present there, AHI is then 100% of AHT. In reality, these irrigated areas are very likely to be concentrated in very few places not represented in GMIA. Second, irrigated pasture in these countries is included in AEI, but excluded in the cropland extent and crop-specific harvested areas grids. Irrigated pasture is of particular importance in Oceania, and probably contained in the CCC-Is as "fodder grasses," with the result of many grid cells with high AHI as percentage of AHT.

3.2. Seasonality of Irrigated and Rainfed Crop Growing Areas

[64] In general, harvested areas of irrigated wheat, maize, rice, and cotton in the Southern Hemisphere are very low (Figure 5, top), while larger areas and percentages of total area occur for rainfed maize and rice (Figure 5, bottom). Global sums of monthly crop-specific growing areas show specific intra-annual seasonality (Figure 5). The distribution of irrigated rice (Figure 5, top) reflects multicropping in the major production regions, mainly Asia, with two peaks in July to August and November to February, with a relative maximum during the summer season of each hemisphere. Monthly growing areas of irrigated wheat reflect predominantly cultivation of winter wheat in the Northern Hemisphere in Asia and North America, with a clear peak within the period January to March. Irrigated cotton and maize are mainly grown during Northern Hemisphere summer, with peaks in June to September and June to October, respectively. Monthly growing areas of rainfed wheat (Figure 5, bottom) in the Northern Hemisphere have one peak in May and June caused by a mixture of winter wheat and spring wheat cropping periods. In the Southern Hemisphere, rainfed wheat is predominantly grown in the winter season from June to November. Growing areas of rainfed maize and rice have their maxima in July and August indicating the peak of

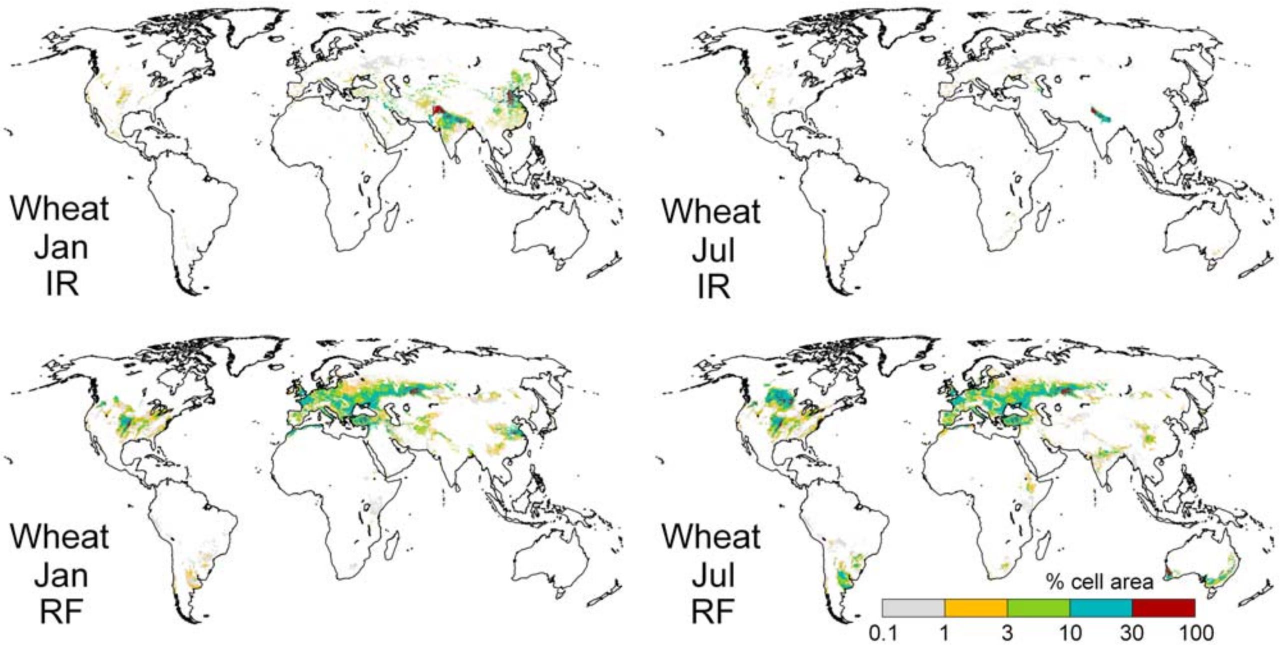

Figure 6. (top) Irrigated (IR) and (bottom) rainfed (RF) monthly growing area of wheat in (left) January and (right) July, in percent of grid cell area, for 1998–2002.

the growing season in Northern Hemisphere summer. In the Southern Hemisphere, both are grown during summer, rainfed maize from November to April, and rainfed rice from December to March. Monthly growing areas of rainfed cotton are much more balanced without any clear peak of the growing season at the global scale.

[65] As an example for the spatial pattern of monthly growing areas provided by MIRCA 2000, Figure 6 shows the growing areas of irrigated and rainfed wheat in January and July. Consistent to Figure 5 (top), much more irrigated wheat is grown in the Northern Hemisphere in January than in July. The pattern of growing areas of rainfed wheat in the Northern Hemisphere is similar for January and July while in the Southern Hemisphere (in Argentina, Brazil, and Australia), rainfed wheat extent prevails in July, during winter.

3.3. Cropping Intensity

[66] Cropping intensity (CI) is generally defined as the average annual number of crops harvested on cropland (yr^{-1}). However, depending on whether temporary fallow land is regarded as cropland or not, the computed CI can differ significantly. We defined a minimum cell-specific cropping intensity CI_min(cell) that takes fallow land into account as

$$CI\_min(cell) = \frac{AH(cell)}{CE_{MIRCA}(cell)} \quad (1)$$

where AH(cell) is the total harvested area (km^2 yr^{-1}) and CE_{MIRCA}(cell) is the MIRCA2000 cropland extent (km^2) that includes temporary fallow land. In contrast, the maximum cell-specific cropping intensity CI_max(cell) was computed as

$$CI\_max(cell) = \frac{AH(cell)}{MMGA(cell)} \quad (2)$$

where MMGA(cell) is the maximum of the sum of monthly growing areas of all irrigated and rainfed crops (km^2). MMGA(cell) was computed by adding up the growing area of all irrigated and rainfed crops for each month and by afterward selecting the maximum of the 12 total monthly growing areas. Thus MMGA(cell) does not include fallow land. Furthermore, the calculation procedure assumed that crops with nonoverlapping cropping periods would be grown on the same piece of land, such as wheat from October to March and rice from April to September. If, for example, in a grid cell half of the cropland is harvested twice a year and the other half of the cropland is fallow, CI_min would be 1.0 while CI_max would be 2.0.

[67] CI_max is large in regions where the climate-based length of the potential growing period and the crop-specific length of the cropping period allow farmers to obtain more than one harvest per year (Figure 7, top). In general, the potential growing period is particularly long in tropical regions where temperature and humidity are high, or in subtropical climates when missing precipitation is replaced by irrigation. Also, cropping periods can be particularly short for specific varieties of annual crops like vegetables or rice. As a result, CI_max(cell) ranges from 0.67 to 3.0. In Asia, maximum cropping intensities higher than 1.6 are found in humid zones with paddy rice cultivation (China, Bangladesh, Viet Nam, Thailand, and Indonesia), or in semiarid zones

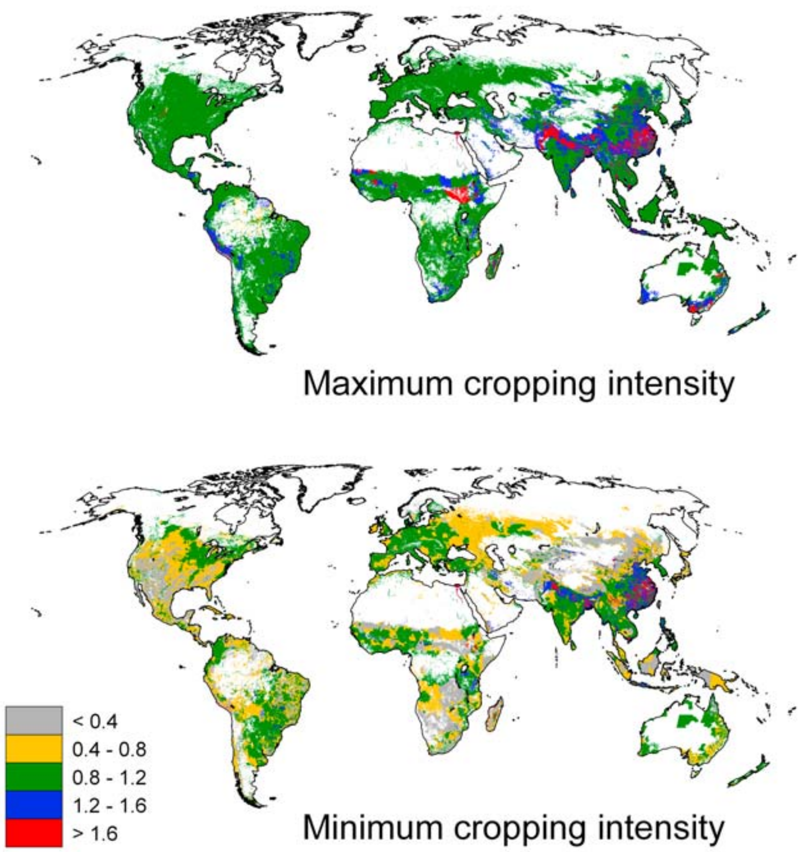

Figure 7. Cropping intensity for 1998–2002, defined by including (bottom) fallow land (CI_min) or (top) not (CI_max).

with irrigation infrastructure (northern India and Pakistan). In Africa, similarly high values of CI_max(cell) are found in irrigated arid areas along the Nile River, but also rainfed areas with relatively small cropping extent in southern Sudan and West Africa. In South America, CI_max was found to be larger than 1.6 in Peru, in irrigation oases in lowlands along the coast. The high values in southwestern and southeastern Australia are associated with rainfed agriculture. Maximum cropping intensities between 1.2 and 1.6 are often found around the aforementioned areas, but also in South Africa and Madagascar, and on the Arabian Peninsula, in Iraq, and in Iran where these areas are associated with irrigation of lower intensity. Maximum cropping intensities in this range are also found in irrigated areas in northern China and in some places in Brazil, Guyana, Suriname, Columbia, Honduras, and the United States. However, by far the largest part of the cultivated areas of the world has a maximum cropping intensity of around 1 (between 0.8 and 1.2), which means that the cultivated areas are cropped only once a year because of limitation of temperature (toward the higher latitudes) or of humidity (in the subtropics and seasonally arid tropics). However, also tropical or subtropical regions, when mainly perennial crops are grown, have a maximum cropping intensity close to 1. Only in grid cells where significant areas were cropped with rainfed cassava, the maximum cropping intensity can be less than 0.8 as we assumed that in general 50% of the harvested area of rainfed cassava was from a late ripening variety with a 21 month cropping period.

[68] CI_min is large in regions with warm temperatures and humid climates like southeast China, Bangladesh, or Ethiopia, but also where missing precipitation has been replaced by irrigation, e.g., in northern India, Pakistan, Mongolia, Iran, Egypt, Madagascar, some selected sites in Tanzania, and in the coastal oases of Peru (Figure 7, bottom). In Brazil, the areas with minimum cropping intensities between 1.2 and 1.6 are associated with rainfed agriculture. A minimum cropping intensity of around 1 is found in the rest of India, and mainly in regions with sufficient rain, e.g., the rest of southeastern Asia, most of Europe (except the Russian Federation), northern parts of the United States, central South America, and in parts of sub-Saharan Africa. Minimum cropping intensities of 0.4 to 0.8 show areas with an increasing share of fallow land, either because of cultivation patterns as in the Great Plains of the United States and in the Russian Federation, or because of drier climate. Finally, minimum cropping intensities lower than 0.4, with large areas of temporary fallow land, are clearly associated to either a dry climate (western United States, parts of sub-Saharan Africa, especially in southern Africa, western Asia, and Mongolia) or shifting cultivation (parts of Indonesia on the islands of Borneo, Celebes, and western New Guinea).

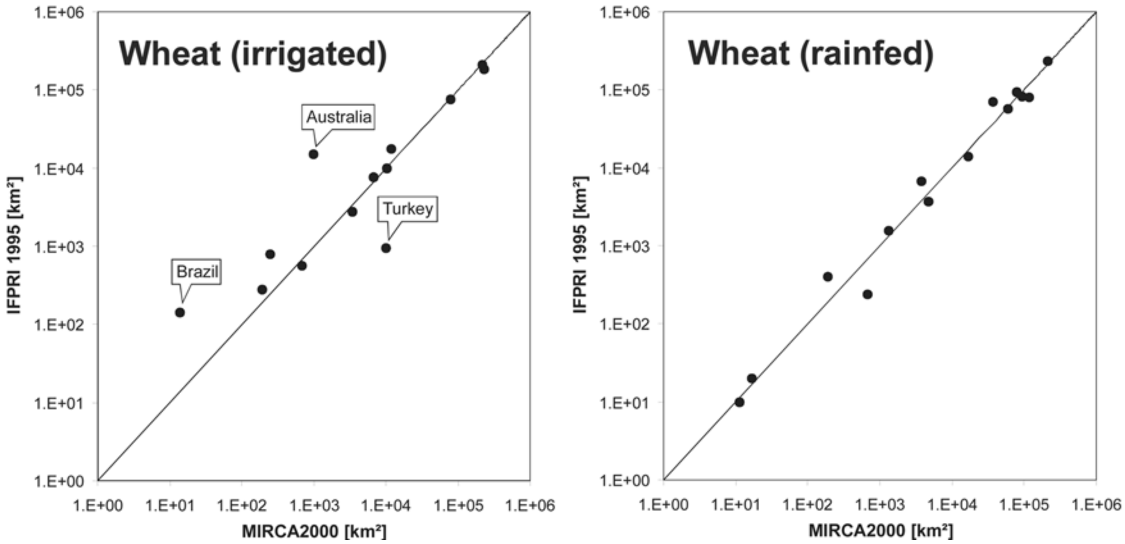

Figure 8. Irrigated and rainfed harvested area of wheat in 21 countries. Comparison of MIRCA2000 values to IFPRI values for 1995.

[69] A small difference between CI_max and CI_min indicates, together with a high cropland density, a large pressure on land resources where not much of the land can be left fallow. Thus it is not surprising to find such small differences in areas of high population density, e.g., in eastern China, India, Bangladesh, on the island of Java, on the Philippines, in Nigeria, Tanzania, southern Brazil, Europe, and the river Nile delta. In contrast, large differences occur in rainfed arid regions (Namibia, western United States, South Australia, and central Asia) or in the aforementioned regions with shifting cultivation.

[70] Globally, total cropland extent is larger than harvested area, resulting in a minimum cropping intensity of 0.84, while for irrigated crops the harvested area exceeds AEI by a factor of 1.12 (Table 5). Total harvested area is larger than MIRCA2000 cropland extent in eastern Asia and southern Asia (Table 5) and also for 14 countries outside these UN regions (Table S2). While irrigated cropping intensity is higher than rainfed cropping intensity, irrigated harvested area is lower than AEI in all UN regions of America and Europe, in western, middle, and eastern Africa, and in central and western Asia (Table 5). This indicates that areas with irrigation infrastructure are either temporarily fallow (particularly in arid regions), or temporarily used by rainfed crops (in more humid regions like Europe or the eastern United States). In contrast, more than one harvest is common on irrigated land in the southern and eastern part of Asia and in the northern and southern part of Africa (Tables 5 and S2).

4. Comparison to Other Data Sets

[71] We compared the MIRCA2000 harvested areas of irrigated and rainfed crops to different inventories per country (section 4.1) or per subnational statistical unit (section 4.2). At the 5 arc min grid scale, cropping periods of MIRCA2000 were compared to cropping periods that were simulated by a dynamic global vegetation model for natural and agricultural vegetation and downscaled from its 30 arc min resolution (section 4.3).

4.1. Comparison to Crop Statistics at Country Level

[72] Totals of harvested area of irrigated and rainfed wheat, rice, maize, and soybeans were compared to data compiled by the International Food Policy Research Institute (IFPRI) [*Rosegrant et al.*, 2002] for year 1995. The squared Pearson product-moment correlation coefficient r^2 (coefficient of determination) was computed by using data reported for 21 countries. Additionally, we computed the Nash-Sutcliffe model efficiency E [*Nash and Sutcliffe*, 1970] as

$$E = 1.0 - \frac{\sum_{i=1}^{n} (O_i - S_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2} \tag{3}$$

where O indicates observed values (here the IFPRI data), $\overline{O}$ is the arithmetic mean of the observed data, and S indicates the simulated (here MIRCA2000) values. Different from r^2, E will only be 1.0 if O and S are identical, not just perfectly correlated.

[73] Irrigated and rainfed harvested areas in the 21 investigated countries generally do not differ much between IFPRI and MIRCA2000, with rather higher values for r^2 and E (Table 6 and Figure 8), particularly for wheat. A likely reason for the good agreement is that IFPRI, like MIRCA2000, used mainly FAO statistics for developing countries (with the exception of China and India). On the global level, MIRCA2000 tends to provide larger rainfed harvested areas than IFPRI. One reason may be the different reference year of the used statistics. Large differences were found for irrigated wheat in Brazil, Australia, and Turkey (Figure 8). For Brazil, MIRCA2000 reports 14 km^2 irrigated wheat on the

Table 6. Comparison of MIRCA2000 Harvested Area to Data From IFPRI, Global Harvested Areas, the Model Efficiencies Nash-Sutcliffe E, and Coefficient of Determination r^2 Calculated From Data for 21 Individual Countries With Validation Data[a]

	Global Harvested Area (km^2 yr^{-1})							
	Irrigated		Rainfed		E		r^2	
Crop	IFPRI	MC2000	IFPRI	MC2000	IR	RF	IR	RF
Wheat	763,340	666,322	1,458,840	1,479,284	0.97	0.95	0.99	0.95
Maize	245,720	299,007	1,135,300	1,216,220	0.80	0.97	0.98	0.97
Rice	871,200	1,031,197	588,860	626,018	0.90	0.88	0.98	0.90
Soybeans	92,960	60,327	528,940	687,782	0.83	0.91	0.88	0.98

[a]IR, irrigated; RF, rainfed.

basis of national census statistics of 1995–1996 [*IBGE*, 1997] expected to be representative for the year 2000 [*Portmann et al.*, 2008], while *Rosegrant et al.* [2002] reported 140 km^2 which is 10 times more. The MIRCA2000 data are more consistent with FAO sources that mention no irrigated wheat at all, e.g., *FAO* [2005a]. For Turkey, the relationship is opposite, with similar total irrigated and rainfed harvested areas in both data sets (ca. 90,000 km^2) but about 10,000 km^2 irrigated wheat according to FAO calendars [*FAO*, 2005a] in MIRCA2000 and only about 1000 km^2 irrigated wheat reported by IFPRI. As in both cases the values differ by the position of the decimal points; the MIRCA2000 sources were reexamined for possible errors, but no transfer error was detected. For Australia, the totals are also of similar order of magnitude (~118,000 km^2 in MIRCA2000 and ~95,000 km^2 in IFPRI) while the irrigated share is very different, ~1000 km^2 as opposed to 15,000 km^2 in IFPRI. The MIRCA2000 value appears to be more reliable here, as the national census lists only 1670 km^2 irrigated harvested area of cereals other than rice [*ABS*, 2002, 2001].

4.2. Comparison to Subnational Crop Statistics

[74] MIRCA2000 harvested areas of irrigated maize and irrigated grapes were compared to statistics of EUROSTAT for 103 first-level subnational units in nine countries (Austria, France, Hungary, Italy, the Netherlands, Portugal, Romania, Slovakia, and Spain). To develop MIRCA2000, statistics on national totals of crop-specific monthly irrigated and rainfed growing areas were used for these countries, each country being a calendar unit. This comparison shows how well the downscaling of national statistics to the grid cell level can reproduce the regional differences shown by the subnational statistics that refer to year 2003. To compare the spatial distribution for both crops, irrigated harvested area

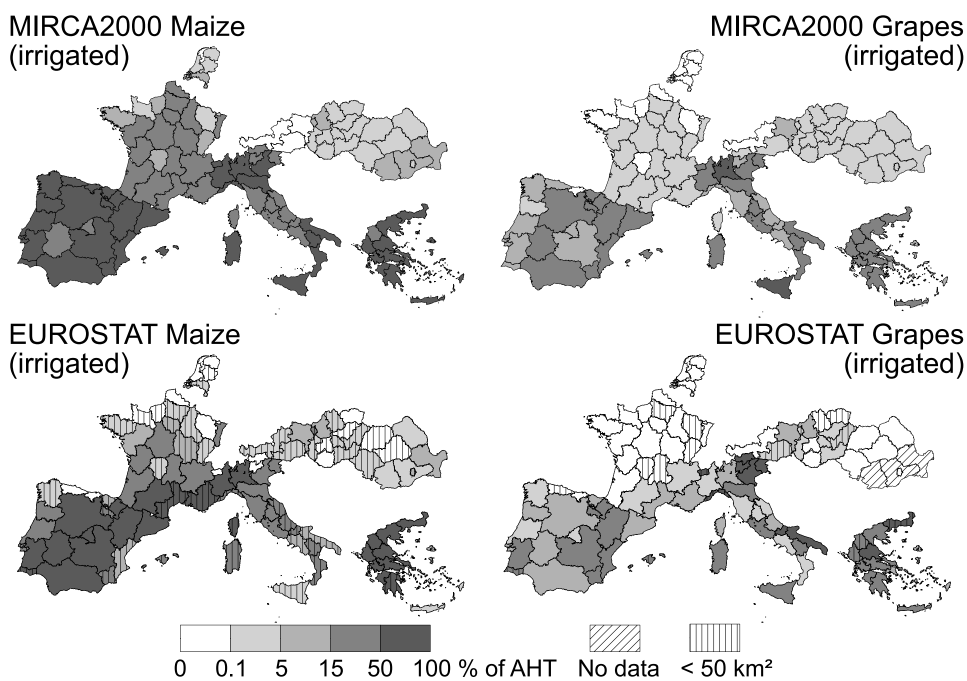

Figure 9. Irrigated harvested area as a percentage of total harvested area for maize and grapes according to (top) MIRCA2000 and (bottom) EUROSTAT for 2003, by EUROSTAT NUTS administrative units of 2003. Units with EUROSTAT irrigated harvested area less than 50 km^2 are marked by vertical hatching, and units with no EUROSTAT data for total harvested area are marked by diagonal hatching.

[*EUROSTAT*, 2008a] as percentage of total harvested crop area [*EUROSTAT*, 2008b] was calculated and compared to MIRCA2000 data generated by summing up the cell-specific areas for each subnational unit (Figure 9). In order to indicate the relevance of the differences, all units with less than 50 km^2 of irrigated harvested crop area are indicated by vertical hatching.

[75] For both maize and grapes, the percentages of irrigated crop area in MIRCA2000 are more evenly distributed than in EUROSTAT, and only a small part of the within-country differences reported by the EUROSTAT reference data was captured. For example, the strong north-south gradient in the percentage of irrigated maize reported for Portugal and France was only partly captured. In Italy there is a good agreement for the subnational regions in the northwest and the center of the country, but differences occur for Emilia-Romagna and Veneto in the northeast and for the minor growing areas in the south of the country. That irrigation is important in France for maize but not for grapes production is well represented in the MIRCA2000 data set. However, this only shows that the national data of irrigated and rainfed maize and grapes are consistent with the subnational data used here. With respect to Austria, the data sources for MIRCA2000 did not specify maize as an irrigated crop [*Portmann et al.*, 2008] such that irrigated maize in Austria as given in EUROSTAT is not represented at all in MIRCA2000. The comparison shows that MIRCA cannot represent well the split of rainfed and harvested areas of specific crops at the scale below the calendar unit if, within a country, a crop is grown both under rainfed and irrigated conditions. Representation of subscale differences in the importance of irrigation for specific crops could be improved if Condensed Crop Calendars were defined for subnational units, in particular for large countries that have zones with very different climate and soil conditions.

4.3. Cropping Periods

[76] MIRCA2000 cropping periods are compared in the following section to simulation results of the dynamic global vegetation model "Lund-Potsdam-Jena managed Land" (LPJmL) [*Bondeau et al.*, 2007; *Rost et al.*, 2008a]. Other available data sets are limited to selected countries like India [*Frolking et al.*, 2006] or China [*Frolking et al.*, 2002]. The latter data set reports multicropping harvested area of rice and other crops for Chinese provinces. However, this data set is based on crop data that were gathered before the 1997 National Agricultural Census which obviously introduced revised census methods, resulting in benchmark data for 1996, e.g., for cropland extent and sown area. The data set could possibly be outdated or inconsistent with the input data used in MIRCA2000 for China [*FAO*, 2005a; *Monfreda et al.*, 2008]. So differences arising in a comparison would rather reflect different input data than differences in methodology concerning multicropping. Also, this data set does not distinguish rainfed and irrigated crops. Furthermore, it considers crop rotations, but does not mention growing areas in specific months. It would have required crop calendars with cropping periods for these crop rotations to compare these in detail with the MIRCA2000 cropping periods.

[77] LPJmL simulates for 13 crop functional types (e.g., temperate/tropical cereals and roots, rice, maize, and pulses) the optimal growing period and related crop yields considering cell-specific climate, soil properties, and agricultural management (in particular, irrigation, fertilization, straw, and residue processing). The spatial resolution of the model is 30 arc min. For each grid cell, the start dates of the cropping periods in the MIRCA2000 Condensed Cropping Calendars (CCC) were compared to mean sowing and harvesting dates simulated by LPJmL. Except for rice, LPJmL does not allow multicropping. The objectives of this comparison were to (1) test the general agreement of the cropping periods between the MIRCA2000 data set to the simulation results of the vegetation model; (2) explore the variability of planting dates inside the 402 spatial units as computed by LPJmL and not taken into account in MIRCA2000; (3) assess where MIRCA2000 assigns growing areas to grid cells where biophysical constraints as taken into account by LPJmL might prevent any crop growth; and (4) evaluate the importance of multicropping practices considered in MIRCA2000 but not yet considered in LPJmL.

[78] We selected maize and wheat (the latter being parameterized as temperate cereal in LPJmL) for this comparison. Maize was selected because it is grown in temperate and tropical climate zones, and because in most regions it is grown as a single crop. In contrast, wheat is mainly cultivated in temperate climate as either winter wheat (with vernalization requirement) or spring wheat. In subtropical regions, wheat is often cultivated in multicropping systems during the winter period. To compare the data sets, the LPJmL results were downscaled to 5 arc min resolution by assigning the cropping periods of the 30 arc min grid cells to each of the 5 arc min cells located within the related 30 arc min cell. Monthly data reported by MIRCA2000 were converted to Julian days as used by LPJmL by assuming that cropping periods started at the first day of the month reported in the Condensed Crop Calendars. For each cell in which LPJmL allowed a cropping period for the specific crop, the difference of the sowing date between MIRCA2000 and LPJmL was calculated. Additionally we computed the percentage of harvested crop areas that were reported in MIRCA2000 but excluded in LPJmL because of biophysical constraints assumed in the model (cAH in Table 7). If more than one subcrop was reported in MIRCA2000, a mean difference was computed by weighting the differences computed for the specific subcrops by their harvested area. Negative values indicated that the cropping period in MIRCA2000 started earlier (Table 7).

[79] Globally, the percentage of MIRCA2000 harvested crop area that was located in grid cells where LPJmL did not allow the crop growth was 2% for irrigated maize, 5% for rainfed maize, 6% for rainfed wheat, and 41% for irrigated wheat (cAH in Table 7). In eastern, middle, and western Africa, Central America, and southeastern Asia, more than 80% of the MIRCA2000 harvested area of irrigated and rainfed wheat was lost in LPJmL. The reason was that in LPJmL, wheat was parameterized as temperate cereal such that wheat growing in tropical regions was not possible.

[80] The absolute area-weighted differences in the start of the cropping periods were relatively large, between 43 days

Table 7. Absolute Difference Between Start of Cropping Period as Computed by MIRCA2000 and LPJmL[a]

	Irrigated				Rainfed			
	Wheat		Maize		Wheat		Maize	
Region[b]	cAH	Start	cAH	Start	cAH	Start	cAH	Start
Africa	17	75	1	98	22	39	8	51
Eastern	98	90	1	105	99	152	6	59
Middle	88	33	0	137	100	-	6	50
Northern	9	78	1	94	4	39	29	48
Southern	34	44	0	97	17	39	22	34
Western	100	-	0	138	100	-	2	48
America	27	65	2	46	4	35	3	42
Caribbean	-	-	6	131	-	-	7	36
Central	84	62	1	117	98	131	1	31
North	0	62	1	15	0	34	3	34
South	11	85	15	75	17	37	5	60
Asia	43	52	2	42	11	68	8	57
Central	0	49	2	21	0	112	-	-
Eastern	2	46	2	28	4	64	5	62
Southeastern	99	52	6	47	96	80	11	73
Southern	73	69	1	125	42	47	10	29
Western	11	41	3	57	2	30	23	34
Europe	1	35	3	27	1	41	3	22
Eastern	1	12	1	5	0	28	1	10
Northern	3	148	4	49	5	116	21	47
Southern	1	68	5	32	2	59	10	52
Western	1	97	1	45	1	47	6	43
Oceania	2	31	1	94	8	16	35	73
World	41	53	2	44	6	44	5	43

[a]In days, together with the MIRCA2000 harvested area in grid cells where, according to LPJmL, constraints do not allow crop growth, in percent of MIRCA2000 harvested area (cAH), for wheat and maize as irrigated and rainfed crops. Unrepresented comparisons are denoted by hyphens. In the case of wheat in MIRCA2000, the start date is an area-weighted average of the start dates for winter and summer cropping periods in those grid cells in which both exist. The values for the UN regions are area-weighted averages derived from grid cell data.

[b]Compare with Text S2 for a definition of the regions.

(rainfed maize) and 53 days (irrigated wheat) at the global scale (Table 7). At the scale of the UN regions, a relatively good agreement was found for rainfed maize, for irrigated maize in regions with temperate climate (Europe and North America), and for wheat in eastern Europe and western Asia. For rainfed and irrigated wheat, the maps of the differences in the start of the cropping period (Figure 10, left) show a similar global pattern, except for South America. In the Russian Federation, LPJmL simulates spring wheat in the north and winter wheat in the south considering the different climate conditions. In contrast, in MIRCA2000 there is winter and spring wheat in all wheat growing areas resulting in large differences in the start of the cropping period in northern Russia. Obviously, the share of winter wheat estimated in the MIRCA2000 CCCs for the whole of the Russian Federation was too high and should be regionally reduced to limit winter wheat growing to zones with a more suitable climate.

[81] The spatial pattern of differences in the start of the cropping period for rainfed maize in western Africa (Figure 10, right) shows that the country-level MIRCA2000 cropping periods start later in the south and earlier in the north so that the differences level out when considering averages. The reason is that the cropping period starts at the same time in MIRCA2000 for all grid cells belonging to the same country while LPJmL considers cell-specific rainfall seasonality and thus better simulates the actual variability of planting dates.

[82] Large differences occur if LPJmL simulates only one cropping period defined by optimum climate conditions, while in MIRCA2000, multicropping practices are manifested. This concerns, e.g., irrigated maize in southeast China or in India. Here, often maize is cultivated in rotation with other crops, and farmers try to optimize the whole multicropping system [*Frolking et al.*, 2002; *Frolking and Li*, 2007]. In particular, if maize is cultivated as a second or third crop in a paddy rice rotation, the maize cropping period will differ largely from its crop-specific optimum. Paddy rice is then cultivated as the main crop in the warm summer season while maize is growing in the winter period. In MIRCA2000 those comparative advantages between different crops are considered (although with reduced complexity) by prescribing the unit-level cropping calendars.

[83] To conclude, there is a good agreement between the MIRCA2000 and the LPJmL cropping periods for small calendar units in temperate regions. Large differences are found for tropical and subtropical regions in particular if multicropping is practiced (not always modeled by LPJmL), or in large calendar units with biophysical constraints resulting in spatially differentiated cropping calendars that are not represented in MIRCA2000 (e.g., Russian Federation and Canada).

5. Discussion

[84] In the following section we first discuss major uncertainties and limitations of the MIRCA2000 data set. We then compare the methodology used to develop MIRCA2000 to other approaches and identify major advantages and shortcomings. Finally, we present ideas for possible improvements of the data set.

5.1. Uncertainties and Limitations of the MIRCA2000 Data Set

[85] MIRCA2000 was developed by combining spatial data layers of harvested crop area, cropland extent, and area equipped for irrigation with unit-level cropping calendars and statistics on irrigated harvested crop area derived from several databases and from literature. Uncertainties contained in these input data were therefore automatically introduced also into the MIRCA2000 data set. The major uncertainties in the input spatial data layers were investigated and discussed already [*Ramankutty et al.*, 2008; *Monfreda et al.*, 2008; *Siebert et al.*, 2005]. To estimate the reliability and precision of the unit-level crop-specific irrigation statistics and the crop calendars used as additional input to MIRCA2000 is very difficult. Most of the data were collected by national census organizations, reported to FAO and complemented there by expert guesses [*FAO*, 2005a]. Because of data gaps in classification and regional coverage, it was furthermore

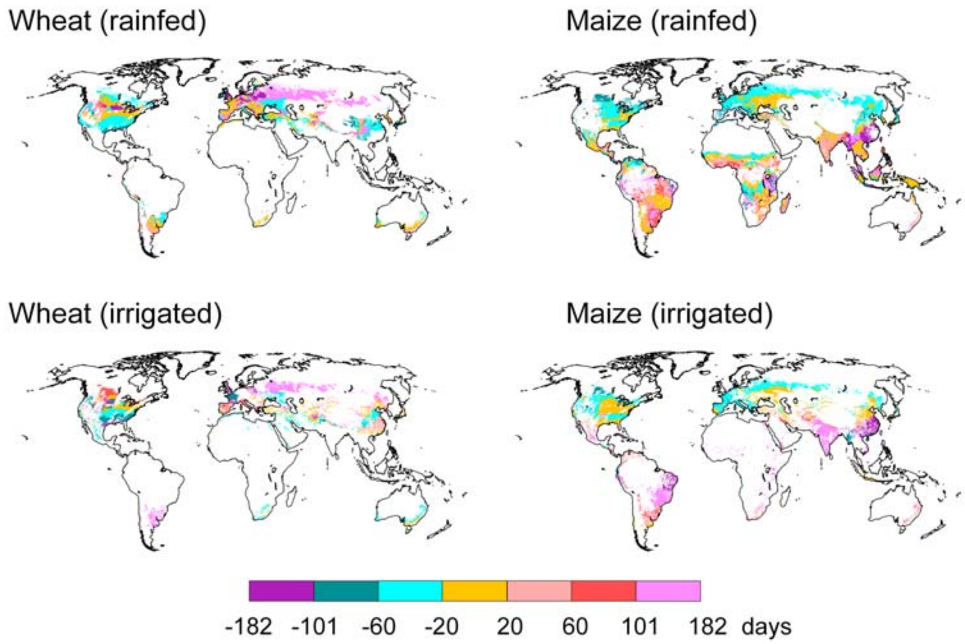

Figure 10. Differences between start of cropping period as computed by MIRCA2000 and LPJmL for wheat and maize as rainfed and irrigated crops, in days. Negative values denote that the period in MIRCA2000 starts earlier. In the case of wheat in MIRCA2000, the start date is an average of the start dates for winter and summer cropping periods in those cells in which both exist.

necessary to estimate irrigated harvested areas for several crops and countries (section 2.2.2). The comparison to other data sets in the last section showed that the MIRCA2000 estimates of the share of crop-specific irrigated harvested area at the country level are very similar to other estimates. Spatial patterns of the importance of irrigated crop area were reasonably reproduced by MIRCA2000, but only at the scale of the 402 calendar units. There are important differences in the MIRCA2000 crop seasonality as compared to cropping periods simulated by a dynamic global vegetation model. The MIRCA2000 data set should therefore be used with caution in areas where local biophysical constraints differ considerably from average constraints in the calendar unit.

[86] Many complex cultivation systems in which more than one crop is grown on the same field at the same time cannot be represented in our data model. Such systems are regionally important, e.g., agroforestry in tropical regions and mixed cultivation in sub-Saharan Africa. Besides, it is very likely that many cropping systems are in reality much more complex than those realized in MIRCA2000, in particular when multicropping is practiced. Field-scale crop rotation is not represented in MIRCA2000, as crop mapping at the field level is impossible at the macroscale. However, monthly growing areas at the grid cell level represent the spatiotemporal average of crop rotations at the field scale.

[87] With respect to the compilation of the Condensed Crop Calendars for irrigated crops, quite often only the areas of major crops are explicitly provided in the statistics, while minor crops are contained in aggregate groups like "other cereals," "other roots and tubers," or "other crops." In many cases, information to disaggregate this area to specific crops (e.g., information with approximate shares of individual crop areas) was not available. As a consequence, if statistical reporting was poor, significant harvested areas of specific crops may be hidden in the crop classes "other annual" or "other perennial crops." Therefore, the MIRCA2000 harvested areas of the specific crops have to be considered as conservatively estimated minimum areas. Likewise, fodder grasses on cropland, fodder crops on cropland, and rangeland are often not clearly distinguished in the statistics. Thus, harvested area of irrigated fodder grasses could be overestimated in some countries such as Australia, where a significant percentage of rangeland is irrigated, and in the United States.

5.2. Discussion of Methodology in Comparison to Other Approaches

[88] In MIRCA2000, the final crop distribution pattern is mainly determined by the attempt to maximize consistency of the spatial data layers on cropland extent, AH, and AEI with the data on harvested irrigated and rainfed crop area and the crop calendars defined for each calendar unit. The cropping periods of specific subcrops in MIRCA2000 are kept constant for all grid cells belonging to the same calendar unit. In contrast, other downscaling approaches include economic factors together with crop distribution probability [*Cai et al.*, 2007], crop suitability [*You and Wood*, 2006; *Fischer et al.*, 2008], or biophysical constraints [*Bondeau et al.*, 2007; *Rost et al.*, 2008a] to define crop distribution patterns or to simulate cell-specific cropping periods. The main advantages of MIRCA2000 are that the reported crop seasonality considers multicropping and is compatible to the

spatial pattern of crop distribution. Furthermore, the sum of harvested area for irrigated and rainfed crops as well as the sum of irrigated area for all crops is compatible to spatially often highly resolved statistical data (section 2.1) or estimates collected for the specific calendar units. Shortcomings of MIRCA2000 are that, because of missing biophysical constraints and the rather coarse resolution of calendar units, crops can grow in areas and/or cropping periods that are not suitable. Advantages of the aforementioned other approaches are that their consideration of crop-specific constraints and crop suitability in conjunction with climate and economic variables introduces an additional predictive power that should improve the reproduction of spatial differences in the crop distribution pattern. Additionally, these approaches can more easily be implemented in the analysis of scenarios of future climate and land use. Drawbacks of such approaches are first, the missing or strongly simplified and idealized consideration of crop seasonality in the downscaling of crop statistics and second, that considering additional variables and assumptions can also introduce additional uncertainties. A general assumption in these approaches is that the difference between different crops is larger than within the represented crop varieties. However, it is, for example, often the case that many characteristics and properties of crops like the length of the cropping period or the crop yield differ more between varieties of the same crop (e.g., traditional landraces versus modern high-yield varieties) than between different crop species [*Doorenbos and Pruitt*, 1977]. This problem has not yet been resolved, and to account for this complexity in the spatial downscaling remains a challenge. Besides, human decisions on crop production are based on complex reasoning that cannot be captured by macroscale modeling approaches. In MIRCA2000, long-term average decisions can implicitly be included in the CCCs. A quantitative comparison of the crop distribution pattern of MIRCA2000 to results of these other approaches was either not possible because global products are not available yet [*Cai et al.*, 2007; *You and Wood*, 2006] or not useful because of incompatibilities in basic land use data layers used to define the crop distribution pattern [*Bondeau et al.*, 2007; *Rost et al.*, 2008a].

5.3. Possibilities for Improving MIRCA2000

[89] It is obvious that considering input data for an increased number of subnational calendar units can improve the spatial pattern of irrigated and rainfed crop areas, as well as the related crop seasonality in MIRCA2000. The focus on gathering new data should be on large countries with different climate zones that are represented in the current version of MIRCA2000 by one calendar unit only, e.g., subnational distribution patterns of winter and summer cereals in the Russian Federation. An aridity indicator (e.g., the ratio of precipitation and potential evapotranspiration) could be used to exclude rainfed cropping in very dry regions or seasons. Artifacts of rainfed cultivation in very arid areas stemming from different total harvested area in the different input data could be avoided by harmonizing the crop-specific harvested area in the CCCs for irrigated crops to the total crop-specific harvested area by *Monfreda et al.* [2008]. A consequent separation of pasture/meadows and cropland could result in a separate data layer of irrigated and rainfed pasture/meadows. The separation is difficult, as data are available for a few countries only, and as in reality, pasture and cropland with fodder grasses are not always clearly separated. However, this would improve estimates in particular for Australia and the United States.

[90] Further possibilities to improve MIRCA2000 may be detected through the comparison of MIRCA2000 results with the results of other spatial downscaling approaches as soon as these data will become available. Cropping periods simulated by LPJmL based on crop-specific harvested areas of MIRCA2000 could be used to improve the estimates of the share of spring and winter varieties for temperate cereals and to improve the CCCs for crops and calendar units where it was necessary to estimate the cropping period based on own expertise.

5.4. Application of MIRCA2000 to Estimate Irrigated and Rainfed Crop Yields

[91] As the productivity on irrigated land is usually higher, the fraction of total harvested area that is irrigated is different from the fraction of total crop production on irrigated land. This was demonstrated in a related paper. The MIRCA2000 data set was used to model crop water requirements and crop production in irrigated and rainfed agriculture for the period 1998–2002 [*Siebert and Döll*, 2009]. The list of globally important cereals encompassed wheat, maize, rice, barley, rye, millet, and sorghum. A separation of fodder versus grain cereals was made for maize, rye, and sorghum, because the productivity is much higher when cereals are harvested as fodder. It was found that 33% of global crop production and 44% of total cereal grain production stem from irrigated agriculture. In contrast, only 24% of the global harvested crop area and 32% of the global harvested cereal area are irrigated (31% when including fodder cereals; see Table 4). The potential production losses when not using irrigation were 18% in total crop production and 20% in cereal production, although differing significantly among countries and crops.

6. Conclusions

[92] The MIRCA2000 data set compiles, for the first time, crop-specific growing areas under irrigated and rainfed conditions with a spatial resolution of 5 arc min. Twenty-six crop classes were selected to cover all major food and fodder crops as well as cotton, while establishment of the classes “other annual” and “other perennial crops” ensures that the complete crop production is covered by MIRCA2000. Also for the first time, cropping calendars were consistently linked to annual values of harvested area at the 5 arc min grid cell level, such that growing areas for each month of the year could be computed, representative for the time period 1998 to 2002. Consistency between the monthly growing data, the cultivable area in form of cropland extent and area equipped for irrigation has been maximized. Finally, MIRCA2000 is the first global agricultural land use data set that includes multicropping.

[93] The MIRCA2000 data set includes four product subsets, each separately for 26 irrigated and 26 rainfed crops: (1) 5 arc min cell-level monthly growing area grid (MGAG); (2) 5 arc min cell-level maximum monthly growing area grid

(MMGAG); (3) 5 arc min cell-level cropping period list (CPL) (with harvested area, start and end of growing periods); and (4) the unit-level condensed crop calendars (CCC) (CPL on unit level).

[94] MIRCA2000 is the result of processing a large amount of different data at different spatial scales such that maximal consistency is achieved. The spatial pattern of cropping intensity which results from the monthly growing areas appears to be plausible (Figure 7). This supports the validity of the chosen approach. Comparison to a European data set on subnational crop-specific harvested areas of maize and grapes under rainfed and irrigated conditions showed that MIRCA2000 reflects rather well the differences in irrigated harvested area among countries (calendar units) but not within countries (Figure 9). This is due to the application of only one crop calendar per country. Thus, efforts are required to decrease the size of the spatial units for which crop calendars are compiled.

[95] The comparison of growing periods between data-based MIRCA2000 and the model LPJmL which simulates growing periods using biophysical constraints indicates that future work should be invested in improving grid cell level data of harvested area that are an input to MIRCA2000. In contrast to the approach used to generate the currently applied data set of *Monfreda et al.* [2008], biophysical constraints should be taken into account for downscaling statistical data of harvested area for administrative units. Then, the MIRCA2000 methodology for temporal downscaling to monthly irrigated and rainfed growing areas could be modified to include consistent biophysical constraints.

[96] MIRCA2000 has an unsurpassed level of detail and is a valuable basis for many different applications. These include the quantification of virtual water flows and water footprints, studies on food security and other agricultural aspects, as well as many other assessments that require a good characterization of crop production. Being based on reference data, MIRCA2000 is suited for global studies and refers to present-day conditions. We encourage researchers to work with our free data set and give feedback on errors or possible improvements.

[97] **Acknowledgments.** We thank Navin Ramankutty and Chad Monfreda for providing preversions of their data sets on cropland extent and crop-specific harvested area. Our students Nicole Stuber, Christian Bauer, Georg Stiebeling, and Frank Königstein were a great help in data processing. We are indebted to the Potsdam-Institute for Climate Impact Research (PIK) where Stefanie Rost provided grids of sowing and harvesting dates of the LPJmL model, while we thank Dieter Gerten and Marianela Fader for very helpful, intensive discussions. This research was funded by the German Research Foundation (Deutsche Forschungsgemeinschaft (DFG)).

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